IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Occupational Radiation Protection during High Exposure Operations

Health Effects Caused by Radiation and
Basis for Radiological Protection

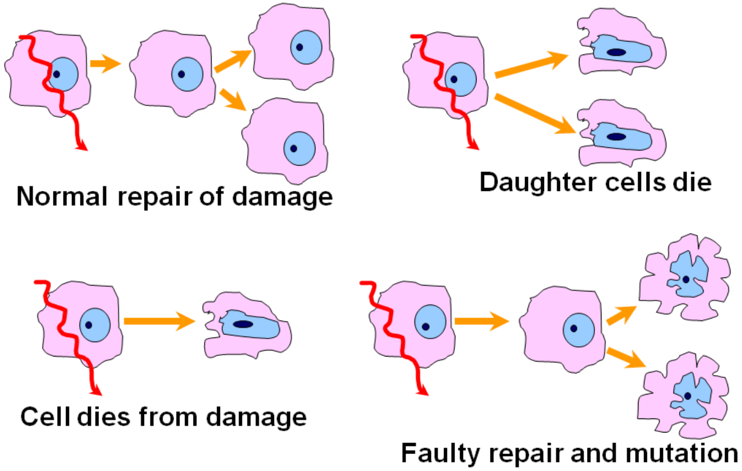
Contents

1. Introduction

When ionizing radiation passes through matter, some of its energy is imparted to the matter by means of ionization and excitation of atoms and molecules. Impartment of radiation energy to matter is the starting point for developing radiation health effects in human, animals, plants and microorganisms – in all living beings.

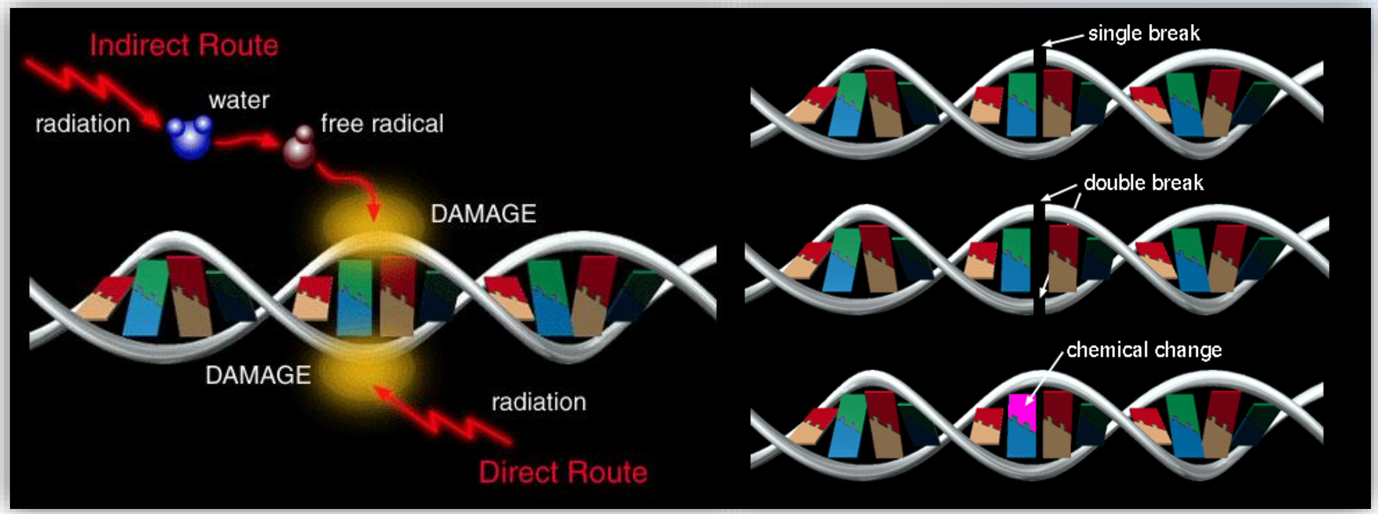
1. Introduction

- Tissues and organs are composed by cells of different kinds and radiation damage of these cells leads to development of radiation health effects.
- The target for most biological effects of ionizing radiation is the genome of the cell, the DNA, which is the macromolecule of desoxyribonucleic acid.



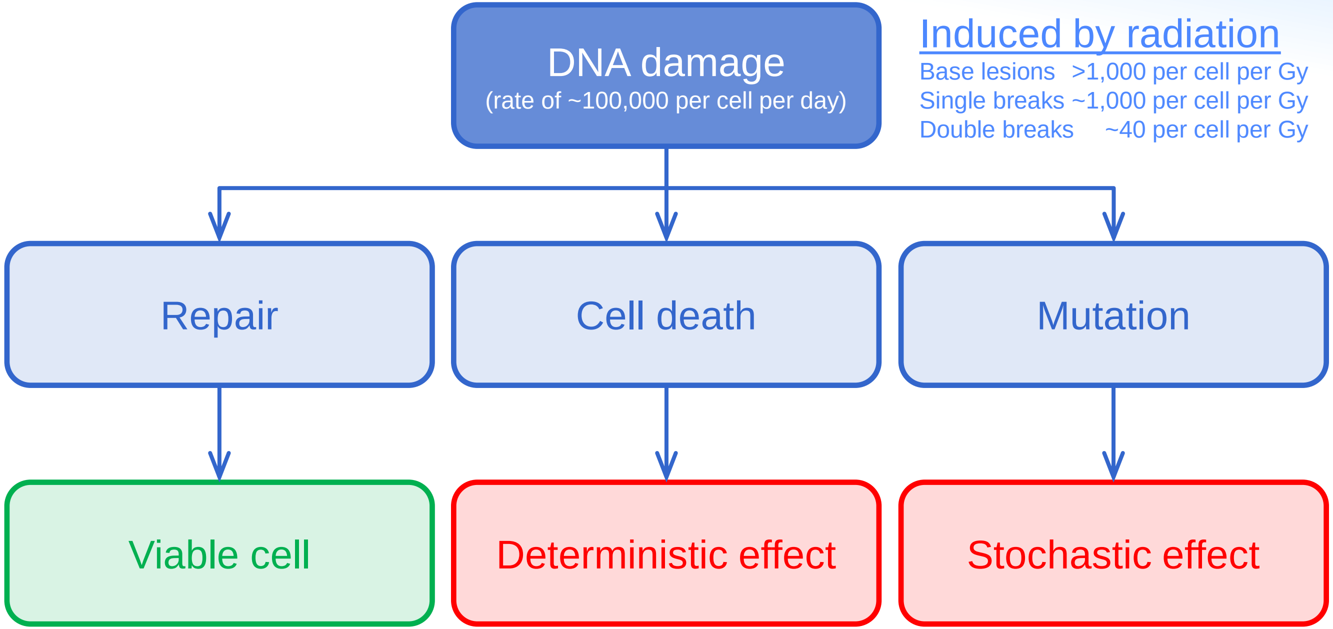
Outcomes of DNA damage

Direct and Indirect Radiation Effects



- Indirect action predominant with low-LET radiation (X- and gamma rays)
- Direct action predominant with high-LET radiation (charged particles)

Consequences of DNA Damage



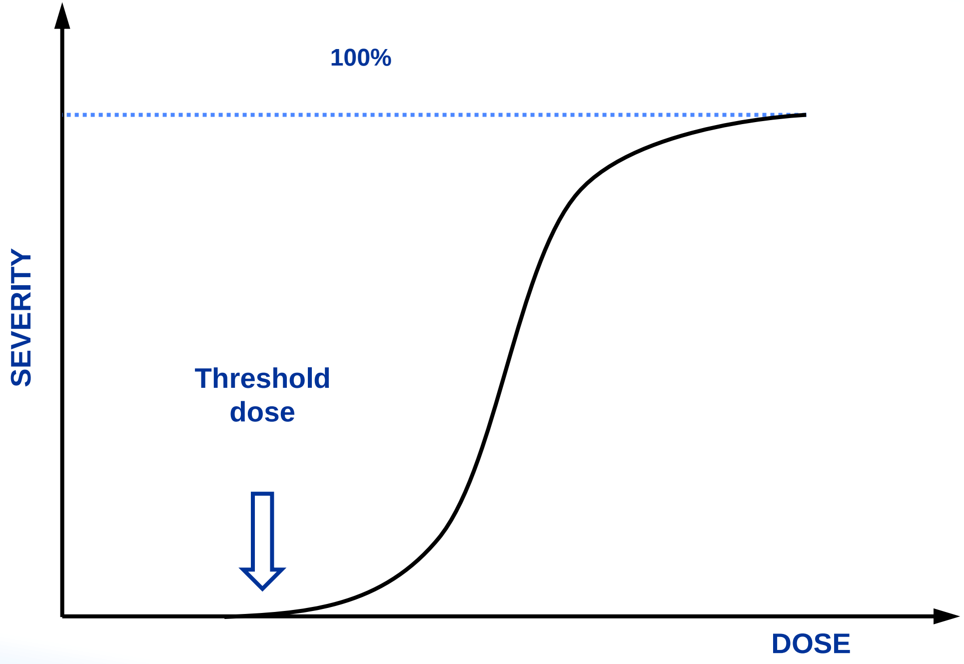
Induced by radiation

Base lesions >1,000 per cell per Gy
Single breaks ~1,000 per cell per Gy
Double breaks ~40 per cell per Gy

Deterministic Radiation Effects

- Occur at high doses when enough cells in an organ or tissue are killed or prevented from functioning normally
- Threshold dose, above which effects are clinically observable
- Severity increases with dose (different individual sensitivity)
- Acute effects, non-malignant late effects
- Examples: Cataracts, erythema, acute radiation syndromes (ARS)

Deterministic Radiation Effects

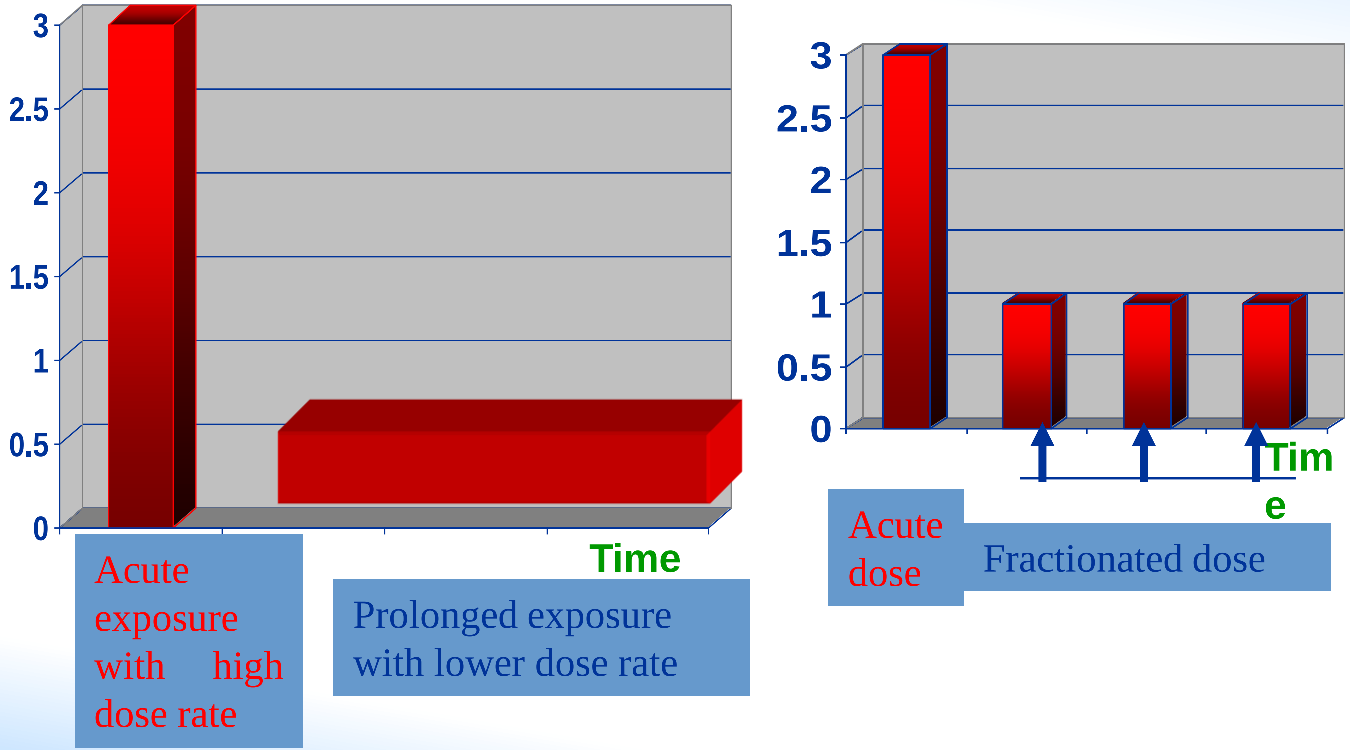


Deterministic Radiation Effects

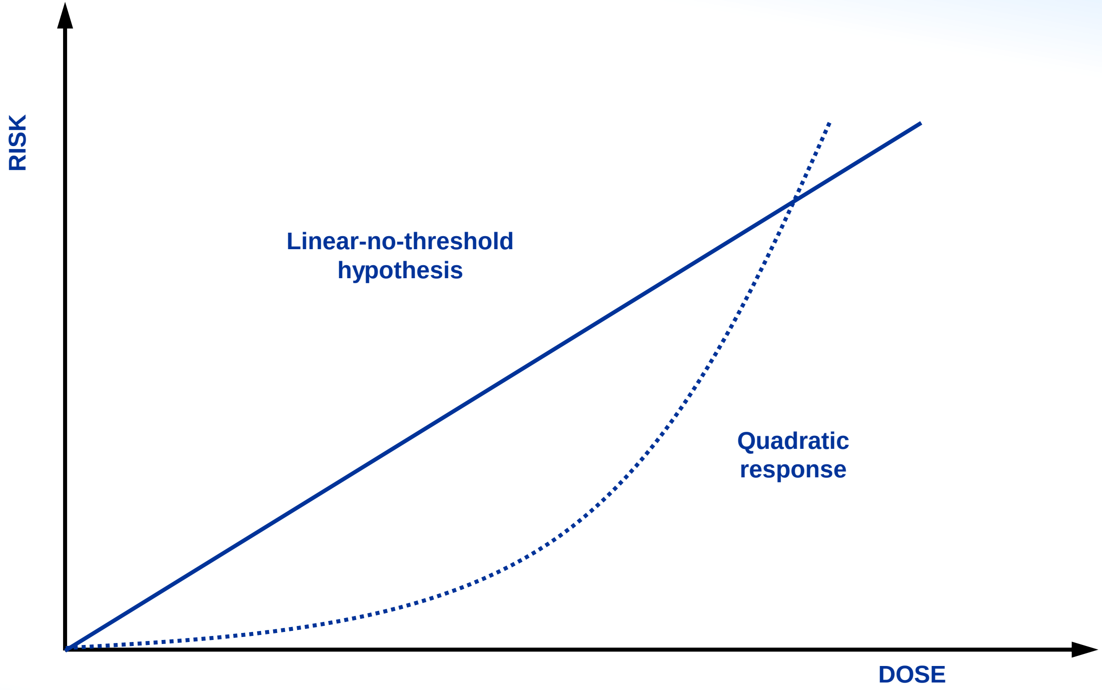
- Data on deterministic radiation effects come from
  - ❖ Survivors of atomic bombs on Hiroshima and Nagasaki
  - ❖ Effects on early radiologists
  - ❖ Consequences of severe accidents with industrial radiation sources
  - ❖ Studies of side effects of radiotherapy
  - ❖ Studies of cataract formation, aircrew and Chernobyl workers

Deterministic Radiation Effects: Modification of radiation injury

Occurrence of deterministic effects is dependent on dose rate



Stochastic Radiation Effects

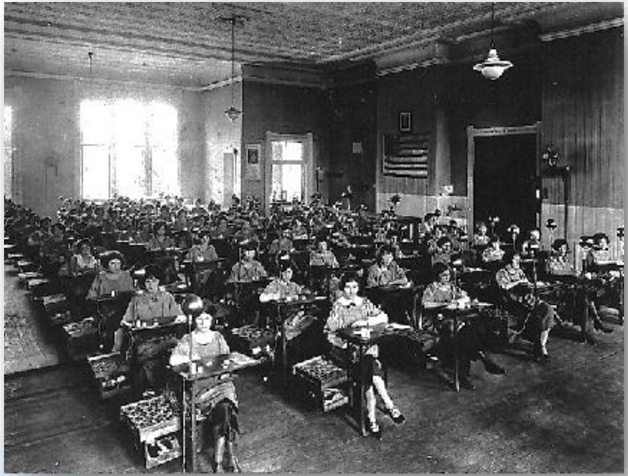


Stochastic Radiation Effects

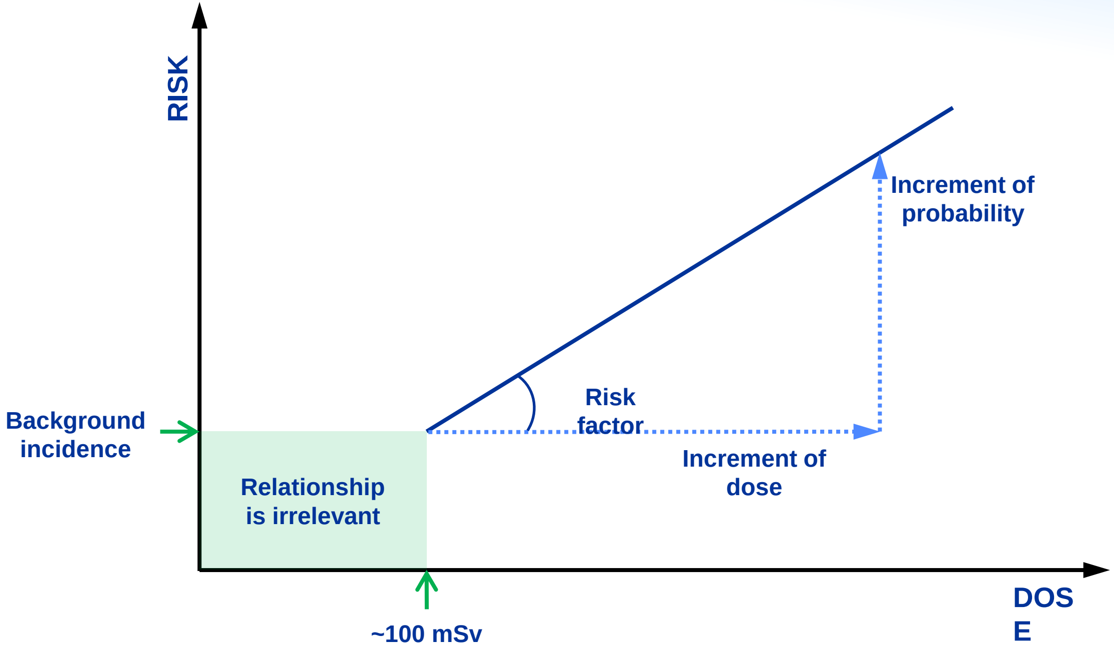
- Occur at all dose levels as a result of damage to the DNA
- Random or non-threshold effects
- Probability of occurrence increases with dose
- Late effects, often decades after exposure
- Examples: radiation-induced cancers,
  hereditary effects

Stochastic Radiation Effects

- Principal sources of information on stochastic effects are
  - ❖ Epidemiological studies on atomic-bomb survivors
  - ❖ Patients exposed to radiation for medical treatment or diagnosis
  - ❖ Some groups of highly occupationally exposed workers (uranium miners, radium-dial painters)



Stochastic Radiation Risks



Critical radiation-induced health effects
(relevant to victims of accidents)

- Severe deterministic effects

Health effect	Target organ or entity
Fatal	
Haematopoietic syndrome	Red marrow
Gastrointestinal syndrome	Small intestine for external exposure or Colon for internal exposure
Neurocardiovascular syndrome	Circulatory system, Brain
Pneumonitis	Lung
Embryo/ foetal death	Embryo/ foetus in all periods of gestation
Nonfatal	
Moist desquamation	Skin
Necrosis	Soft tissue
Cataract	Lens of the eye
Acute radiation thyroiditis	Thyroid
Hypothyroidism	Thyroid

Critical radiation-induced health effects

- Severe deterministic effects (cont.)

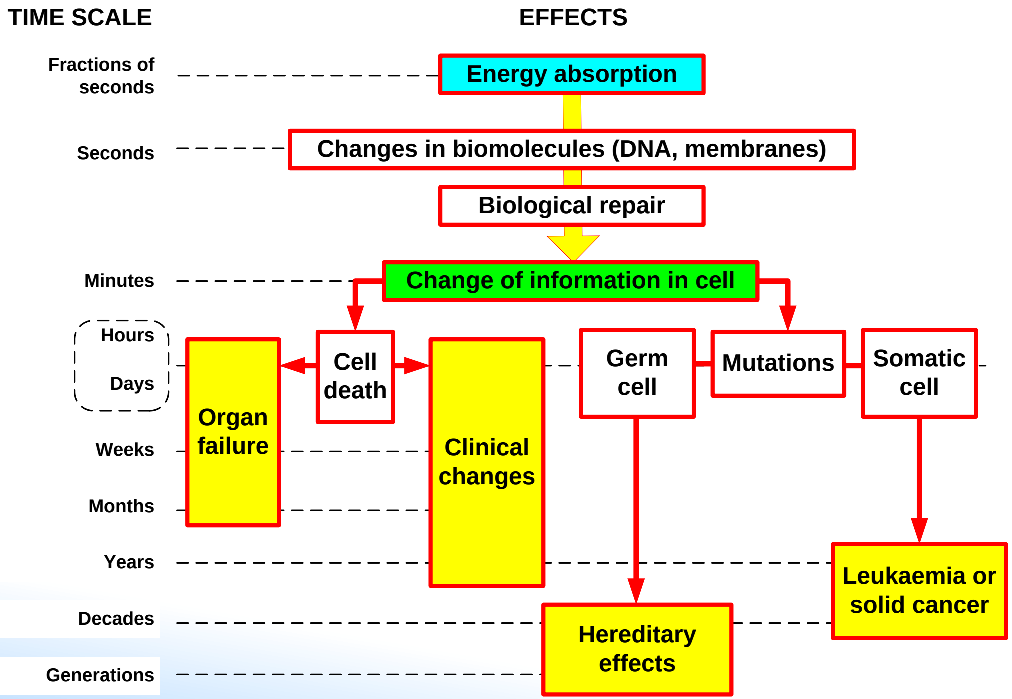
Health effect	Target organ or entity
Nonfatal	
Permanently suppressed ovulation	Ovary
Permanently suppressed sperm counts	Testes
Severe mental retardation	Embryo/ foetus 8-25 weeks of gestation
Verifiable reduction in IQ	Embryo/ foetus 8-25 weeks of gestation
Malformation	Embryo/ foetus 3-25 weeks of gestation
Growth retardation	Embryo/ foetus 3-25 weeks of gestation

- Stochastic effects

Health effect	Target organ or entity
Thyroid cancer	Thyroid
All stochastic health effects	All organs taken into account in definition of effective dose

Biological effects of radiation in time perspective

The health effects of ionizing radiation need a time for development from physical act of energy absorption to medical syndrome.



Biological effects of radiation in time perspective

Deterministic effects appear shortly after the exposure and stochastic effects appear years after the exposure.

- At high doses cell death and loss of ability for reproduction leads to development of deterministic health effects.

- At low doses, when probability of cell survival after irradiation is high, the development of mutated cell could give a rise for stochastic health effects of radiation,

2. Dosimetric quantities for use in characterization of exposure situation

Biological effects of radiation are correlated with the energy absorbed by ionization and excitation in unit mass of tissue (the absorbed dose).

- The averaged dose in organ and tissue;

$$D_{R,T} = \frac{\Delta E_{R,T}}{m_T} \quad [Gy]$$

$\Delta E_{R,T}$: energy absorbed in tissue or organ T

m_T : mass of that tissue or organ

Dosimetric quantities used to characterise exposure situations used in radiation protection

Dosimetry quantity		Symbol	Purpose	Unit
Radiation protection quantities				
	Absorbed dose in organ or tissue	D_T	For evaluating the absorbed dose due to exposure of an organ or tissue	Gy
	Equivalent dose in organ or tissue	H_T	For evaluating stochastic health effects induced due to exposure of an organ or tissue	Sv
	Effective dose	E	For evaluating detriment related to the occurrence of stochastic health effects in an exposed population	Sv
Operational quantities				
	Personal dose equivalent	$H_p(d)$	For monitoring external exposure of an individual	Sv
	Ambient dose equivalent	$H^*(d)$	For monitoring a radiation field at the site of an emergency	Sv

The equivalent dose

- The equivalent dose in organ or tissue;

$$H_T = \sum_R D_{R,T} \times W_R \quad [Sv]$$

W_R: The radiation weighting factor

The equivalent dose is intended to account for differences in biological effectiveness in producing stochastic health effects in organs or tissues of reference man due to the quality of radiation. The values of an equivalent dose to a specified tissue from any type of radiation can therefore be compared directly.

Radiation weighting factors

Radiation	Radiation weighting factor
Photons, electrons, positrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments and heavy ions	20
Neutrons	A continuous function of neutron energy: $W_R = \begin{cases} 2.5 + 18.2\exp(-[ln(E_n)]^2/6) & E_n < 1\ MeV \\ 5.0 + 17.0\exp(-[ln(2E_n)]^2/6) & 1\ MeV \le E_n \le 50\ MeV \\ 2.5 + 3.25\exp(-[ln(0.04E_n)]^2/6) & E_n > 50\ MeV \end{cases}$

The effective dose

- The effective dose;

$$E = \sum_T H_T \times W_T$$

W_T: the tissue weighting factor

The effective dose is intended to account for differences in biological effectiveness in producing stochastic health effects due to the quality of radiation and its distribution in the body of reference man. Total effective dose for specified period (e.g., day, year, etc.) is widely used for regulatory purposes (setting of dose limits). Values of effective dose from any type(s) of radiation and mode(s) of exposure could be compared directly.

Tissue weighting factors (ICRP 103)

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

Same ERR(excess relative risk) compared to radiation

Excess relative risk	Radiation	Other factors
1.50-2.49	1Sv-2Sv	Smoking (everyday)
1.30-1.49	500mSv-1Sv	Half a bottle of wine (everyday)
1.10-1.29	200mSv-500mSv	Obesity (BMI>30)
1.01-1.09	100mSv-200mSv	Lack of vegetable
undetectable	Below 100msv	Many (UV, air pollution…)

Loss of life expectancy

Dose	Loss	Note
1mSv/y (50 years)	11-18 days	
5mSv/y (50 years)	62-99 days	
100mSv (one time)	34-51 days	UNSCEAR 1988
20mSv/y (50years)	168 days	ICRP 1990
Passive smoking	50 days	
Accident in home	95 days	

Cancer risk by radiation exposure

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- When applying epidemiological data of A-bomb survivors, the excess absolute risk of cancer death at 70 years old with exposure of 1000 mSv at age 30, will increase by 50% compared to when the person was not exposed.

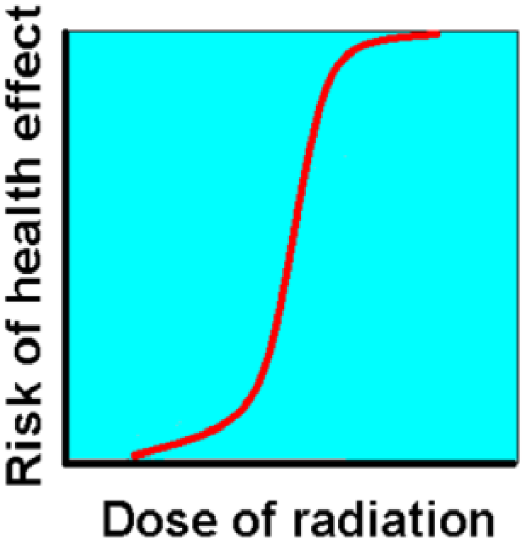
- According to the linear hypothesis of the dose-effect relationship, if the exposure dose is 100 mSv, the relative risk will increase by 5%.

- In the absence of exposure, the lifetime risk of dying from cancer is reported to be about 20%, and the lifetime risk when there is 100 mSv exposure is calculated as 20 x 1.05 = 21% (increasing 1.0%)

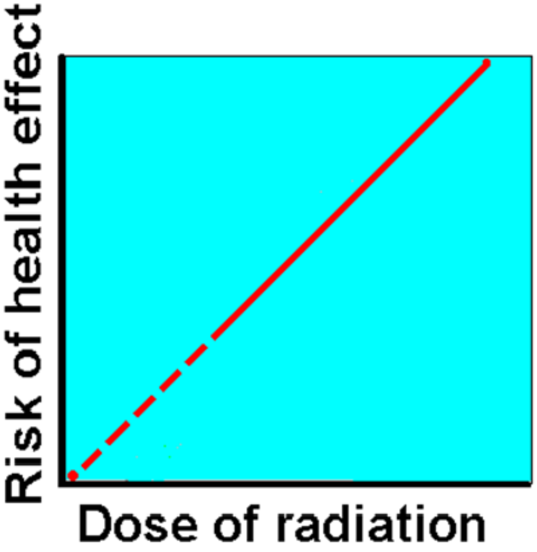
- However considering the epidemiological data which became the basis is acute exposure by the atomic bomb, the lifetime risk will increase by 0.5%

3. Health effects caused by ionizing radiation

Dose-response function for deterministic effects

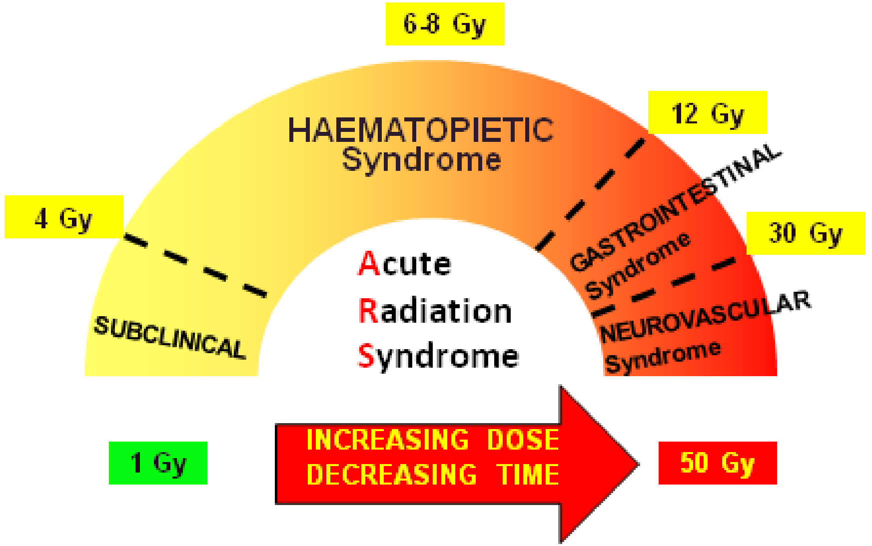


(a) Deterministic effects



(b) Stochastic effects

Severity of acute radiation syndrome



- 4 Gy threshold (5% probability of death) for haematopoietic syndrome
- 6-8 Gy threshold for radiation pneumonitis
- 50 Gy very fast death

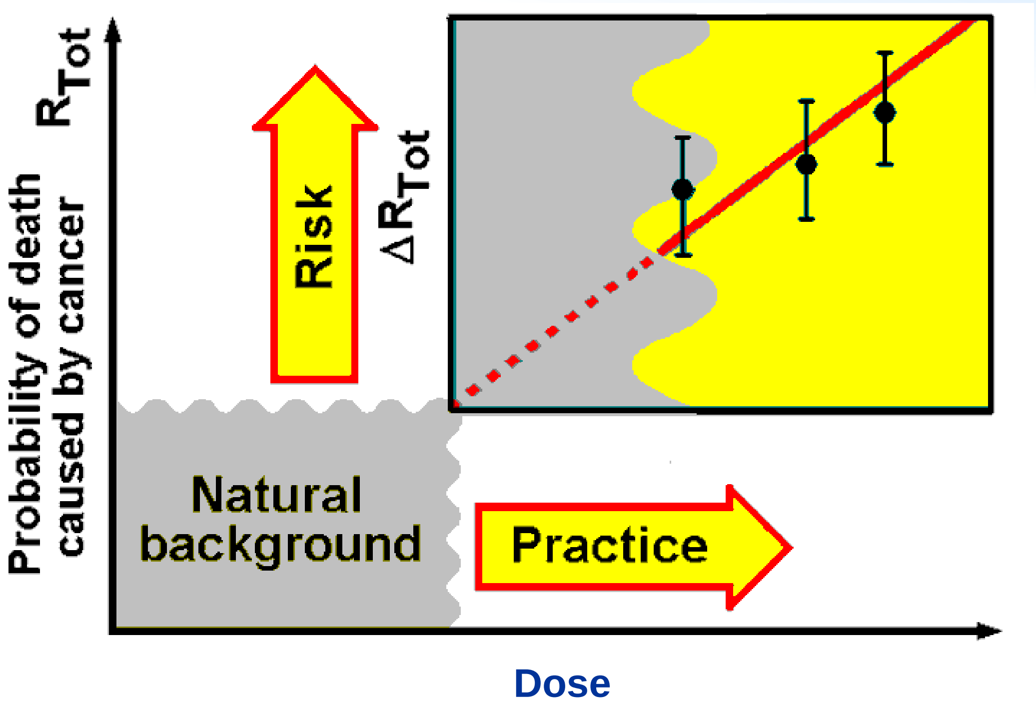
Responders with ARS following the Chernobyl accident

ARS: Acute Radiation Syndrome

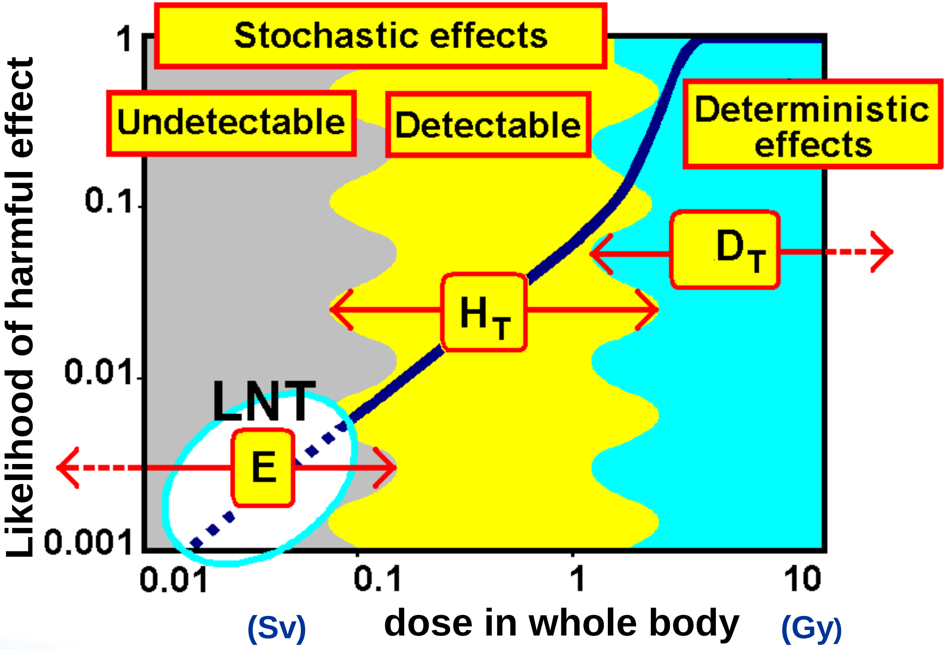
Degree of ARS	Whole body dose (Gy)	Number of patients treated	Number of deaths
Mild (I)	0.8 – 2.1	41	-
Moderate (II)	2.2 – 4.1	50	1
Severe (III)	4.2 – 6.4	22	7
Very severe (IV)	6.5 – 16	21	20
Total	0.8 - 16	134	28

Most fatal deterministic effects in Chernobyl emergency workers were caused by combination of high doses of external exposure to penetrating radiation and extensive skin burns caused by heavy contamination of wet protective clothes by beta emitting fission products, presumably by Ru-106 and Rh-106.

Use of the Linear Non-Threshold hypothesis



Probability of severe health effects as a function of brief exposure of whole body to external penetrating radiation



Criteria for preventing or minimizing severe deterministic effects

Dose quantity	Dose criterion
External acute exposure (<10 h)	
$AD_{Red\ marrow}$	1 Gy
AD_{Foetus}	0.1 Gy
AD_{Tissue}	25 Gy at 0.5 cm
AD_{Skin}	10 Gy to 100 cm^2
Internal exposure from acute intake (A = 30 d)	
$AD(\Delta)_{Red\ marrow}$	0.2 Gy for radionuclides with Z>90 20 Gy for radionuclides with Z<89
$AD(\Delta)_{Thyroid}$	2 Gy
$AD(\Delta)_{Lung}$	30 Gy
$AD(\Delta)_{Colon}$	20 Gy
$AD(\Delta)_{Foetus}$	0.1 Gy

4. Summary

- In case of high dose exposures, when the dose in whole body is greater than 2 Gy, contribution of stochastic effects to total probability of early premature death is negligible, and only the absorbed dose should be used;

- In the case when the dose in the whole body is in the range of 1-2 Gy, contribution of deterministic and stochastic effects to total probability of premature death is comparable, and it is reasonable to use equivalent dose in organs and effective dose in Sv and absorbed dose in Gy as the characteristics of human exposure in that field of exposure assessment;

4. Summary

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- In case of intermediate dose exposure, when the dose in whole body is in the range of 0.1-1 Gy, the contribution of deterministic effects to total probability of premature death is negligible, and it is reasonable to use only equivalent dose in organs and effective dose in Sv;

- In case of low dose exposures, when the dose in whole body is less than 0.1 Gy, the development of undetectable effects is possible, so the equivalent dose in organs and effective dose in Sv are used as the characteristic of human exposure in that field of exposure assessment to set limitations for human exposure.