Biological Effects and Risks of Ionizing Radiation;
Principles of Protection
Objective

To achieve an understanding of:

- the biological consequences and hazards of ionizing radiation exposure;
- the units used to measure ionizing radiation exposures in order to control biological consequences;
- the biological consequences and hazards of ionizing radiation exposures from the legal point of view.
Contents

• Radiation dose and units
• Deterministic and stochastic effects
• Radiation exposure vs contamination
• Controlling the hazard (time, distance, shielding)
When a person is exposed to ionizing radiation, energy may be deposited in the cells of the tissues exposed giving rise to a radiation dose. However, the biological effect of that dose depends on several factors, including:

- the **type of radiation** (e.g. x-rays, beta particles, neutrons, etc.);
- the **energy of the radiation and the rate at which the radiation dose is delivered**, and
- the **tissue exposed** (i.e. its sensitivity to radiation).
Radiation Dose

The following tissues and organs are listed from most radiosensitive to least radiosensitive:

<table>
<thead>
<tr>
<th>Most Sensitive: Blood-forming organs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digestive system</td>
</tr>
<tr>
<td>Reproductive organs</td>
</tr>
<tr>
<td>Skin</td>
</tr>
<tr>
<td>Bone and teeth</td>
</tr>
<tr>
<td>Muscle</td>
</tr>
<tr>
<td>Least sensitive: Nervous system</td>
</tr>
</tbody>
</table>
Absorbed and Equivalent Dose

- The unit of absorbed dose (received by an organ or tissue) is the **gray (Gy)**.
- The absorbed dose is modified by a radiation weighting factor to account for the type of radiation (and its ionization density). This results in the equivalent dose to the organ or tissue.

As an example, 1 Gy of alpha radiation is many times more biologically damaging than 1 Gy of X or gamma radiation.

- The unit of equivalent dose is the **Sievert (Sv)**.
• The equivalent dose to all exposed organs or tissues can be further modified by tissue weighting factors (which account for the different radiation sensitivities of the individual organs or tissues) and these are summed to give an effective dose.

• The effective dose is the sum total of such weighted equivalent doses for all exposed tissues in an individual.
Measuring Radiation

Radiation means the photons (gamma or x-rays) and particles emitted by radioactive sources during decay, or from electrically generated sources (e.g. x-ray equipment, linear accelerators, etc.)

- Radiation is measured as a dose (Gy) or as dose rate (Gy/h)
- Sievert (Sv) is the SI unit of equivalent dose and effective dose, equal to 1 J/kg and Gray (Gy) is the SI of absorbed dose, equal to 1 J/kg
- However, smaller fractions of these units are often used, e.g. microgray per hour (µGy/h) or millisievert per hour (mSv/h).
One should be aware that limits for occupational and public exposure will usually be prescribed in the regulations as either:

- effective dose limits (whole body); and
- equivalent dose limits for specific organs such as the skin, lens of the eye and the extremities.
Occupational Dose Limits

Recommended limits from the IAEA Basic Safety Standards (GSR Part 3)

<table>
<thead>
<tr>
<th>Effective Dose Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mSv per year averaged over 5 years</td>
</tr>
<tr>
<td>50 mSv in a single year</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equivalent Dose Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens of the eye</td>
</tr>
<tr>
<td>20 mSv per year averaged over 5 years</td>
</tr>
<tr>
<td>50 mSv in a single year</td>
</tr>
<tr>
<td>Skin</td>
</tr>
<tr>
<td>500 mSv per year</td>
</tr>
</tbody>
</table>

mSv – millisievert.

Compared to the average annual dose from natural background radiation of ~ 2.4 millisievert per year (UNSCEAR)
Recommended limits from the IAEA Basic Safety Standards (GSR Part 3)

<table>
<thead>
<tr>
<th>Effective Dose Limits</th>
<th>1 mSv per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>In special circumstances a higher effective dose could be allowed in a single year provided that the average over 5 years does not exceed 1 mSv per year</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equivalent Dose Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lens of the eye</td>
</tr>
<tr>
<td>Skin</td>
</tr>
</tbody>
</table>
Factors determining the biological effects of radiation exposure include:

- the total dose received;
- exposure rate;
- portion of body exposed;
- radiation characteristics;
- biological variability.
The biological effects of ionizing radiation are broadly divided into two classes: deterministic and stochastic

- **Deterministic effects** (which can include blood changes, burns, nausea, diarrhoea, death) arise early (and/or late) in the exposed individual as a result of high radiation doses received over a short time. **Severity** increases with radiation dose.

- **Stochastic effects** (primarily cancer and hereditary effects) may affect the exposed individual or future generations. The **probability of their occurrence** increases with radiation dose. (“Stochastic” means “pertaining to chance”)

Deterministic Effects

- are the result of high doses;
- have a threshold before they appear;
- appear early (and/or late);
- have a severity depending on the dose.

Stochastic Effects

- may arise from any dose;
- have no known threshold;
- have a long latency period;
- have a probability of occurrence depending on the radiation dose.
Deterministic Effects - Example

Severity of Effect

Threshold

Dose

Elbow injury from irradiator accident

Burn from very high dose interventional x-ray procedures
### Whole body acute doses for deterministic effects

<table>
<thead>
<tr>
<th>Gy</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>No discernible effect</td>
</tr>
<tr>
<td>1.00</td>
<td>Blood changes, no illness</td>
</tr>
<tr>
<td>2.00</td>
<td>Radiation sickness, no death</td>
</tr>
<tr>
<td>4.50</td>
<td>Death to 50% of exposed people</td>
</tr>
<tr>
<td>10</td>
<td>Death to 100% of exposed people</td>
</tr>
</tbody>
</table>
Acute Radiation Syndrome

- Loss of appetite
- Nausea
- Fatigue
- Diarrhoea
- Vomiting
- Loss of hair

- Nose bleeding
- Sub-cutaneous bleeding
- Anaemia
- Infection
- Death
Acute Radiation Effects – Chernobyl 1986

<table>
<thead>
<tr>
<th>Number of People</th>
<th>Estimated Dose</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>6 - 16 Gy</td>
<td>20</td>
</tr>
<tr>
<td>21</td>
<td>4 - 6 Gy</td>
<td>7</td>
</tr>
<tr>
<td>55</td>
<td>2 - 4 Gy</td>
<td>1</td>
</tr>
<tr>
<td>140</td>
<td>&lt; 2 Gy</td>
<td>0</td>
</tr>
</tbody>
</table>

Chernobyl. Ten Years On. Nuclear Energy Agency OECD Nov 1995 Table 6
Deterministic effects can be clearly identified with a specific exposure source and:

- a failure to provide appropriate safety measures or security for a radiation source;
- a failure to follow prescribed safe working procedures; or
- an accident.

All of these also might suggest a poor safety culture or security culture.
“For most tumour types in experimental animals and in man a significant increase in risk is only detectable at doses above about 100 mGy.”

UNSCEAR 2000
Stochastic Effects - Example

Crude incidence of leukaemia per 10,000 males per annum following radiotherapy for ankylosing spondylitis.

Derived from Radiation Physics with Applications in Medicine and Biology, 2nd ed Norman Dyson 1993
Stochastic Effects - Example

Breast Cancer (Hiroshima and Nagasaki)

Health Physics Vol 41 No 4
October 1981 pp 667-8

(100 rad = 1 Gy)
Stochastic Effects - Example

Thyroid cancer incidence rate in children exposed before the age of 14 years as a result of the Chernobyl accident (1986)
UNSCEAR 2000
Hereditary Effects

“Cancer is the major Stochastic effect of radiation exposure that has been demonstrated in human population.

*Hereditary Effects have only been observed in animal populations exposed to relatively high doses of radiation, although they are also presumed to occur in humans.*

UNSCEAR 2008

However, Ionizing radiation is a universal mutagen and experimental studies in plants and animals have clearly demonstrated that radiation can induce genetic effects; consequently, humans are unlikely to be an exception.

Published risk factors are available
The possibility that a cancer (or hereditary effect) might have been caused by exposure to ionizing radiation poses considerable challenges.

- The adverse outcome might be due to some other agent, known or unknown.
- There is likely to have been a lengthy period of time between the alleged cause (the radiation exposure) and the adverse outcome.
- Stochastic effects are probability based with the risk of occurrence increasing with dose.
“With respect to direct observations of radiation effects, which all carry statistical and/or methodological uncertainty, there are no circumstances where it is scientifically valid to equate the absence of an observable biological effect with the absence of risk.”

UNSCEAR 2000

As there is very little information on the effects of low radiation doses, it is cautiously assumed that the risk of stochastic effects exists at all doses without a threshold.
• Estimates of risk are based on studies of people who were exposed to fairly high radiation doses. They include the survivors of the atomic bombs in Japan, patients exposed to radiation for treatment or diagnosis of disease, and groups of workers in some industries.

• In radiation protection it is assumed that however low the dose there is some risk of harmful effects and that the risk is proportional to dose.
Risks associated with practices involving radioactive materials may be a result of either:

• exposure to the emitted radiation; or
• contamination
Exposure to radiation, such as this patient being exposed to gamma radiation (from Cobalt-60) during radiotherapy treatments, does not make the individual radioactive.

Note: Exposure to some neutrons or to very high energy photons may induce radioactivity.
Contamination is the presence of uncontained radioactive material on surfaces where it should not be found.

- Contamination may be:
  - fixed; or
  - removable (non-fixed)
Contamination most frequently arises from poor working practices with unsealed radioactive sources (e.g. in research, nuclear medicine and well logging tracer applications).

- It also may be caused by leaking sealed sources (where the radioactive material breaches its encapsulation).
- Skin and clothing can be contaminated (causing exposure).
- Contamination also might be inhaled, ingested, or absorbed through the skin.
The Radiation Hazard

- The hazard from ionizing radiation may be due to whole or partial body exposure.
- Being exposed to ionizing radiation does not (normally) make you radioactive.
- Fixed radioactive contamination presents an external radiation hazard.
- Non-fixed radioactive contamination presents both an external and internal radiation hazard.
- Radioactive material taken into the body presents a potential long-term exposure hazard.
Controlling the Radiation Hazard

The three principles by which radiation dose (and the radiation hazard) can be minimized are:

- reduce the time exposed to the radiation;
- increase the distance from the radiation source;
- use appropriate material to provide shielding from the radiation.
Where to Get More Information

• UNSCEAR, Sources and Effects of Ionizing Radiation, 2000 Report to the General Assembly with Scientific Annexes, United Nations, New York, 2000


• International Atomic Energy Agency, Postgraduate Educational Course in Radiation Protection and the Safety of Radiation Sources (PGEC), Training Course Series 18, IAEA, Vienna (2002)