November 1895: Roentgen discovers x rays

February 1896: Becquerel discovers radioactivity

Ernest Rutherford 1898-99

Ernest Rutherford: 1898-99

\[ \text{\textbf{ALPHA (a++) DECAY}} \]

\[ \text{\textbf{BETA (\beta^-) DECAY}} \]
The Electromagnetic Spectrum

Interaction of Charged Particles with Matter: Ionization

Relevant Quantities & Units - for Individuals

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>DEFINITION</th>
<th>UNITS</th>
<th>New</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed Dose</td>
<td>Energy per unit mass</td>
<td>Gray (Gy)</td>
<td>rem</td>
<td></td>
</tr>
<tr>
<td>Equivalent Dose</td>
<td>Average dose X radiation weighting factor</td>
<td>Sievert (Sv)</td>
<td>rem</td>
<td></td>
</tr>
<tr>
<td>Effective Dose</td>
<td>Sum of equivalent doses to organs and tissues exposed, each multiplied by the appropriate tissue weighting factor</td>
<td>Sievert</td>
<td>rem</td>
<td></td>
</tr>
<tr>
<td>Committed Equivalent Dose</td>
<td>Equivalent dose integrated over 50 years (relevant to incorporated radionuclides)</td>
<td>Sievert</td>
<td>rem</td>
<td></td>
</tr>
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<td>Committed Effective Dose</td>
<td>Effective dose integrated over 50 years (relevant to incorporated radionuclides)</td>
<td>Sievert</td>
<td>rem</td>
<td></td>
</tr>
</tbody>
</table>

How does ionizing radiation damage DNA?
Principal Hazards of Ionizing Radiation

- Genetic effects
- Carcinogenic effects
- Effects on the developing embryo/fetus

The Carcinogenic Effects of Radiation

Radiation and Cancer

How does radiation cause cancer?

Radiation and Cancer

Ionizing radiation does cause cancer
- Parts of the mechanisms are understood
- The full picture is still very unclear

Radiation and Cancer

Ionizing radiation is quite efficient at inducing chromosomal aberrations such as deletions and translocations

Chromosomal Deletions
Chromosomal Translocations

Links between chromosomal aberrations and cancer

<table>
<thead>
<tr>
<th>Chromosomal Translocations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 different pre-replication chromosomes</td>
</tr>
<tr>
<td>1 break in each chromosome</td>
</tr>
<tr>
<td>Exchange of broken chromosome pieces</td>
</tr>
<tr>
<td>Replication (3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Translocations or Inversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deletion</td>
</tr>
<tr>
<td>Translocation</td>
</tr>
</tbody>
</table>

Radiation and Cancer

What do we know quantitatively about the risks of radiation-induced cancer in humans?

Radiation and Cancer: Sources of Information

- Extrapolation from animal data
- Relevant human cohorts
- Mechanistic information

Radiation and Cancer: Are animal data useful?

- Useful for indicating relative patterns (dose, dose rate, radiation quality)
- Not useful for assessing absolute risk

Radiation and Cancer

What are the problems in estimating the risks of radiation-induced cancer in humans?
Problems estimating cancer risks

Many!

Problems estimating cancer risks

- Dose reconstruction
- Statistics
- Controls
- Latency

Problems estimating cancer risks

- Dose extrapolation
- Dose rate extrapolation
- Age and time dependencies
- Transfer models
- Neutrons at Hiroshima

The BIG caveat

Radiation risk estimates at low doses are based on plausible assumptions, but are estimates nevertheless.

They are not, and can never be, direct measurements!

Radiation and Cancer: Relevant Human Cohorts

- A bomb survivors
- TB patients (multiple fluoroscopies)
- Tinea Capitis children
- Ankylosing Spondylitits
- RT patients

Radiation and Cancer: Emerging Human Cohorts

- Chernobyl
- Mayak
- Airline personnel
**Radiation and Cancer**

Most of our information comes from studies of A-bomb survivors

**Radiation and Cancer:**

A-bomb survivors

- 87,000 survivors followed
- 7,800 cancer deaths observed
- 7,400 expected
- Therefore 400 excess cancers

**Extrapolating from High to Low Doses**

At low doses the Japanese dose-response relations are consistent with a linear relation between dose and cancer risk.

Although controversial, a linear model (implying no low-dose threshold for risk) is most likely valid.

**A Linear Extrapolation from High to Low Doses?**

**Solid Cancers – A-Bomb Survivors**

Can low-dose risks be estimated directly from groups exposed to low doses of radiation?

Recent study of 120,000 nuclear workers exposed to ~40 mSv consistent both with:

- Zero risk
- A risk appropriately extrapolated from A-bomb survivor data.

**Radiation and Cancer**
The Nuclear Worker Study
Cardis et al 1995

Estimated excess fatal cancers (ICRP) % / Sv

<table>
<thead>
<tr>
<th></th>
<th>High Dose / High Dose Rate</th>
<th>Low Dose / Low Dose Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>General population</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>Working population</td>
<td>8%</td>
<td>4%</td>
</tr>
</tbody>
</table>

Distribution of uncertainties in radiation risk

Radiation and Cancer
Individual Susceptibility to Radiation Carcinogenesis

ATM: Ataxia Telangiectasia

Non-Cancer Radiation Risks
... are not quantified as well as the cancer risks
Radiation Risks

<table>
<thead>
<tr>
<th>Teratogenic risks</th>
<th>Order of magnitude larger than</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogenic risks</td>
<td>Order of magnitude larger than</td>
</tr>
<tr>
<td>Hereditary risks</td>
<td></td>
</tr>
</tbody>
</table>

Gene Mutations

<table>
<thead>
<tr>
<th>Single Dominant</th>
<th>Polydactyly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Huntindon's chorea</td>
</tr>
<tr>
<td></td>
<td>Retinoblastoma</td>
</tr>
<tr>
<td>Recessive</td>
<td>Sickle-cell anemia</td>
</tr>
<tr>
<td></td>
<td>Tay-Sachs disease</td>
</tr>
<tr>
<td></td>
<td>Cystic fibrosis</td>
</tr>
<tr>
<td>Sex linked</td>
<td>Color blindness</td>
</tr>
<tr>
<td></td>
<td>Hemophilia</td>
</tr>
</tbody>
</table>

Radiation-Induced Mutations

Radiation does not produce new, unique mutations, but simply increases the incidence of the same mutations that occur spontaneously.

My father was a health physicist and assures me that radiation is not hazardous.

Heritable Effects

Children of the survivors of the A bomb attacks have been studied for:

- Untoward pregnancy outcomes
- Death of live-born children
- Sex chromosome abnormalities
- Electrophoretic variants of blood proteins

But no statistically significant effects have been observed.

We are heavily reliant on animal data for hereditary risk estimates.
Hereditary Effects - ICRP
Probability / caput of severe hereditary disorder (working population)
0.6% / Sv

Teratogenic Risks
(i.e., to the embryo/fetus, if relevant)
Moderate doses of radiation can produce catastrophic effects on the developing embryo and fetus.

Factors Influencing Probability of Teratogenic Effects
- Dose to embryo/fetus
- Stage of gestation at time of exposure

IN UTERO EFFECTS OF RADIATION

The principle effects of radiation on the developing embryo and fetus are:

- Growth retardation
- Embryonic, neonatal, or fetal death
- Congenital malformations and functional impairment, such as mental retardation.

A-bomb survivors irradiated in-utero, with microcephaly
Microcephaly at Hiroshima

In utero exposure & mental retardation

Severe mental retardation, after in-utero exposure (8-15 weeks gestation period)

Risk: 40% / Sv

Radiation Risks

Teratogenic risks
order of magnitude larger than
Carcinogenic risks
order of magnitude larger than
Hereditary risks

Typical sources of exposure to ionizing radiation

Stanley Watras at the Limerick nuclear power plant, 1984
Stanley Watras and family, Boyertown, PA, 1985

Number of articles about radon in the New York Times

The uranium-238 decay chain

The Reading Prong: A granite formation

Radon: From Rocks to Lungs

Radon, polonium and basal cells in the lung
Radon risks are estimated by studying uranium miners.

Estimated lung cancer risks from lifetime exposure to radon

<table>
<thead>
<tr>
<th>Radon Level (pCi/l)</th>
<th>Percent Risk of Lung Cancer in Smokers (%)</th>
<th>Percent Risk of Lung Cancer in Non-Smokers (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7%</td>
<td>0.05%</td>
</tr>
<tr>
<td>4</td>
<td>3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>20</td>
<td>14%</td>
<td>1%</td>
</tr>
</tbody>
</table>

Estimated lung cancer deaths per year in the US due to radon

In the range 15,000 to 22,000 (~1 in 8 of all lung cancer deaths)

About 85% of these deaths are attributable to radon + smoking.

Testing houses for high radon levels

Radon remediation:
Sub-slab ventilation

1-800-SOS RADON