Nuclear 3

Biological Effects of Radiation
History with a different emphasis

- 1895: Roentgen discovers X-rays
- 1896: Becquerel discovers that photographic plates placed near uranium become exposed
- 1896: Edison develops fluoroscope
- 1904: Edison’s assistant, Clarence Dally dies from radiation sickness
- Early radiologists & shoe salesmen tended to have chronic, slow-healing lesions.
Ionizing Radiation

- Ionizing radiation can detach an electron from an atom.
- Depends on energy of particles, not numbers.
- For photons, this is X-rays and gamma rays.
- Ionizing radiation can break chemical bonds.

IAEA sign
Four major forms of radiation

Interaction of ionizing Radiation with Matter

- **α** (Alpha particles): Charged particles interact strongly and ionize directly.
- **β** (Beta particles): δ-Electron. Neutral particles interact less, ionize indirectly and penetrate farther.
- **γ** (Gamma rays): Bremsstrahlung.
- **n** (Neutrons): Recoil Proton, n capture photon.
DNA and radiation

- direct effect
  dislodges e from H in H₂O
- indirect effects ⇒ OH

both e and OH radical
can: - break double strand
  - delete a base
  - chemically crosslink

- 3 possibilities:
  * repair
  * programmed cell death (apoptosis)
  * continued existence with damage (may lead to cancer)
Ionizing radiation

X-rays or \( \gamma \)-rays

Radiation particles act like “bulllets” but act differently depending on
- energy
- mass and charge of radiation particle
- density of absorbing tissue

Each dot is an ionization event

\( \alpha \)-particles

Living cells
Biological Effects of Radiation

- Short term: acute radiation syndrome (radiation poisoning)
- Longer term: cancer
- Genetic and teratogenic effects
- Other

Mechanisms are not fully understood
Measuring Radiation: *Activity*

\[ R(t) = \lambda_d N(t) = \frac{\ln 2}{T_{1/2}} N(t) = \frac{0.693}{T_{1/2}} N_0 2^{-t/T_{1/2}} \]

Units

- 1 Bq = 1 dps
- 1 Ci = 3.7 x 10^{10} dps

Activity not enough to determine effects of radiation

Need also:

- type of radiation (some more harmful than others)
- how much is absorbed
- where it is absorbed
Measuring Radiation: Grays

Relevant measure is the energy absorbed per kg measured in Grays:

1 Gray (Gy) = 1 Joule per kg = 1 J / kg
Old unit: 1 rad = 0.01 Gray or 100 rads = 1 Gray
Energy deposited by 1 R (1 roentgen) is close to 1 rad

What is the concern?
Radiation with sufficient energy can break chemical bonds
⇒ ionizing radiation
Like X-rays & γ-rays
neutrons
α-rays (⁴He nuclei)
β-rays (electrons / positrons)
Relative Biological Effectiveness (RBE)

Character of radiation taken into account by “Quality Factor” or RBE
Dose Equivalent

Measure of damage by radiation given by

**DOSE EQUIVALENT** (DE) measured in **Sievert** (Sv)

or rem (old unit)

\[
DE = \text{RBE} \times \text{absorbed energy} / \text{mass}
\]

So

\[
\text{Sv} = \text{Gy} \times \text{RBE}
\]

or

\[
\text{rem} = \text{rad} \times \text{RBE}
\]

**Lethal dose** (short time) :

400 - 600 rem = 4-6 Sv

**Example:** DE = 450 rem for radiation with RBE = 3

Absorbed dose = 150 rad = 1.5 Gy = 1.5 J / kg

70 kg person absorbs 70 kg * 1.5 J / kg = 105 J

enormous damage but absorption goes unnoticed

Exposure time must also be considered & decay law
Sources of Exposure to Radiation

- **Natural background radiation**
  - Cosmic rays
  - Solar radiation
  - External terrestrial sources
  - Radon, especially in poorly ventilated houses

- **Man-made radiation sources (decreasing order)**
  - X-rays, especially cat scans
  - Nuclear medicine/radiation therapy
  - Consumer products: smoke detectors, watches
  - Nuclear power industry
Worldwide Background: 2.4 mSv / year

BEIR VII

LET = Linear Energy Transfer
Exposure from Man-made Sources
Example Doses

- Mammogram 0.13 mSv
- Full-body CT scan: 12 mSv - 30 annual CT scans would increase lifetime cancer mortality by almost 2% (1 in 50)
- 1980 US radiation worker: 1 mSv per year; NRC limit is 50 mSv/year
- Voluntary max dose for emergency life-saving work: 750 mSv
- Low-level radiation sickness: 500-1000 mSv
Louis Slotin
1910-1946
Acute Radiation Syndrome

Aka radiation sickness, or radiation poisoning

- 0.2-0.5 Sv: asymptomatic; RBC count drops
- 0.5-1 Sv: headache; increased infection risk
- 1-2 Sv: light- vomiting; 10% fatality after 30 days (LD 10/30)
- 2-3 Sv: severe- LD 35/30; nausea; hair loss; sterility
- 3-4 Sv: severe- LD 60/30; uncontrollable bleeding in mouth, skin, kidneys
Acute Radiation Syndrome 2

- 4-6 Sv: acute- LD 60/30; symptoms after 2 hrs.; death in 2-12 months due to infection and internal bleeding
- 6-10 Sv: acute- LD 100/14; symptoms in 15-30 minutes; bone marrow transplant only hope
- 10-50: acute- LD 100/7; symptom in 5-30 minutes; massive diarrhea, coma, delirium
- 50-80 Sv: disorientation or coma in seconds to minutes; death in hours
- >80 Sv: immediate death. One worker receiving 100 Sv survived for 49 hours; another survived 36 hours after 120 Sv
How much is safe?

- Dose-response curves
- Linear and non-linear models
- Are there thresholds?
- Radiation hormesis: an unproven hypothesis
Leukemia rates of survivors

Big question: How to extrapolate from high to low doses?
Possible extrapolations

Relation between exposure to radiation and excess fatal cancers studied by

National Academy of Sciences
National Research Council

BEIR-V in 1990

Conclusions:
Linear model for most cancers but linear-quadratic for leukemia
Linear No-Threshold Model

- Linear more: twice the dose, twice as bad
- No threshold means no amount of radiation is considered safe
Radiation Hormesis

- Controversial hypothesis that chronic low doses of ionizing radiation (at the level of natural background radiation) stimulates repair mechanisms that protect against disease.
- As many as 40% of studies do observe some evidence for hormesis.
- Mechanism unknown.
BEIR VII and the National Academy

http://books.nap.edu/openbook.php?isbn=030909156X
http://www.nasonline.org/site/PageServer?
pagename=ABOUT_main_page

- National Academy of Sciences: chartered by Congress in 1863
- BEIR = Biological Effects of Ionizing Radiation
- BEIR VII: 2006 report on low energy radiation effects
- Low here is defined as 100 mSv (0.1 Sv) or less. Worldwide annual background exposure is 2.4 mSv.
- US background is 3 mSv
Key Conclusions of BEIR VII

- The LNT (linear no-threshold) model is preferred
- In a lifetime, 42 of 100 people will be diagnosed with cancer. Approximately one cancer fatality per 100 people could result from a single exposure of 100 mSv (0.1 Sv).

**BEIR-V**

Some numbers:

- **Exposure**
  - once 0.1 Sv (10 rem)
  - continuous lifetime of 1 mSv/yr
  - continuous age 18 to 65 of 0.01 Sv/yr

- **Excess fatal cancers / 100,000 exposed**
  - 790
  - 560 (as high as 3% of normal rate)
  - 3000 (16% of normal rate)

**Recommendations for workers**

**Conclusion?**

Avoid it, if possible
Populations at Elevated Risk

- Survivors of Hiroshima and Nagasaki. Extremely well-studied population.
- Veterans exposed through weapons testing. From 1945-1962, 210,000 received exposures as high as 31 mSv (equivalent to 390 chest X-rays).
- Workers in health care, mining, milling, or nuclear weapons. Federal limit is 50 mSv per year (whole body).
Monitoring Radiation

Dosimeter

Geiger Counter
Minimizing Exposure

- Minimize time
- Maximize distance
- Containment
- Shielding
Shielding from Radiation

α  Alphas stopped by paper
β  Betas stopped by aluminum plate
γ  Gammas require meters of lead
Radiation sickness (prodromal syndrome)

Acute effects of radiation

The symptoms of acute effects appear soon after the exposure to radiation, within an hour or two (or even within minutes after very high doses), but death as a result of the exposure may not occur for some time. It is generally believed that death from acute effects comes within two months after exposure, but there is evidence from the bombings in Japan that it may be much later, up to several years. By that time deaths from long-term effects, in particular leukaemia, begin to occur, so there is no clear-cut division between acute and long-term effects in the time of occurrence of death.

Acute effects may manifest themselves when the whole body or a large part of it is exposed in a short time to a radiation dose from about 0.2 Gy upwards. The early symptoms, such as anorexia, nausea and headaches, are part of the so-called prodromal syndrome. With doses up to 1 Gy these symptoms soon disappear and recovery is apparently complete. With increasing dose mortality increases, reaching 100 per cent for a dose of about 5 Gy (midline tissue dose), although in healthy adults survival is possible even for somewhat larger doses if special treatment is provided. Death in the dose range 1–5 Gy is mainly due to damage to the blood-forming organs. Larger doses are invariably fatal, death being due to disturbances of the gastro-intestinal system and—at still higher doses—to damage to the central nervous system.
Effects on the blood-forming system

The main lethal effect of radiation is produced by the damaging action on the cells of which the body is made. With high doses the energy imparted to the cells is sufficient to destroy them completely, but much lower doses can inhibit mitosis, the ability of cells to divide. For the proper function of the organism it is vital that certain types of cell, which are continually lost, should be replenished by mitosis. But if after exposure too few dividing cells are left, the organism will not be able to function and death will occur. The most important of the cellular effects of radiation occur in the blood-forming tissues, particularly in the bone marrow.

Bone marrow stem cells and lymphocytes belong to the most sensitive components of the human body, as far as radiation is concerned. For example, the sensitivity of lymphocytes is so high that even a dose of 0.1 Gy will lead to structural abnormalities in them, and a dose of 2.5 Gy will reduce their number to less than 10 per cent. The other circulating blood cells are less radiosensitive, but they have to be continually renewed, and the destruction of bone marrow cells leads to an inhibition of the formation of all types of blood cell. Perhaps the most striking of the changes associated with radiation exposure is the reduction in the number of white blood cells. The purpose of these cells is to resist infection and remove toxic products from the body; a drastic reduction in their number will make the organism vulnerable to any infection. The platelets, which play an important role in clotting of the blood, show an even greater decrease in number for a given dose, leading to haemorrhage and purpura. Reduced production of red blood cells leads to severe anaemia.

In the dose range 1–5 Gy, the prodromal syndrome is followed by other clinical symptoms if too many bone marrow stem cells have been destroyed. These symptoms are haemorrhage under the skin, bleeding in the mouth and bleeding into internal organs. There is greater susceptibility to infection which causes a step-wise rise in temperature; severe emaciation and delirium lead to death, usually within six weeks.
Effects on the gastro-intestinal system

In the range of doses 5–20 Gy, death results earlier from changes in the gastro-intestinal system. Within minutes of the exposure there is a decrease in the rate of cell division in the lining of intestinal vessels; later the cells degenerate and a large proportion of them die. Without replacement of the cells the villi shrink; ulceration and gangrenous inflammation follow. There is high fever and persistent diarrhoea, rapidly progressing from loose to bloody stools. Abdominal distention and dehydration follow and the person becomes comatose. Death results principally from enteritis following infection, toxaemia and disturbance of body fluids. The chances of recovery after doses in this range are nil, except near the low limit of the range if special treatment is provided.

Effects on the central nervous system

At very high doses of 20 Gy and upwards, prompt death results from pathological changes in the nervous system. These include degeneration of brain cells, cerebral oedema and inflammation of cerebral vessels. After the initial phase of radiation sickness, as described above, there is a rapid progression from drowsiness to severe apathy and lethargy. There is generalized muscle tremor, lack of muscular co-ordination, coma, convulsions and shock. Persons exposed in this range of doses would be disoriented and incapacitated immediately, even if death were not to occur for a few days. Neutron doses in this range are planned to be used in the neutron bomb as a military weapon against tank crews (see section 4.1.4).
This sequence of the symptoms, and the time of their onset and severity, may provide some guidance to the dose (if unknown) and to the prognosis. The higher the dose the earlier the onset and the more severe the symptoms. At moderate doses the symptoms subside after a few days and the person exposed may then feel quite well for a week or so. But subsequently they reappear and together with other signs of malaise may lead to death if the dose was high enough. Protracted vomiting during the first two days, and in particular the occurrence of diarrhoea, indicate a bad prognosis. Persons with intractable nausea, vomiting and diarrhoea will most likely die.

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