Radiation and Health

Radiation related illnesses

- Principal means of cell damage is through ionization, with an energy typically 5 to 10 eV, followed by dissociation of the molecule (DNA), which only requires of the order of 1 eV of energy.
- Radiation related health problems
  - **Acute radiation**
    - large doses generally received in a short period of time
    - exposure to highly radioactive sources
    - macroscopic, destruction of a large number of cells, injury to organs
    - generally referred to as radiation sickness
    - Symptoms include
      - Nausea
      - Vomiting
      - Diahorrea
      - Fatigue
      - Bleeding
      - In severe cases death may occur within two to four weeks. Those who survive six weeks after the receipt of a single large dose of radiation to the whole body may generally be expected to recover.
  - **Chronic radiation**
    - Accumulated effect of radiation acquired at low level over a long period of time.
    - Microscopic, changes to cell structure, particularly DNA
    - Symptoms include
      - Cancers
      - Birth defects

Cause of damage

- The energy carried by the radiation is the mechanism by which damage is caused. Energy can be
  - kinetic energy of particles (electrons, alpha particles, neutrons, etc)
  - energy of a photon (uv, X rays, gamma rays)
- Radiation must be capable of penetrating into the body, and also doing damage. These can be contradictory requirements.

Electromagnetic Spectrum

- The following are all forms of the same phenomenon, electromagnetic waves. In order of increasing frequency they are

- Radio waves
- microwaves
- infra red (heat or thermal) radiation
- light
- ultra violet radiation
- X rays
- gamma rays

- At the microscopic level all these forms come in small packets called ‘quanta’ or photons
  - the energy of a photon is determined solely by the frequency

$$E = h\,f$$

  - where h is called Planck’s constant, 4.15×10^{-15} eV.s
  - as the frequency increases the energy increases. The above list is therefore also a list on increasing energy
    - for light with $f = 5 \times 10^{14}$ Hz, $E = 4.15 \times 10^{-15} * 5 \times 10^{14} = 2.1$ eV
    - for uv with $f = 1.24 \times 10^{15}$ Hz, $E = 4.15 \times 10^{-15} * 1.24 \times 10^{15} = 5.1$ eV
    - for gamma rays with $f = 3 \times 10^{20}$ Hz, $E = 4.15 \times 10^{-15} * 3 \times 10^{20} = 1.25 \times 10^{6}$ eV = 1.25 MeV

Ionizing Radiation

- In order to ionize a molecule an energy > 3 eV must be supplied.
- Any radiation with energies greater than this are termed ionizing radiations. They include
  - alpha particles
  - beta particles
  - photons in the uv, X ray, and gamma ray portions of the electromagnetic spectrum
- Any radiation with energies less than this are termed non-ionizing radiations. They include
  - radio waves
  - microwaves
  - infra red radiation
  - light

Penetrating effects of radiation

- **Alpha particles**
  - Fast helium nuclei
    - relatively massive, mass = 4 amu = 6.7×10^{-27} kg
      - relatively slow
      - 2 MeV alpha particle moves at about 10^{7} m/s

    - charge = +2
    - very strong interaction with electrons of atom
        - very efficient ionizer
    - can keep on damaging cells until kinetic energy is exhausted
- **Beta particles**
    - Fast electrons
        - relatively light, mass = 9.11 x 10^{-31} kg
            - relatively slow
            - 2 MeV beta particle moves at about 3 x 10^{8} m/s
        - charge = -1
        - strong interaction with electrons of atom
            - efficient ionizer
        - can keep on damaging cells until kinetic energy is exhausted
- **Gamma rays**, X rays, uv
    - charge = 0
        - interaction with atoms is weak
    - all of energy must be absorbed in one go
        - can only damage one cell

- **Alpha particles** are likely to cause cell damage, but are easily stopped
    - alpha particles outside the body are very unlikely to cause a risk
    - alpha particles which have been ingested are a severe risk
- **Beta particles** are less likely to cause damage, but are more penetrating
- **Gamma rays** penetrate into the body the most, but are the least likely to cause damage. Most pass right through you.

Activity

- From first semester, when defining radiation we have

activity = k * number of radioactive nuclei

- where the activity is measured in disintegrations/second
    - Bequerel
        - 1 Bq = 1 disintegration/second
    - Curie
        - 1 Ci = 3.7 x 10^{10} Bq = 3.7 x 10^{9} disintegrations/second
        - 1 microCi = 10^{-6} Ci = 37,000 disintegrations/second
        - 1 nanoCi = 10^{-9} Ci = 37 disintegrations/second

Activity and mass

- Activity depends on two factors, both of which you will need to know for any given isotope
  - half life, which determines the decay constant k = ln2/T
  - amount of material, which determines the number of nuclei. The atomic mass is the mass of the nucleus in amu, where 1 amu = 1.66×10^{-27} kg.
  - **Example**, what is the activity of 20 kg of ^{238}U?
    - Half life of ^{238}U = 4.5 billion years
      - Converting to seconds
        - T = 4.5×10^{9} years * 3.15 seconds/year = 1.4×10^{17} s
        - k = ln2/T = 4.95×10^{-18}
    - Mass of nucleus = 238 * 1.66×10^{-27} = 3.95×10^{-25} kg
      - Number of nuclei = 20 kg / 3.95×10^{-25} kg = 5×10^{25}
    - Activity = 4.95×10^{-18} * 5×10^{25} = 2.5×10^{8} disintegrations per second
      - = 2.5×10^{8} Bq
      - = 0.0068 Ci
        - Note: even a lot of ^{238}U has a low activity because it has such a long half life
  - **Example**, what is the activity of 1 mg of ^{131}I?
    - Half life of ^{131}I = 8 days
      - Converting to seconds
        - T = 8 days * 86,400 seconds/day = 6.9×10^{5} s
        - k = ln2/T = 1×10^{-6}
    - Mass of nucleus = 131 * 1.66×10^{-27} = 2.2×10^{-25} kg
      - Number of nuclei = 10^{-6} kg / 2.2×10^{-25} kg = 4.6×10^{18}
    - Activity = 1×10^{-6} * 4.6×10^{18} = 4.6×10^{12} disintegrations per second
      - = 4.6×10^{12} Bq
      - = 125 Ci
        - Note: even a little ^{131}I has a low activity because it has such a short half life

Energy, Power, Intensity

- Note: Energy = Power * Time won't work, because the power is not a constant
- **Power**
  - calculated by the equation

Power = energy per dissociation * number of dissociations / second

  - For example, take the 125 Ci ^{131}I source from above
    - each dissociation releases 0.971 MeV of energy
      - 0.971 MeV * 1.6×10^{-13} J/MeV = 1.55×10^{-13} J
    - With 4.6×10^{12} disintegrations per second
      - power = 1.55×10^{-13} * 4.6×10^{12} = 0.7 W

    - Note that as time progresses and the ^{131}I nuclei gradually decay (to ^{131}Xe) the number of ^{131}I nuclei decreases and so the power also decreases.
- **Intensity**
  - defined as power per unit area
  - assuming a source which radiates uniformly in all directions, and that there is no absorption of the radiation by the intervening medium, the radiation from the source spreads outwards such that at a distance r from the source the radiation has to cross a sphere of area $4pr^2$.
    - at a distance of 3 m (about 10 feet)
      - area = $4pr^2 = 4p(3)^2 = 113\ m^2$
      - intensity = 0.7 W / 113 m^2 = 0.006 W/m^2
- **Energy**
  - for the case of energy the only meaningful statement is the energy released by the time all the nuclei have decayed.
  - for the ^{131}I case above eventually (that is in a time much longer then the half life) all of the atoms will give off 0.971 MeV is the form of the kinetic energy of a beta particle
    - energy released = 4.6×10^{18} * 0.971 MeV = 4.5×10^{18} MeV
    - 4.5×10^{18} MeV * 1.6×10^{-13} J/MeV = 7.1×10^5 J

Radiation Dose

- Takes into account
- radiation intensity
- size of person
- amount of radiation absorbed (some passes right through)
- Units
  - rad = 100 ergs/gram = 0.01 J/kg (rad is short for **r**adiation **a**bsorbed **d**ose)
  - gray = 100 rad = 1 J/kg

Roentgen Equivalent Man

- Combination of radiation dose and the biological damage
  - alpha particles are very damaging, Q = 25
  - beta particles are less damaging, Q ~ 5
  - gamma and X rays are the least damaging, Q = 1
- Units
  - rem = rad * Q
  - Sievert = gray * Q = 100 * rem

Radiation Exposure

- The following was developed by the National Council on Radiation Protection and Measurement (NCRP 93) and is a breakdown of the sources of radiation for the population of the United States. These numbers are averages and were obtained by estimating the total dose for the US, and dividing by the number of people in the US.

Annual Effective Dose Equivalent			
SOURCE	DOSE (mrem/yr)	DOSE (mSv/yr)	PERCENT OF TOTAL
Natural			
Radon	200	2.0	55%
Cosmic	27	0.27	8%
Terrestrial	28	0.28	8%
Internal	39	0.39	11%
Total Natural	300	3	82%
Artificial			
Medical X ray	39	0.39	11%
Nuclear medicine	14	0.14	4%
Consumer products	10	0.1	3%
Other			
Occupational	0.9	<0.01	<0.3
Nuclear Fuel Cycle	<1	<0.01	<0.03
Fallout	<1	<0.01	<0.03
Miscellaneous	<1	<0.01	<0.03
Total Artificial	63	0.63	18%
Total Artificial and Natural	360	3.6	100%

- Natural Radiation
  - Radon from the decay of Uranium, a natural element.
  - Carbon-14
  - Potassium 40
- Radiation in the home
  - television set - produces a few low energy x-rays.
  - Smoke detectors contain small sources in them. (^{241}Am).
- Radiation in the work place

- Persons in many occupations encounter radiation above normal background as a natural part of their jobs. Some of these occupations include doctors, nurses, radiographers, astronauts, dental hygienists, researchers, pharmacists, welders, airplane and jet crews. The doses received can be up to several rem of exposure over the course of a year.
- Current standards allow 5 rem per year (http://www.digistar.com/boston/)
  - 1.5 rem per year in UK.

- Medical uses of radiation
  - Medical uses of radiation are roughly broken into therapy and diagnosis. Therapy is primarily used for tumor killing of cancer, but in the past has been used for other treatments. Most of the dose is received in a small area of the body. Diagnosis runs from fairly routine x rays to injections of radioactive material and imaging. These doses can be several hundred mrem for diagnosis and up to several hundred rem locally for treatments. The physician who prescribes radiation treatments and diagnosis weighs the risk of the radiation with the benefit of the treatment.

Cosmic Rays

- In flight there are two principal sources of natural radiation to consider:
  - Galactic Cosmic Rays (GCR) which are always present, and
  - Solar Energetic Particle (SEP) events, sometimes called Solar Cosmic Ray (SCR) events, which occur sporadically.
- The resulting dose equivalent at aircraft also varies quite strongly with altitude and latitude.

Dose Equivalent Rate (micro-sieverts per hour (μSv/h)				
	Solar Minimum (10/86)		Solar Maximum (7/89)	
Altitude (x1000 ft)	35 degrees North Latitude	70 degrees North Latitude	35 degrees North Latitude	70 degrees North Latitude
0	0.0401	0.0412	0.0374	0.0380
10	0.190	0.207	0.173	0.181
20	0.985	1.14	0.875	0.953
30	3.25	4.06	2.85	3.24
40	6.78	9.02	5.88	6.99
50	9.71	13.8	8.36	10.3
60	11.1	17.1	9.49	12.3
70	11.4	19.2	9.68	13.3
80	11.2	20.6	9.44	13.8

- Natural Sources of Radioactivity
  - http://www.lbl.gov/lbl-programs/tritium/natural-dosage.html

- The average person in the U.S. receives an annual dose from natural radioactive sources approximately 100 to 400 millirems.
- In the Bay Area, the average annual exposure is estimated to be 260 millirems.
  - Cosmic rays, 28 millirem
  - Rocks and soil, 28 millirem
  - Medical x-rays, 39 millirem
  - Nuclear medicine, 14 millirem
  - Radon, 200 millirem (average U.S.)
  - Radon, 100 millirem (average Berkeley)
  - Radium wrist watch, 3 millirem
  - Tritium wrist watch, .6 millirem
  - Radium dial alarm clocks, .7 to .9 millirem
  - Cigarettes (1 1/2 packs day, to lung), 8,000 millirem
  - Building materials, masonry, 7 millirem
  - Road construction materials, 4 millirem
  - Coal-fired power plant, to lung, 1 to 4 millirem
  - Cooking with natural gas stove, 6 to 9 millirem
  - Home ionization smoke detector, 1 millirem
  - Porcelain in false teeth, to gum, 60,000 millirem
  - Thorium rose-tinted eyeglasses, to eye, 4,000 millirem
  - Uranium glaze in dinnerware, to skin, 2,400 millirem
  - Gas lantern mantles for camping, .1 to .4 millirem
- Among occasional exposures are the following:
  - Dental x-rays (each, to mouth), 25-35 millirem
  - Chest x-ray (each) 25 millirem
  - GI series or cardiac catheterization, 2,000 to 10,000 millirems

- Health Risks Arising From Low Doses of Ionizing Radiation
  - http://www.arpansa.gov.au/is_rad.htm#The natural

Effect	Risk	Normal Incidence
Risk of cancer from 1 mSv of radiation	1 in 17,000*	57 in 17,000**
Risk of severe hereditary effect from 1 mSv of radiation	1 in 77,000	1,770 in 77,000

* Age standardized lifetime probability for whole population.
**Age standardized incidence rate for whole population (not necessarily fatal).

The risk of obtaining cancer from 1 mSv of radiation exposure is equivalent to the risk of getting cancer from smoking 400 cigarettes.

- An assortment of typical radiation doses (in mrem)
  http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/R/Radiation.html

Approximate lethal dose ("LD50") if no treatment and given to the entire body in a short period	450,000
Causes radiation sickness (when absorbed in a short period)	>100,000
Increase in lifetime dose to most heavily exposed people living near Chernobyl	43,000
Average annual dose (excluding natural background) for medical x-ray technicians	320
Maximum permissible annual dose (excluding natural background and medical exposure) to general public	170
Natural background, Boston, MA, USA (per year)(excluding radon)	102
Natural background, Denver, CO, USA, (per year)(excluding radon)	180
Additional annual dose if you live in a brick rather than a wood house	7
Average dose to person living within 10 miles of Three-Mile Island (TMI) caused by the accident of 28 March 1979	8
Most heavily exposed person (a fisherman) near TMI	<100
Approximate dose received by a person spending 1 year at the fence surrounding a nuclear power station	0.1 - 0.6
Average dose to each person in the U. S. population from nuclear power plants (per year)	0.002
Received by the bone marrow during a set of dental x rays*	9.4
Annual dose to the gonads from TV sets	0.2 - 1.5
Received by the bone marrow during a barium enema	875
Received by the bone marrow during a chest x ray	10
Received by breast during mammogram	50 - 700
Average airline passenger (10 flights/year)	3
Flight crew and cabin attendants (per year)	160
Hourly dose to skin holding piece of the original "Fiesta Ware" (a brand of pottery)	200 - 300
Annual dose to each person in the U. S. population from fallout (former weapons testing plus Chernobyl)	0.06

* Dose much higher (several thousand mrem) to the skin in the path of the beam, but bone marrow is more susceptible to damage (e.g., leukemia).

What is the risk estimate?

- According to the Biological Effects of Ionizing Radiation committee V (BEIR V), the risk of cancer death is 0.08% per rem for doses received rapidly (acute) and might be 2-4 times (0.04% per rem) less than that for doses received over a long period of time (chronic). These risk estimates are an average for all ages, males and females, and all forms of cancer. There is a great deal of uncertainty associated with the estimate.
- Risk comparison
  - how much will radiation exposure increase my chances of cancer death over my lifetime?
    - the current death rate from cancer is approximately 20 %
    - contracting cancer is a random process, where given a set population, we can estimate that about 20 percent will die from cancer, but we cannot say which individuals will die.
    - a conservative estimate of risk from low doses of radiation is thought to be one in which the risk is linear with dose.

Three Mile Island

- 30,000 people within 5 miles of TMI on date of accident
  - Maximum possible dose was around 100 mrem
  - Largest known dose to one individual was around 37 mrem
  - Average dose was around 8 mrem (0.008 rem)
- Taking the rise as 0.08% per rem (0.08% = 0.0008) the total number of expected deaths from cancer can be estimated as
  - 0.0008 * 0.008 rem * 30,000 = 0.2
  - conclusion, there is only a one in five chance that even one person died as a result of cancer from the accident.

Chernobyl

- Average dose 80-160 mSv (8 rem - 16 rem)
  - (http://www.iaea.org/Publications/Booklets/ChernoBook/exposure.html)
- 160,000 people evacuated

- within this population the number of expected deaths from cancer can be estimated as
  - 0.0008 * 16 rem * 160,000 = 2000