MP

pqi

Contents

Welcome

This is my personal understanding about Medical physics.

Chapter 1

Introduction

1.1 Atomic Representation

Atoms = Nucleus (neutron and protons)[1] + Orbital electrons[2]

$$^{A}_{Z}X$$

- A (*mass number*) - the number of protons and neutrons
- Z (*atomic number*) - the number of proton number
- X - chemical symbol for the element

1.2 Classification of Atoms

Atomcs can be classified in terms of the number of protons, neutrons, mass, and (meta)state.

- Isoto**p**e
- Isoto**n**e
- Isob**a**r
- Iso**m**er (same A, Z, N but different energy (meta)states; eg $^{99m}_{43}Tc$ is in metastable[3] state and $^{99}_{43}Tc$ is in stable state)

1.3 Stability

The stability depends on the ratio of neutron and proton (see Figure 1)

[1] Rutherford interpreted the results of the gold foil experiment or Geiger-Marsden experiment and established the Rutherford model of atom, which constitutes a tiny (10^{-15} m), heavy nucleus which consists of protons and/or neutrons. He also won the Nobel Prize in Chemistry 1908 "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances". He discovered three types of radiation: α, β, and later γ radiation.

[2] In 1913, Bohr proposed a theory for the hydrogen atom based on **quantum theory** that (a) electrons orbit around the nucleus; (b) electrons orbits at a certain discrete set of distances from the nucleus without radiation and energy loss; (c) electrons can only gain and lose energy by jumping from one allowed orbit to another, absorbing or emitting electromagnetic radiation with a frequency: $v = \frac{E_m - E_n}{h}$. He won the Nobel Prize in Physics 1922.

[3] *Metastable* state is an excited state of an atom that has a longer lifetime than the ordinary excited states but generally has a shorter lifetime than the lowest, often stable, energy state, called the ground state. britannica

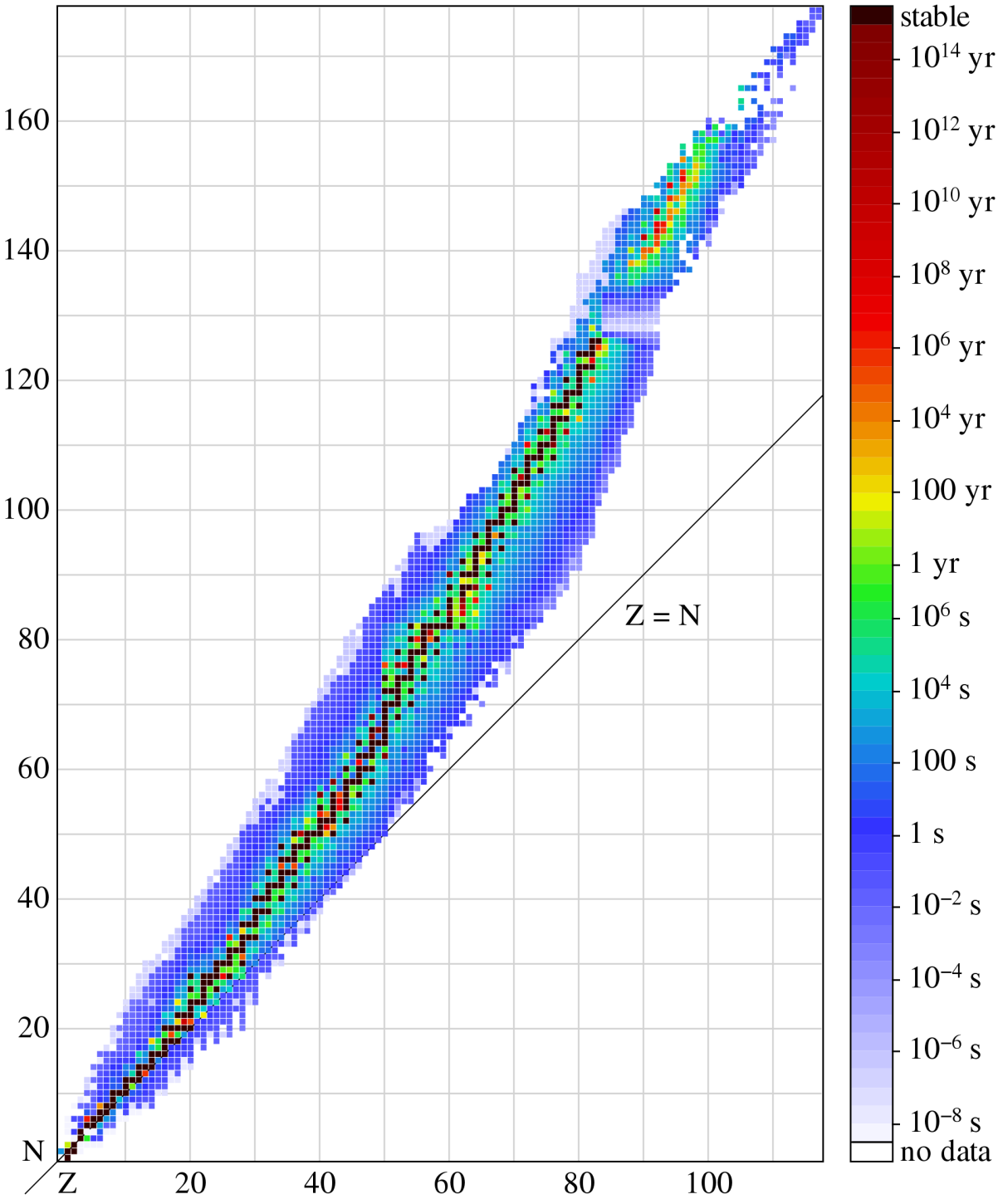

Figure 1.1: Stability (The image is from wiki)

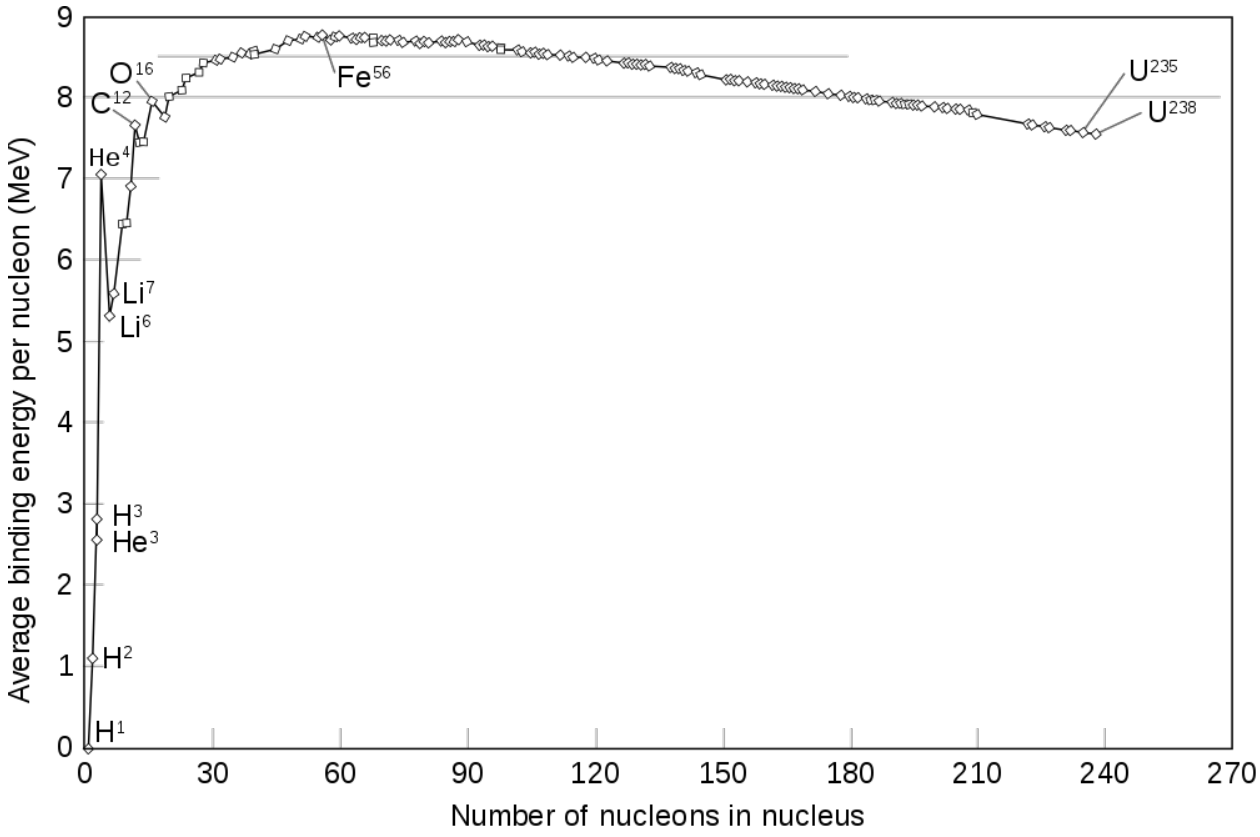

Figure 1.2: Nuclear binding energy per nucleon (The image is from wiki)

1.4 Mass Defect of a $^{12}_{6}$C

The mass of an atomic nucleus is less than the sum of the individual masses of the free constituent protons and neutrons. This "missing mass" is known as the *mass defect*.

Basic Particles

- Electron: 0.0055 amu[4]; **0.511** MeV; 9.11×10^{-31} kg
- Proton: 1.00727 amu; **938.3** MeV; 1.673×10^{-27} kg
- Neutron: 1.00866 amu; 939.6 MeV; 1.675×10^{-27} kg

For a ^{12}C atom,

$$\text{Mass effect} = 6 \times m_p + 6 \times m_n + 6 \times m_e - m_C = \boxed{0.0988\ amu}$$

where $m_C = 12$ (the ratio of mass to 1 amu). The complete list of mass number can be found in the NIST database.

The mass effect is closed related to *nuclear bind energy*. If we divide the above energy by 12 and times 931.5 MeV/amu, we obtain the bind energy per neuleio for ^{12}C is 7.67 (see figure belwo)

A complete table of nuclear bind energies can be found on Lawrence Berkeley National Laboratory (link).

[4]atomic mass unit; 1/12 mass of $^{12}_{6}$C atom in quantity; $1amu = 1.66 \times 10^{-27}kg$ or **931.5** MeV.

1.5 High energy charged particles

The mass of a moving particle (not a photon) depends on its velocity v and its rest mass m_0.

$$E_{total} = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1.1}$$

or

$$E_{total} = E_{rest} + E_{K.E} \tag{1.2}$$

For an electron and a proton accelerated to the velocity of 0.96 c, the kinetic energy will be about 2 MeV and 2400 MeV. Therefore, high energy electrons coming out of linac head will have the speed close to the speed of light. To achieve similar high speed, you need give much more energy to a proton than an electron.

1.6 High energy photons

The energy of a photon is given by

$$E = h \cdot v \tag{1.3}$$

where h is the *Plancks constant* ($6.626 \times 10^{-34} J \cdot s$), v is the frequency in unit of $s^{\{-1\}}$.

Or

$$E(eV) = \frac{1.24 \times 10^6}{\lambda(m)}, \tag{1.4}$$

1.7 Electron Shell

- *Principal quantum number* ($n = 1, 2, 3, ...or K, L, M, ...$) – the main energy level (or shell) occupied by an electron. The energy can be calculated by

  $$E_n = \frac{Z^2 \hbar^2}{2 m_0 \alpha_B^2 n^2},$$

  where α_B is the *Bohr radius* ($5.29 \times 10^{-11} m$). The **K shell** (binding) energy for Lead, Tungsten, and Carbon are 88, 69.5, and 0.28 KeV.
- *Secondary quantum number* ($l = s, p, d, ...$) – the energy sublevel (angular monentum) occupied by the electron.
- *Magnetic quantum number* ($m_l = -l, -l+1, ..., 0, ..., l-1, l$) – the number of possible orientations (projections) for each of energy sublevels.
- *Spin quantum number* ($m_s = -1/2, 1/2$) – the two possible orientations that an electron can have in the presence of a magnetic field.

1.8 Solutions

Q1: a), c), (e) see Section **??**
Q2: b), d); a) is wrong because they are isotopes; c) is wrong because they are isobars.
Q3: a), b), and c)
Q5: b), c); a) should be 6 neutrons and d) should be 12 times 931 MeV.
Q6: see above
Q7: b)
Q8: d) see Section **??**
Q9: c)
Q10: a)
Q11: b)
Q12: a), b), c), e)
Q13: b), c)
Q14: c)
Q15: b) using Eq. (**??**)
Q16: c) using Eq. (**??**)

Chapter 2

Nuclear Transformation

Radioactivity was discoverred in 1986 by A.H. Becquerel when he wa 44 years old.[1] He received 1903 Nobel Prize in Physics along with Maria and Pierre Curie.

Radiation Sources (Siebers 2009 AAPM talk)

- Radioactive decay (Chapter **??**)
  - Alpha-decay
  - Beta-decay (Section **??**)
  - Electron capture
  - Isometric transitions
  - Gamma-ray
- Atomic energy transitions
  - Characteristic x-rays
  - Auger electrons
- Accelerated charge particles
  - Direct (electrons, protons)
  - x-ray generators (synchrotron radiation (magnetic field), Bremmstrahlung)
- Interaction products (?)

2.1 Decay (disintegration)

General balance equations of radioactive decay

$$ {}^{A}_{Z}P = {}^{A-A_R}_{Z-Z_R}D + {}^{A_R}_{Z_R}R + \sum Q, \tag{2.1} $$

where P and D stand for parent and daughter element, R for radiation, and Q is reaction energy ($\sum Q = M_P - M_D - M_R$). To find out the Q-value, you can use a online Q-calculator (http://www.nndc.bnl.gov/qcalc/).

Atoms found in nature are either stable or unstable. An atom is unstable (radioactive) if these forces are unbalanced if the nucleus has an excess of internal energy.[2] The instability of a radionuclide may result from an excess of either neutrons or protons. Radionuclides attempt to reach stability through

[1] A good read from Wikipedia (https://en.wikipedia.org/wiki/Henri_Becquerel).
[2] http://www.epa.gov/radiation/understand/radiation.html

1. ejecting neutrons and protons (C area; Alpha-decay);
2. converting one to the other with ejection of a beta particle or positron (B area; Beta decay);
3. the release of additional energy by photon emission (Gamma decay).

Alpha − decay occurs in nuclides with atomic numbers above 82 (only the first 92 occur naturally) and where the ratio of neutrons to protons is low, thus resulting in the repulsive coulomb force of the protons overcoming the attractive strong nuclear force.

$$\underline{\text{Example}} \quad {}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha + \gamma + Q$$

Beta − decay, a neutron within the nucleus is converted into a proton, and an electron and an antineutrino are emitted, or a proton is converted into a neutron, and a positron and a neutrino are emitted. The forces responsible for the β-decay are weak (referred to as *weak nuclear force*) compared with both the strong nuclear force and the electrostatic force among the nucleons.

$$\underline{\text{Example}} \quad \begin{array}{ll} \beta^- \text{ decay} & {}^{27}_{60}Co \rightarrow {}^{60}_{27}Ni^* + \beta^- + \bar{\nu} \\ \beta^+ \text{ decay} & {}^{18}_{9}F \rightarrow {}^{18}_{8}O + \beta^+ + \nu + 1.022 \text{ MeV} \end{array}$$

$Neutrino$ (ν) and $anti - neutrino$ ($\bar{\nu}$) results in spectrum of β energies, and they are non-ionizing particles so we don't consider them in dose calculation.

Electron capture (EC) is an alternative to positron decay. In this process, an electron, usually in the K shell, is captured within the nucleus and combined with a proton to create a neutron. Electron capture most often is followed by characteristic x-ray or Auger electron.

Gamma decay occurs when a nucleus undergoes a transition from a higher to a lower energy level. These γ-rays are identical to the x-rays emitted by excited atoms, except that γ-rays originate from within the nucleus and x-rays originate from outside the nucleus.

Example ${}^{60}_{27}Ni^*$ decay to stable ${}^{60}_{27}Ni$ by emitting two gamma rays with energies of 1.17 and 1.33 MeV.

The decay scheme can be found (http://atom.kaeri.re.kr:8080/gamrays.html)

2.2 Activity

The *activity* (A) of a sample is the average number of disintegrations (decay) per second,

$$A = \frac{\Delta N}{\Delta t} = \lambda N, \tag{2.2}$$

where λ is the *decay constant* which is the probability that a nucleus will decay per second. Remember that Radioactive decay is a **stochastic** process. We can find certain laws only by observing a large number of events (decays here).

From the equation above, we can obtain the radioative decay law at a certain time t:

$$N = N_0 e^{-\lambda t}, \tag{2.3}$$

or

$$A = A_0 e^{-\lambda t}. \tag{2.4}$$

More frequently, we use $half - life\ time$ ($T_{1/2}$) instead of the decay constant λ. Their reqlationship is

$$T_{1/2} = \frac{\ln 2}{\lambda}. \tag{2.5}$$

The *mean* or *average* life is the (arithmetic) average lifetime for the decay of radioactive atomes.

$$T_a \equiv \frac{1}{\lambda} = 1.44 T_{1/2}. \tag{2.6}$$

2.3 Unit

The SI unit for radioactivity is *Becquerel* (Bq). The historic unit for radioactivity is Curie (Ci), and 1g of radium is 1 Ci. The relationship between Curie and Becquerrel is

$$1\ Ci = 3.7 \times 10^{10}\ Bq \tag{2.7}$$

In practice, the more frequently used formula is

$$\boxed{1\text{ GBq} = 27\text{ mCi}} \tag{2.8}$$

2.4 Solutions

Q1 Decays

Using Eq. (**??**) or (**??**) and (**??**), we get

$$\text{Residual activity} = 1 - 0.02 = e^{-\frac{ln2}{30}t} \rightarrow \boxed{t = 0.87\text{ years}}$$

It is easy to solve the above equation, but it will be faster to find a good estimation using the `Taylor's expansion` with first two terms $e^{-\frac{ln2}{30}t} \approx 1 - \frac{0.693}{30}t$. The caveat of using Taylor expansion is make sure the exponents are much smaller than 1. You can try this approach for question 3, but you will not get the correct answer.

`Q2 b), e)`
`Q4 a) b)`
`Q5 c)`

Q6 Calculation of total decay

$$\begin{aligned}\text{Decay}_{total} &= 1.44 \times T_{1/2} \times A \\ &= 1.44 \times 30 \times 3.15 \times 10^7 \times 3.7 \times 10^9 \\ &= \boxed{5.04 \times 10^{18}}\end{aligned}$$

Q6 Average life time

$$A = A_0 e^{-\lambda T_a} = A_0 e^{-\lambda \frac{1}{\lambda}} \rightarrow \frac{A}{A_0} = e^{-1} \approx \boxed{37\%}$$

For question 6, with 1 year = 31536000 s and Eq. (**??**), the total number of decays is equalt to total activity of 10 mCi Cs-137 is

$$10e^{-\frac{0.693}{8.05}t} = 4e^{-\frac{0.693}{14.3}t} \xrightarrow{\text{take ln() on each side}} ln10 - \frac{0.693}{8.05}t = ln4 - \frac{0.693}{14.3}t \rightarrow t = \boxed{24.3\text{ days}}$$

Q7 c)

Q8

b); For higher electrons coming out of linac head, the electron velocity is close to the speed of light.Q9 a)Q10 b)Q11 d)Q12 b) d)Q13 c)‘

Chapter 3

Production of X-rays

We describe our methods in this chapter.

Chapter 4

Clinical Treatment Generators

4.1 Microwave amplifier

The possibly best simple explanation about how a klystron amplifier and microwave oscillators work can be found on YouTube.

A `Klystron` is a microwave (300 MHz – 300 GHz) amplifier tube that makes use of two (or more for better bunching result) resonant cavities. For a simple two cavity Klystron,

1. The first resonance cavity is energized by very low-power microwaves through a coaxial cable.
2. The microwave will cause alternating "E" fields across the gap between left and right cavity wall.
3. As the electrons from the accelerated through the first cavity, half of them will be decelerated and the other help will accelerate (velocity modulation), and thus form electron bunches as they drift towards the second cavity.
4. The Catcher cavity is resonant at the arrival frequency of the bunch.
5. This will generates a retarding "E" field for slowing down electrons and in turn the electrons give their energies in the form of high-power microwaves (more electrons in a bunch $\rightarrow$ more kinetic energy $\rightarrow$ more EM energies induced in the 2nd resonant cavity).

A `Magnetron` is a device that produces microwaves.

1. The electrons emitted from the heated cathode are accelerated by the pulse electric field, EP, toward the anode across the evacuated drift space between cathode and anode.
2. A static magnetic field, H, is applied perpendicular to the cross section of the device.
3. The accelerated electrons induce an additional charge distribution shown on the anode poles and an electric field Em of microwave frequency between adjacent segments of the anode (similar to that in the catcher cavity of the klystron).

4.2 Microwave frequency

The microwave pulse frequency in most medical linear accelerators is about **3 GHz**, which falls into the category of IEEE `S-band` (2-4 GHz, Wiki). The Mobetron and Cyberknife machines use higher frequency (8-12 GHz, categorized as in IEEE `X band`, for compact design (Hanna 1999 Applications of X-band Technology in medical accelerators).

4.3 Penumbra

The term `Penumbra` means the region, at the edge of a radiation beam, over which the dose rate changes rapidly as function of lateral distance. The overall penumbra was contributed from three sources:

- *Geometric penumbra* is caused by the source (or focal spot) having a finite size and the location of the collimator. It can be reduced by decreasing the focal spot and move the collimator closer to the patient (e.g. Varian tertiary MLC).
- *Transmission penumbra* is caused by photons transmitted through the edge of the collimator. It can be reduced by aligning the collimator following the beam divergence (e.g. X and Y photon jaws).
- *Physical (total) penumbra* is the combination of transmission, geometric penumbra, and lateral scatter of radiation (photon and electrons) within the patient. Lateral electron disequilibrium (# of electrons projected laterally outward (# of electrons projected laterally inward). Because the range of these laterally projected electrons increases as energy increases, higher energy beams have a slightly greater penumbra than low energy beams.

Chapter 5

Interaction

Follow the energy

5.1 Photoelectric interactions

The probability[1] of *photoelectric interaction* $\propto \frac{Z^3}{E^3}$.

- incident photon interact with bound atomic electron;
- **all energy** is given to electron;
- an orbital electron is ejected possessing most of incident photon, and a vacancy is present;
- Characteristic x-ray and *Auger* electron (The energy released by the downward transition is given to one of the outer electrons instead of to a photon).

5.2 Compton interactions

The probability of *Compton interaction* $\propto \rho_e$

- interaction between incident high energy photons and loosely bound orbital electrons.
- With $\alpha = \frac{hv_0}{m_e c^2}$ and θ is the angle between incident and scattered photon, the scattered photon energy is

$$E_p = hv_0 \frac{1}{1 + \alpha(1 - \cos\theta)} \tag{5.1}$$

  - with $\theta = 0^o$ (grazing hit) electron acquires minimum energy, $\Delta\lambda = .00243(1 - \cos\theta)$
  - with $\theta = 90^o$ for mega-voltage linacs with $\alpha > 10$, scatter photons always have energy of about 0.5 MeV (shielding consideration);
  - with $\theta = 180^o$ (photon is scattered back) electron acquires maximum K.E and photon has an energy of 0.255 MeV

`Q2: d)`

[1]The basic quantity in collisional dynamics is *cross section*. The SI unit is cm^2 and the unit is *barn* ($1\ b = 10^{24}\ cm^2$) in nuclear physics.

5.3 Pair production

The probability of *pair production* $\propto Z \cdot E$.

- occurs when a photon approaches closely enough to the target nucleus;
- the incident photon energy may be converted directly into an electron-positron pair. When the positron comes to rest, it combines with an electron, and both particles then undergo annihilation, with the appearance of two photons with energy of 0.511 MeV traveling in opposite directions.

```
Q3: b) The threshold energy for pair production is 1.022 MeV.
```

5.4 Compton interactions

If the photon is scatter back at $\theta = 180^o$, the electron gains the maximum energy 0 2 1+2 . Therefore, a) is incorrect and d) is correct. According to equation,

$$\lambda' - \lambda = \frac{h}{mc^2}(1 - cos\theta) \tag{5.2}$$

The scatter photon will have longer wavelength than the incident photon so the choice of (b) is incorrect as well (c) (if

Attenuation of radiation is removal of photons or energy from a beam by different interactions including absorption and scatter. Like the process of radioactive decay, the attenuation is also a stochastic process

For a thin absorber, with absorber far away from the source (so effect of beam divergence is negligible – ignore inverse square law[2]), or in a narrow beam geometry†, we get $-\Delta N = \mu N \Delta x$, and overall = 0 − where is linear attenuation coefficient which can be thought as the fraction of photons or energy removed from beam per cm of absorber beam per cm. Half-value layer (HVL) relates to the linear attenuation coefficient by

$$HVL = \frac{0.693}{\mu} \tag{5.3}$$

Mass attenuation coefficient is often used to remove the dependence of the physical density.

$$\left(\frac{\mu}{\rho}\right) \propto \frac{\sigma_{tot}}{\rho} = \frac{\sigma_{coh}}{\rho} + \frac{\sigma_{pe}}{\rho} + \frac{\sigma_{comp}}{\rho} + \frac{\sigma_{pair}}{\rho} + \frac{\sigma_{trip}}{\rho} + \frac{\sigma_{ph.n}}{\rho}$$

[2]The intensity of a point radiation source follows inverse square law. This a kind of geometric concept as the area of a sphere is A = $4\pi r^2$. The inverse square law is valid under two assumptions: (1) point source – small enough compare to distance; (2) photon undergoes no interaction – TBI with spoiler.

Chapter 6

Measurement of Ionizing Radiation

Attempts were made to measure ionizing radiation based on chemical and/or biological (skin) effects. But those measurements were not reliable. The ICRU adopted the roentgen, denoted by R, as the unit of measuring x- and -ray exposure.

The ICRU No.33 (1980) (1980) definition of exposure:

$$X = \frac{dQ}{dm},$$

where dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in air of mass dm are completely stopped in air.

From the book "Fundamentals of Radiation Dosimetry" (chapter 5 - good chapter to read): the photons first interact with a defined mass of air. They will produce electrons by the photoelectric and Compton effect and both electrons and positrons by the pair production process. All those secondary charged particles must travel through the air until their energy is

6.1 Collection volume

A free air ionization chamber has a 10 mm diameter aperture, a plate separation of 90 mm, and a collection length of 70 mm. Calculate the mass of air in the collection region.

$$mass = \rho \cdot V = 1.293\ kg/m^3 \cdot \frac{1}{4}\pi \times (10\ mm)^2 \times 70\ mm = 2.3 \times 10^{-7} kg$$

6.2 Signal of an ion chamber

The signal from an ionization chamber is proportional to the charge (ionization) collected (so to the numbers of gas molecules in the cavity. Combining the ideal gas law ($P \cdot V = nRT$), we have

$$signal \propto \frac{P \cdot V}{T}$$

In this case, $V_{unsealed} = (1/2)^3 V_{sealed}$ and P_unsealed = 1atm = 1/3 P_{sealed}.

6.3 Temperature and pressure correction

Most likely, the local measurement condition will be different from the standard environment condition (22^oC and 760 mmHg) under which the ion chamber (and possible its electrometer) is calibrated. Therefore we need to correct the reading with a factor (AAPM TG-51):

$$P_{TP} = \frac{(237.2 + T)}{(273.2 + 22.0)} \times \frac{760}{P}, \tag{6.1}$$

wehre T is in the unit Celsus and P is in the unit of mmHg.

Pressure drops about 1 inch per 1000 feet.

So the pressure is 760 – 3600/1000 x 25.4 = 668.6 mmHg. $P_{TP} = \frac{273.2+24}{273.2+22.0} \times \frac{760}{668.6} = 1.14$ $P_{TP_wrong} = \frac{273.2+24}{273.2+22.0} \times \frac{760}{760} = 1.006$; If we used the wrong P_{TP}, the "corrected" reading (machine output) will be thought as 13% lower than the actual value. If we increase linac output to compensate this 13% difference, we will overdose the patient by 13%.

Q6: a); Q7: d); Q8: d); Q9: b)

C); but this is different from my calculation! The plate separation of 90 mm is not used here. E)

Chp6 c c d e b a d d b b d bcd b bc acd

Rogers's talk

6.4 Guard electrode

The guard electrode in a Farmer-type chamber can (1) prevent leakage from the high-voltage collector electrode; (2) define the ion-collecting volume; and (3) minimize polarity effect (?).

a), c), d)

Good reading materials include Deward A good document can be found here.

Figure Radiographs (above) and drawings (below) of five Baldwin–Farmer-style ion chambers plus an Exradin A12 . In the drawings, the heavy black lines represent the extent of guarding, as also indicated by the arrows on the left. The grey blocks indicate the insulator in closest contact with the active air volume, indicated by the arrows on the right. The A12 has no insulator other than air in contact with the active air volume. (PMB 50 N121, 2005)

Chapter 7

Quality of X-rays

We have finished a nice book.

Chapter 8

Absorbed Dose

> "Perhaps one of the greatest contributions physics has made to radiation oncology and radiology, x-ray imaging and all of its forms has been in developing ways to measure radiation accurately and precisely (commonly 'using ion chamber)."
>
> — Peter Almond

To measure the absorbed dose from ionizing radiation within a medium, we need to know

1. The number of particles or photons, or the quantity of energy, passing through the medium (*fluence*)
2. The quantity of energy transferred from initial particles (often photons, which are uncharged) to charged particles in the medium (*KERMA*)
3. The rate at which energy is transferred from the charged particles in the medium, to the medium itself (stopping power, leading to absorbed dose).

Fluence is defined as the number of particles dN incident on a sphere of cross-sectional area da. The SI unit is m^{-2}

$$\Phi = \frac{dN}{da} \tag{8.1}$$

Energy fluence (Ψ, unit: $J \cdot m^{-2}$) is defined as the energy dE incident on a sphere of cross-sectional area da. The SI unit is $J \cdot m^{-2}$.

$$\Psi = \frac{dE}{da} \tag{8.2}$$

If you have a fluence Φ of particles all of energy E, then the energy fluence is simply $\Psi = \Phi \cdot E$.

KERMA (Kinetic Energy Released per unit MAss) is defined as the mean kinetic energy transferred to charged particles from uncharged particles in a mass dm of a given material. The SI unit is J/kg, and the special name for the unit for Kerma is gray (Gy).

$$K = \frac{d\bar{E}_{tr}}{dm} \ (J \cdot kg^{-1} \ or \ Gy) \tag{8.3}$$

The relation between Kerma and fluence can be expressed as

$$K = \int \Psi(E) \frac{\mu_{tr}(E)}{\rho} dE$$

Where $\frac{\mu_{tr}(E)}{\rho}$ is the mass energy transfer coefficient of the material for uncharged particles of energy E.

Unrestricted stopping power for charged particles (electrons) is defined as

$$S = \frac{dE}{dx}$$

- Collisional stopping power (S_{coll})
- Radiative stopping power (S_{rad}) – cause by the interactions of charged particles with nuclear electric field – bremsstrahlung radiation The relationship of fluence and stopping power to absorbed dose is given by:

$$D_{med} = \int \Phi_{med,E}(E) \frac{S_{coll}(E)}{\rho} dE$$

8.1 Optical density

The details about the radiographic films can be found in AAPM TG-69: Radiographic film for megavoltage beam dosimetry.

8.2 Q9 OD

A pivotal assumption in film dosimetry is that the dose to the film is reflected in the resulting "blackness" or optical density (OD) of that film.

$$OD = log_{10}\left(\frac{1}{T}\right) = log_{10}\left(\frac{I_0}{I_t}\right)$$

The details about radiochromic films can be found in AAPM TG-55 and its update AAPM TG-235 as well an excellent review article by Butson et al. "Radiochromic film for medical radiation dosimetry" (2003). Table 1 lists the radiation interaction processes and their variation with Z.

Relative dosimeter

- Diode (single or 2D diode array MapCheck)
- TLD
- OSL
- MOSFET
- Film

Chapter 9

Dose Distributions

9.1 TAR

The first three factors are used for the source-to-axis distance (SAD) technique (mechanical isocenter and radiation isocenter roughly coincidence with the tumor centroid).

With d is the depth from the surface to the isocenter in a phantom and r is the field size at the level of the isocenter, we can define

- `Tissue-air-ratio` (TAR) is defined by

$$TAR(d, r_d) = \frac{Dose_{phantom}(d)}{Dose_{air}} \tag{9.1}$$

- `Backscatter factor` (BSF) is a special case of TAR, in which $d = d_max$

$$BSF = \frac{Dose_{phantom}(d_max)}{Dose_{air}} \tag{9.2}$$

- `Scatter-air factor` (SAR) can be calculated by

$$SAR(d, r) = TAR(d, r) - TAR(d, 0) \tag{9.3}$$

THe `Mayneord factor` is used to find a new PDD from a known PDD value

$$f = \frac{PDD_2}{PDD_1} = \left(\frac{SSD_2 + d_{max}}{SSD_1 + d_{max}}\right)^2 \cdot \left(\frac{SSD_1 + d}{SSD_2 + d}\right)^2 \tag{9.4}$$

Chapter 10

Dose calcuation

We have finished a nice book.

Chapter 11

Treatment Planning I: Isodose Distribution and Plan Evaluation

11.1 Penumbra

The dose distribution outside the field boundaries is significantly affected by geometric penumbra, depth, leakage radiation through collimator. The flattening filter mostly affect dose within the field boundary.

11.2 Wedges

- Physical wedge
  - External physical wedge
  - Internal physical wedge (aka motorized wedge, as in Elekta^{TM} machines) typically consists of a single large wedge (e.g., 60 degrees) placed above the secondary collimating jaws. The smaller angle is form by combining the open (o) field and the 60^o degree wedge field:

    $$Dose_\theta = W_o Dose_o + W_{60^o} Dose_{60^o},$$

    where $W_{60^o} = \frac{tan\theta}{tan60^o}$.
- Non-physical wedge
  - *Virtual wedge* (as in Siemens^{TM})
  - *Enhanced dynamic wedge* (EDW) in Varian^{TM}, which is implemented by moving one of the collimating jaws from one end of the field to the other.

Wedge (isodose) angle is defined as the angle between wedged isodose curve (see figure wedge isodose) and the normal to the central axis at a specific depth (e.g., 10 cm). What we typically measure is wedge profile.

Wedge Commissioning

- Salk et al Physical aspects in the clinical implementation of the EDW - **1D ion chamber**.
- Fontanarosa et al Commissioning Varian EDW in the PINNACLE treatment planning system using **Gafchromic EBT film**.
- Njeh EDW output factors for Varian 2300 CD and the case for a reference database.
- Shao et al the accuracy of dynamic dose computation in the ADAC Pinnacle RTP system.
- Zhu et al Performance evaluation of a diode array for EDW dosimetry - **mapcheck**.
- Ahmad et al Study wedge factors and beam profiles for physical and EDW

Chapter 12

Treatment Planning II: Patient Data, Corrections, and Setup

12.1 Inhomogeneity

In the presence of inhomogeneity, the dose calculation needs to address two issues (https://www.utoledo.edu/med/depts/radther/pdf/JC%20Chapter%2011%20handout.pdf):

1. Change in primary fluence (see Eq. (**??**)) due to change in attenuation
2. Change in scatter contributions.

calculation either indirectly through a correction factor (CF) or directly inherent in the algorithm (Papanikolaou AAPM presentation)

12.2 Range

The energy loss of electrons in a medium can be evaluated using `mass stopping power` (S/) in unit of $\frac{MeV}{g \cdot cm^2}$

$$\begin{aligned}\left(\frac{S}{\rho}\right) &= \left(\frac{S}{\rho}\right)_c + \left(\frac{S}{\rho}\right)_r \\ &= \frac{\frac{dE}{dl}}{\rho}\end{aligned}$$

The detailed information about stopping power for electrons can be found on the NIST website (https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions).

In the range of therapeutic energies, 4 MeV to 20 MeV, the total‘mass stopping power is almost a constant, e.g.,

$$\left(\frac{S}{\rho}\right) \approx 2\frac{MeV \cdot cm^2}{g} \tag{12.1}$$

For water, the `stopping power` (S) is equal to $S = \left(\frac{S}{\rho}\right) \times \rho \approx 2\frac{MeV \cdot cm^2}{g} \times 1\frac{g}{cm^3} = 2\frac{MeV}{cm}$.

For an electron beam of energy E, which is specified as the most probable energy at the surface $(E_P)_0$, the practical range of a broad electron beam in water can be estimated by $R_P = E/12MeV$.

12.3 MRI

Shimony's Youtube video and more resources at 2:41.

Basics

1. A strong, uniform magnetic field B_0[1] is applied (clinical: 1.5-7 Tesla and research: 7-11.7 Tesla);
2. The magnetic field will algin protons (hydrogen atoms) which are normally randomly orientaed within human boday. This can also explained as the magnetic creates two separated energy levels, and the energy difference is $\Delta E = hf$, and the frequency f, the resonance (*Larmor*) frequency, can be written as
$$f = \gamma \cdot B_0,$$
where γ is called `gyromagnetic ratio` and is equal to 42.6 MHz/T. For $B = 3.0\ T$, the Lamor frequency is 130 MHz.
3. As
4. To excite the atoms from lower to higher energy levels (RF coil) and an additional magnetic field is applied in the x-y plane to create a flip angle (90° or 180°);
5. The emitted RF waves can be picked by an antenna; to relate the spatial information with precisely controlled magnetic field (`gradient foil`)

The RF signal for a spin-echo sequence can be written as

$$Singal = \rho \cdot M_Z \cdot \left(1 - e^{-\frac{TR}{T1}}\right) \cdot M_{XY} \cdot e^{-\frac{TE}{T2}},$$

- ρ is the proton density;
- M_Z and M_{XY} areh the magnetization along the Z and XY direction
- TR: `repetition time` - time between each RF pulse;
- TE: `echo time` - time between delivery of RF pulse and receipt of the echo signal.
- T1: `longitudinal relaxation time` - a measure of the time taken for spinning protons to realign with the external magnetic field; for example, T1 = 4,000 ms and 250 ms for *water* and *fat*;
- T2: `transverse relaxation time` - a measure of the time taken for spinning protons to lose phase coherence among the nuclei spinning perpendicular to the main field; for example, T2 = 250 ms and 70 ms for *water* and *fat*;

  T1-weighted image is called (fluid) dark image and T2-weighted image is called (fluid) bright image

  It is all about water and fat

12.4 PET

Positron decay (see Section **??**)

[1]For a simple long solenoid with uniform winding density, the magnetic field will be
$$B = \mu_0 IN/L,$$
where B is field strength, μ_0 is the permeability constant of free space ($1.27 \times 10^{-6} mks^{-2}A^{-2}$; about the same as those for water, hydrogen, and human body), I is current per turn, N is the number of turns, L is the coil length. For B = 1 T, L = 1 m, N = 10,000, the current will be around 80 A Aarnink. We thus have to use superconducting technique - thanks to Fermilab Tevatron.

Chapter 13

Treatment Planning III: Field shaping, skin dose, and field separation

13.1 HVL

To calculate transimssion or attenuation problems, you can use one of three formula with given parameters

1. $2^{-t/HVL}$ given HVL
2. $10^{-t/TVL}$ given TVL
3. $e^{-\mu t}$ given linear attenuation coeffieients

You can directly calculate the result from $2^{-n\times HVL/HVL} \leq$ 0.02. Or using 0.02 = 1/50, 2^(-5)=1/32 and 2^(-6)=1/64, we can guess the result is d).

Related references Calibration: TG-21 (1983) → TG-51 (1999) + Addendum to the TG-51 (2014) Parallel-plate chamber: TG-39 (1994) Clinical electron therapy: TG-25 (1991) → TG-70 (2009) Total skin electron therapy: TG-30 (1987) IORT – Mobetron: TG-72 (2006) Comprehensive: ICRU Report 71 (2004) IAEA Radiation Oncology Physics Chapter 8

13.2 Q2, 3, 4, and 7 Range

The energy loss of electrons in a medium can be evaluated using mass stopping power (S/) in unit of $\frac{MeV}{g\cdot cm^2}$

$$\left(\frac{S}{\rho}\right) = \left(\frac{S}{\rho}\right)_c + \left(\frac{S}{\rho}\right)_r = \frac{\frac{dE}{dl}}{\rho}$$

The detailed information about stopping power for electrons can be found on the NIST website (https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions).

In the range of therapeutic energies, 4 MeV to 20 MeV, the total mass stopping power is almost a constant, e.g.,

$$\left(\frac{S}{\rho}\right) \approx 2\frac{MeV\cdot cm^2}{g}$$

For water, the stopping power (S) is equal to $\left(\frac{S}{\rho}\right) \times \rho \approx 2\frac{MeV \cdot cm^2}{g} \times 1\frac{g}{cm^3} = 2\frac{MeV}{cm}$.

For an electron beam of energy E, which is specified as the most probable energy at the surface (EP)0 , the practical range of a broad electron beam in water can be estimated by R_P=E/S E=R_P S=6cm×2 MeV/cm= 12MeV.

Chapter 14

Electron

14.1 History

- late 1930s Van de Graaff Accelerators (at MIT by Van de Graaff and Trump); low energy < 3 MeV
- late 1940 Betatron; beam quanlity is not good
- 1960s linear accelerators

14.2 Treatment Sites[1]

A lot sites (located with 6 cm of the surface) but only accounts for 10-15% of treatment.

- Head (Scalp, ear, eye)
- Breast/Chest wall
- Skin
- extremities

However, the competing techonology (VMAT, BT, …), inaccurate dose calculation (account for bolus scatter, backscatter, eye shield,…), and most importantly, lack of motivation from the vendor have reduced the number of electron treatment in radiotherapy.

14.3 Interactions

With orbital electrons

- Elastic collision
- Inelastic collision (ionization and excitation - to higher energies) - dose deposition

With nuclei

- Elastic collision
- Inelastic collision (Bremsstrahlung)

[1] Electron Radiotherapy, Past, Present, and Future (https://vimeo.com/78553521)

14.4 Delivery

- Double scattering foil system (spread + flattern)[2]. Excerpt from Niroomand-Rad: *In a Siemens machine, the electron beams pass through dual scattering foils. The first (primary) foil, made of stainless steel, serves to scatter the electron beam. Its thickness is 0.075 mm for 5-7 MeV beam and 0.030 mm for 10 MeV beams. The second (secondary) foil, made of 0.8 mm thick aluminum, for all the electron beams, produces a homogeneous radiation mainly by absorption.*
- Collimation cones (typically multi-leveled to block electron spread at different distance)
- Jaws set at a much larger size than the cone sizes

14.5 Beam quality

PDD

- Surface dose (70%-90%)
- R90 (*therapeutic range* ~ E/4) is the depth for tumor edge
- R10 - R90 for estimating dose fall-off to spare oARs
- Rp (*practical range* ~ E/2) - where beam stops
- x-ray contamination (from linac and phantom and patient, about 50% each)

  With energy, field size, and SSD increase, PDD will increase, decreases, and stays roughly the same.

`Example: Electron treatment with cicular cutout of 3 cm and 2 cm diameter. the measured output factor is 0.85 and 0.67`

$$OP\left(d_{max}(r), r, SSD\right) = \frac{D\left(d_{max}(r), r, SSD\right)}{D\left(d_{max}(r_0), r_0, SSD\right)}$$

where $d_max(r)$ and $d_max(r_0)$ are from PDDs of the custumized cutout or the reference cone. The reference cone size of 15 cm by 15 cm is recommended with higher energy is equipped.

The PDDs are normally measured using ion chambers and diode in an automated scanning system. The

$$PDD_w(d) = PDI_w(d) \times \frac{\left[(\overline{L}/\rho)^w_{air} \times P_{repl}\right]_d}{\left[(\overline{L}/\rho)^w_{air} \times P_{repl}\right]_{dmax}}$$

14.6 Internal shielding

is useful to protect the normal structures around the high Z shaping material. For electrons in the range of 1-25 MeV, the range of the backscattered electrons is about 1-2 g/cm2 of polystyrene (see TG-70 table IV below).

Example 3.1 A buccal mucosa lesion is treated with a 9 MeV electron beam incident externally on the cheek. Assuming cheek thickness including the lesion, to be 2 cm, calculate (1) the thickness of lead required to shield oral structures beyond the cheek; (2) magnitude of electron backscatter, and (3) thickness of bolus or aluminum to absorb backscattered electrons. (1) Electron energy at depth z, $E_z = E_0(1 - z/R_p) \sim 5$ MeV, lead thickness is $5/2 = 2.5$ mm. (2) For the polystyrene-lead interface, the electron backscatter factor (EBF) can be calculated as , and thus EBF = 1.57 or 57% backscattering.

[2]Scanning electron beams have better beam quality but suffered from the Therac 25 incident; Scanning technqiue is widely used in proton beam delivery

14.7 Total skin electron irradiation (TSEI)

The total skin irradiation (TSI) is one of the most efficient techniques in the treatment of the cutaneous T-cell lymphoma (mycosis fungoides). (Diamantopoulos) Its purpose is to deliver the prescribed dose (average 36 Gy over 18 fractions) to patient skin, without damaging any healthy organ. The main prerequisite for TSE installation is a linear accelerator capable of producing large (200 cm x 80 cm) and uniform fields (acceptable variation of dose distribution: ± 8% vertically and ± 4% horizontally within the central 160 cm x 60 cm field area according to AAPM TG-30) of relatively low energy electrons (4-10 MeV at the exit window, 3-7 MeV at patient's surface) at an extensive SSD.

Our institutional experience

Treatment:

- Dose rate: 2500 MU/min (Truebeam High Dose Electron) or 900 MU/min (Artiste)
- Energy: 6 MeV
- technique: large-field technique - 6 patient positions, and two gantry angles per position
- Schedule: 6 beam per day;
- wear paper short
- Protection: Finger and toe nail shields
- Internal eye shields
- TG-51 was performed on this beam, with the machine output adjusted to 1cGy/MU at the depth of 1.3 cm deep (dmax) with 100 cm SSD with a 15 x 15 cm^2 cone.
- The TG-51 setup was replaced with solid water and a PTW 23343 Markus chamber. A transfer factor was established for this chamber, 0.019675 nC/cGy.

The gantry was then angled to 270° and the chamber placed a varying extended distances from the isocenter. At 330 cm SSD an acceptable dose rate was found, 59 cGy/min, without reducing field size and uniformity. Film was placed on the back side of the scatter screen at 330 cm SSD. The film was irradiated with 450 MU, with varying sets of beam angles. A ±10% uniformity was achieved using beam angles of 253° and 287°, over a height of 200 cm (figure 1). The patient treatment will then be 12 beams. The patient will be treated by the two gantry angles at each of 6 positions, 3 one day, 3 the next, per fraction. The patient will face the accelerator (AP beams) and be irradiated by 253° and 287° gantry angle beams. The patient will then rotate 120° (RPO), receive the two beams again, then rotate 120° (LPO) for the last two beams. The next day the patient will face away from the accelerator (PA), then rotate 120° (LAO), and again (RAO). A 1 cm thick scatter screen will be placed at 310 cm SSD. A cylindrical phantom, 30 cm in diameter was then placed at 330 cm SSD, centered with the lasers, with the scatter screen 20 cm in front of it. Powder Thermo-Luminescent Dosimeters (TLD)s were placed around the circumference of the cylinder. Additional TLDs were placed around the circumference under 5mm of wax bolus. This phantom was irradiated with the two beams, (gantry angles of 253° & 287°), and then rotated 60, 120, 180, 240 and 300° about its vertical axis, irradiated at each position with the two beams. This simulates the patient treatment. Each beam was 450 MU, 6MeV at 900 MU/min, with a 33x33cm field size. The average TLD reading was 67.6 with a standard deviation of 2.8 cGy. This gives the beam calibration factor of 67.6 cGy/450 MU per beam.
The TLD value was compared to the chamber measurement from the two beams, but no phantom rotation. This is 26.2 cGy/450 MU. This implies B factor of 2.58 (expect 2.5-3). The B factor represents the increase in dose due to the overlapping of the surface exposed at each phantom rotation and the oblique angle of incidence. The Percentage Depth Dose (PDD) was determined using film (figure 2), chamber (figure 3) and TLD measurements. The chamber measurements are only based on directly incident beams, ie the phantom is not rotated. They give a PDD at 5 mm of around 93%. The film and TLD measurement used all 12 beams

(6 phantom positions, 2 beams per position), therefore the surface dose is greatly increased by the oblique angles of incidence of the electron beams. This reduces the PDD. The film and TLDs both see a PDD of 85% at 5 mm.

PDD at 5 mm is 85%. Calibration factor: 67.6 cGy / 450 MU MU = dose per fraction / (PDD * Calibration Factor) = 200 / (0.85 * 67.6/450) = 1566

Patient treated on TSET stand. 1 cm thick plastic scatter plate 20 cm in front of patient. 3 cm thick plastic shield for lower half of body 3 mm thick lead shields on fingernails and eyes Stand against wall* (how you make sure SAD and SSD setup?)

Every patient gets **same MU**!

Boost fields are required at various locations: Vertex of scalp; Mid forehead; Lt. (Rt.) Axilla; Sternum; Under Lt. (Rt.) Breast; Back at T5; Umbilicus; Lt. (Rt.) Gluteal fold; Middle gluteal fold; Under scrotum (perineum); Lt. (Rt.) Anterior Thigh; Lt. (Rt.) Anterior Finger; Lt.(Rt.) Anterior toe; Calibration TLDs

6 MeV boost with 1 cm bolus.

14.8 Solutions

Q1: a) see section **??**
Q2: c)
Q3: c); the energy of clinical electron beams is specified as the most probable energy at the surface
Q4: c)
Q5: b)
Q6: a)
Q7: b)
Q8: a) b)
Q9: c)
Q10 Virtual SSD d); Virtual electron source-surface distance is not a physical distance. It is a distance with which the inverse square law could be used for different SSDs. In reality, however, this output and pdds are measured for different SSDs instead of using the method of virtual SSD.Q11: a) b) c) d)Q12 Photon and electron beam junction a); more scattering from the electron beam will enter the side of the photon beam.Q13 b)Q14 a) c)‘

Chapter 15

Brachytherapy

> Brachytherapy began at the turn of 20th century, contemporary with external beam radiotherapy. Physicsits and physicians together developed the field. There has not been a period since the beginning that has not witnessed innovations and progress in brachytherapy
>
> — B.R. Thomadsen in "Anniversary paper: past and current issues in brachytherapy physics"

Dose rates defined in ICRU 38 (1985) and 10 CFR 35

- Ultralow dose rate: **0.01-0.3 Gy/hr** (prostate implants)
- Low dose rate: 0.4-2.0 Gy/hr
- Medium dose rate: 2-12 Gy/hr
- High dose rate: **>12 Gy/h**; modern HDR can deliver about **430 Gy/hr**
- Pulsed dose rate

Brachytherapy category depending on placement of sources

- `Plaques` or `mold` - eye plaques
- `Interstitial` - prostate implants
- `Intracaitary` - HDR cylinder
- `Intraluminal` - IVBT

15.1 Isotopes

15.1.1 Radium sources

Radiumsources used for implant therapy contain ^{226}Ra in `secular equilibrium` (takes about 1 month) with its decay products (^{226}Ra to stable lead ^{206}Pb).

The radium was supplied in the form of a salt, which was mixed with an inert filler such as magnesium oxide or barium sulfate. The small crystals of radium salt and filler were contained within cylindrical cells about 1 cm long. The cells were made of gold foil 0.1 to 0.2 mm thick and were sealed to prevent the escape of radon gas. Each source of radium contained 1 to 3 cells surrounded by a wall of platinum, reinforced with iridium (10%). The thickness (usually 0.5 or 1 mm) of the platinum-iridium wall was sufficient to absorb α and β radiation from the source. Gamma rays were attenuated only slightly by the wall.

The exposure rate from a 1 mCi point source of ^{226}Ra that is in secular equilibrium with its decay products and enclosed within a 0.5 mmPt-Ir wall is 8.25 R/hr at a distance of 1 cm. The value of **8.25 R·cm^2/hr·mCi** is referred to as the `exposure rate constant`.