Chapter 7 - Determining Radiation Intensity

- We now know how to detect radiation
- Now we most quantify it.
  - need to take the measurements of ionization and relate them to exposure and/or dose

- In the beginning, radiation effects were determined by Skin Erythema Dose - the amount of radiation needed to redden the skin of a fair-skinned person.
- This concept led to very wide variations in exposures (285 - 1120 R in one study).

- In 1925, Fricke + Glasser standardized exposure measurements by making an air-equivalent, 1cc ionization chamber.
- This allowed them to very accurately measure the ionization effects in a known volume of air (1 cc)

- In 1956, the ICRU defined the Roentgen.

$$1 \text{ roentgen} = 1R = 2.58 \times 10^{-4} \text{ Coulomb}/(\text{kg of dry air})$$

- remember that the coulomb is a measure of charge. (electron - 1.6×10^{-19} C)

- Limitations of the Roentgen.

① The unit assumes that all corpuscular radiation is detected.
That may not always be the case

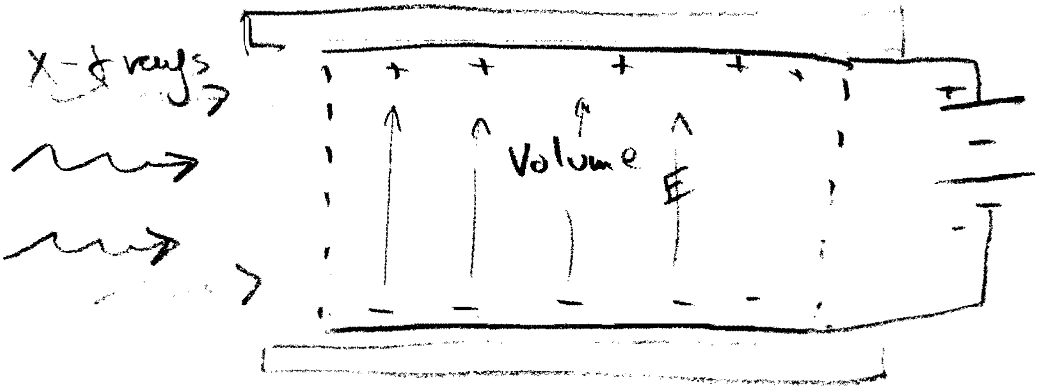
② Applies only to x & γ-rays
- not particulate radiation.

③ - The instrumentation must be unique.
needs to be air equivalent & have elec. equil.

→ Free-Air Ionization Chamber: (how is Roentgen measured?)

The Main instrument used to measure exposure (R) is the Free Air Ionization chamber.

It's composed of an open air volume which is precisely defined, and a voltage bias

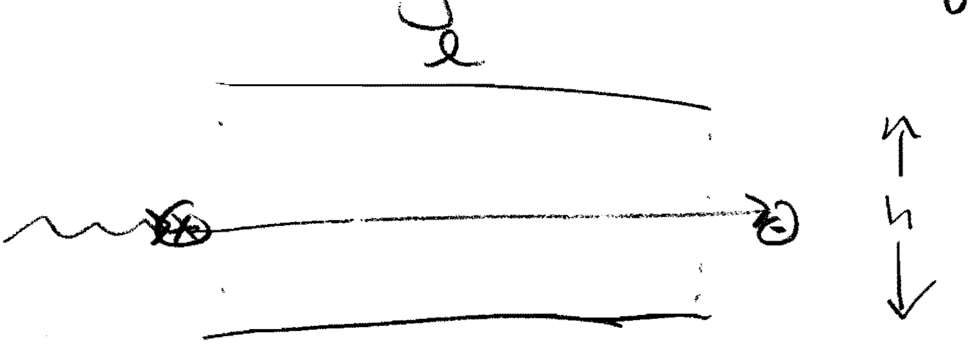


the electrons out of the measuring volume.

- This will result in too little ionization being measured.

- If the two processes exactly cancel each other out (# in = # out), then we have electronic equilibrium.
  - this will accurately measure all corpuscular radiation

- How can we guarantee electronic equilibrium?



- The length of the chamber must be $\geq$ the Range of the electrons, otherwise #Out > #In.

- So, to measure higher & higher photon energies, we need to build longer & longer chambers.

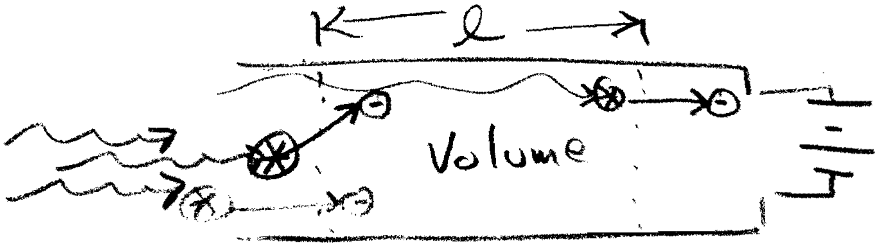
- As the chamber gets larger & larger (l & h), it is harder & harder to maintain a uniform electric field.
- For this reason, the Roentgen is not defined above an energy of 3 MeV.

The electric field is set-up to be very stable and uniform.
The volume is known very accurately.

∴ All of the "corpuscular" radiation is detected and the volume is known so we can measure charge/volume which is Roentgen.

In the definition of R, we must measure all of the "associated corpuscular emissions" from the x-ray beam — In the volume only!! and no other.

Consider the case of incoming photons:



- interactions occur outside of the volume and the electrons are propelled into the measuring area.
- This would cause too much charge to be measured.

- On the other end of the chamber, interactions are taking place inside the volume, but are propelling

(Lab #2)

- Roentgens as units are used at lower energies (<3MeV)
- Superficial, orthovoltage, etc.

- TO calibrate an x-ray machine, we need to expose our chamber and convert the reading to Roentgens.

Formula:

$$\frac{R}{min} = \frac{(\text{reading})(\text{Calib. Factor})(C_{TP})}{(\text{exp. time})} \qquad (p.79)$$

where, $$C_{TP} = \frac{760\,\text{mm Hg}}{\text{Press}}\left(\frac{273.15 + T\,(^{\circ}C)}{295.15}\right)$$

Calib. Factor is obtained from an accredited calibration laboratory and relates the chamber/electrom reading to Roentgens (R/reading)

C_{TP} - Temp, Pressure correction factor.
This is needed to correct for the condition of the "gas" (air) that may be different from the calibration conditions.

STP - standard temp & pressure
22°C, 1 atm (760 mm Hg)

- So, to use the example in the book :

$T = 23°C$ Reading = 95.5 units
$P = 763\,mmHg$ Calib factor = 1.04 R/unit
$C_{TP} =$ exp. time = 1 minute

the chamber is 51 cm from the x-ray source. at the tip of a 50 cm SSD cone.
The exposure is made at 250 kvp, 10 mA, with a Thoraeus II filter.

$$\frac{R}{min} = \frac{(95.5\,units)(1.04\,R/units)}{1\,min}\ \frac{760\,mmHg}{763\,mmHg}\left(\frac{273.15 + 23.0}{295.15}\right)$$

$$= 99.3\ R/min.\ @\ 51\ cm.$$

But we want the output at the cone end since that is where the patient will be.
So we'll use the inverse square law

$$\frac{R}{min} = 99.3\frac{R}{min}\left(\frac{D}{d}\right)^2$$

$$= 99.3\frac{R}{min}\left(\frac{51\,cm}{50\,cm}\right)^2$$

$$= 103.3\frac{R}{min}$$ @ 50 cm for 250 kvp, 10 mA, a Thoraeus filter

- It is important to note that this calibration is only good for this arrangement of parameters (kvp, mA & filter).

- Also, the calibration factor must be measured at the same kvp.

- These three parameters affect the output of an x-ray tube.

① Filtration - less filtration, more output.

② mA - output increases linearly with mA

mA	output
10.0	64
2.5	16

reduce mA by $\frac{1}{4}$, output $\frac{1}{4}$

③ kvp - as kvp increases, output increases ~ 100 kvp, output increases with the square of the kvp

kvp	Output
100	64
140	125

increase kv by 40 output doubles

Since the Roentgen is limited to 3MeV, we need to come up with methods/measurements to measure higher energies.

Also, although exposure measures the <u>amount</u> of radiation present, it does not tell us anything about the <u>effect</u> or in our case, the <u>dose</u>

Kerma:

- As the photons interact with matter, they interact with atoms and transfer their energy to electrons, ionizing them.

- The total amount of energy transferred to the electrons is call KERMA.

<u>K</u>inetic <u>E</u>nergy <u>R</u>eleased in <u>M</u>atter

- KE is measured in joules
- matter is expressed as Mass (kg)
- units of kerma is <u>joules/kg</u>

- a special unit of Gray (Gy) is assigned to Kerma
  Gy (joules/kg)

But ↓

We wish to know the energy absorbed by the matter which is what causes biological effects.

Radiation Absorbed Dose (rad)

- The rad was defined to describe the energy absorbtion in tissue

- The original definition was

$$1 \text{ rad } (r) = 100 \text{ ergs/gm}$$

- Again, it is energy (ergs) per mass (gm).

- The rad has been replaced by the SI unit of Gray (Gy)

$$1 \text{ Gray } (Gy) = 1 \text{ Joule/kg}$$

and

$$1 \text{ cGy} = 1 \text{ rad}$$

- Advantages over the Roentgen
  ① Applies to all ionizing radiations
    - X-ray, γ-ray, charged particle & uncharged
  ② Applies to areas where elec. equil doesn't exist (i.e. — close to surface)

  ③ Directly related absorbtion of energy and ∴ biological effects.

- (We can relate the roentgen and the rad (cGy).
- i.e. what is the dose to air if it is exposed to 1R of radiation?

In Air (on average), it takes approx. 33.85 eV to create an ion pair. (energy deposited)

$1\ R = 2.58 \times 10^{-4}\ C/kg$ (by definition)

- each ion pair (ip) releases one e^-

$1\ e^-$ charge $= 1.60210 \times 10^{-19}\ C$

So, how many i.p. are created? (in 1 Roentgen)

① $\dfrac{2.58 \times 10^{-4}}{1.6021 \times 10^{-19}} = 1.61 \times 10^{15}$ i.p./kg (on avg.)

It takes ~33.85 eV of absorbed energy to create an i.p.

② $D_{air} = (1.61 \times 10^{15}\ \text{i.p./kg})(33.85\ eV/ip)$

$= 54.49 \times 10^{15}\ eV/kg$

Convert to J/kg

$= (54.49 \times 10^{15}\ eV/kg)(1.602 \times 10^{-12}\ ergs/eV)$

$= 87.3 \times 10^{3}\ ergs/kg \left(\frac{J}{10^7\ erg}\right)$

$= 87.3 \times 10^{-4}\ J/kg$

$= 0.873 \times 10^{-2}\ J/kg$

$= 0.873 \times 10^{-2}\ Gy \left(\frac{100\ cGy}{Gy}\right)$

$$\boxed{③\ D_{air}(R) = 0.873\ cGy}$$

$$\boxed{\therefore\ D_{air} = X(R) \cdot 0.873 \frac{cGy}{R}}$$

The "f" Factor:

- We need to convert our D_{air} into a meaningful dose to tissue (or whatever substance)
- This is done with the "f" factor
- also known as the "rad to roentgen" conversion factor.

Definition: Mass energy absorption coeffient:

$$\mu_M = \frac{\mu_{en}}{\rho}$$

μ_{en} ≡ linear attenuation coeff $\left(\frac{1}{cm}\right)$

ρ ≡ density $\left(gm/cm^3\right)$

$$\therefore\ \mu_M = \frac{\mu_{en}}{\rho} \text{ has units } \left(\frac{1}{cm}\right)\left(\frac{cm^3}{gm}\right) = \frac{cm^2}{gm}$$

$$\text{or } \left(\frac{m^2}{kg}\right)$$

each material has a unique $\frac{\mu_{en}}{\rho}$ for each energy.

If we could measure a dose in one material (medium) and a dose for the same conditions in another material; (e.g. Air) Then, the ratio of the doses is the same as the ratio of the mass energy absorption coefficients.

$$\frac{D_{med}}{D_{air}} = \frac{(\mu_{en}/\rho)_{med}}{(\mu_{en}/\rho)_{air}}$$

$$D_{medium} = D_{air}\left[\frac{(\mu_{en}/\rho)_{medium}}{(\mu_{en}/\rho)_{air}}\right]$$

But, we've already shown that:

$$D_{air} = X(R) \times 0.873\,cGy/R$$

So, combining the 2 equations:

$$D_{med} = X(R) \times (0.873\,cGy/R)\left[\frac{(\mu_{en}/\rho)_{med}}{(\mu_{en}/\rho)_{air}}\right]$$

We define the "f-factor" as:

$$f_{med} = 0.873 \frac{cGy}{R} \left[\frac{(\mu_{en}/\rho)_{med}}{(\mu_{en}/\rho)_{air}} \right]$$

and our equation becomes:

$$D_{med} = f_{med} \cdot X(R)$$

Table 7.2 on page 84 gives examples of the f factor.

You will notice that there is a different f-factor for each energy-medium combination.

The f-factor takes an exposure X in Roentgens, and converts it to a dose in cGy.

It is also referred to as the Roentgen-to-rad conversion factor.

Example: For 100 keV photons, what is the dose delivered to muscle if the exposure to that muscle is 100 R?

$$f_{med} = 0.956\, cGy/R$$

$$D_{muscle} = (100 R)(.956\, cGy/R) = 95.6\, cGy$$

Cavity Theory:

The f-factor works fine for energies below 3MV, where the Roentgen is defined.

But for higher energies, another approach must be used.

Bragg-Gray Cavity Theory:

Relates the ionization measured in a small cavity (your chamber) to the dose received by the medium without the chamber.

The cavity must be small enough so that it doesn't perturb the electron motion through the medium.

For higher energy beams, a new facter A_{eq} is introduced to correct the chamber reading.

For Co-60, $A_{eq} = 0.985$

Then, our equation becomes:

$$D_{med} = A_{eq} \cdot f_{med} \cdot X$$

$$= \underbrace{0.985 \cdot f_{med}} \cdot y$$

$$D_{med} = C_{\lambda} \cdot X$$

↳ reading converted to Roentgens

C_λ is a value we look up for the energy beam we are measuring (table 7.4, p 88).

Example: 10 MV x-rays, $C_\lambda = 0.943$ for an exposure of 100 R

$$D_{water} = (0.943)(100) = 94.3\ cGy$$

For the calibration of Electrons, a similar approach is used

$$D_{med} = (C_e)(X)$$

where C_e depends on the electron energy and the depth of measurement.

- as electrons penetrate deeper, the lose energy
  - lower energy electrons have different μ_{en}/ρ (energy-dependent)
- different μ_{en}/ρ mean different C_e.

The dose calculation method just described is an older method known as SCRAD

There have been Two major enhancements to the SCRAD approach.

① TG-21 - Task Group 21 (1983)

② TG-51 - Task Group 51 (1998)

These protocols refine the measurements and allow for greater accuracy.

But - they all still depend upon the Bragg-Gray cavity theory.

Dose Equivalent

Dose Equivalent is used to compare the biological effects of different types of radiation.

The Dose Equivalent is the amount of "Standard" X-rays needed to produce the same biological effect as the othe radiation.

Other types of radiation are:
- electrons
- protons
- neutrons
- etc.

The symbol of Dose Equivalence is H.

The Units of Dose Equivalence are Seiverts or rem.

The Dose Equivalent is obtained by multiplying the absorbed dose by a <u>Quality Factor (Q)</u>

$$H(\text{Sv}) = D(\text{Gy}) \times Q$$

or

$$H(\text{rem}) = D(\text{rad}) \times Q$$

Typical values for Q are given in Table 7-6.

Example: A dose of 5 Gy from electrons is equivalent to:

$$H(Sv) = (5.Gy) \times 1.0$$
$$= 5.0\,Sv$$
$$=$$ [illegible]
$$=$$ [illegible]

but a dose of 5 Gy from Alpha particles is equivalent to:

$$H(Sv) = (5Gy)(20)$$
$$H(Sv) = 100\,Sv$$

Why is the dose equivalent different for different types of radiation?

This is due to Linear Energy Transfer (LET)

LET is the amount of energy the radiation deposits per mm as it travels in tissue.

Heavier particles deposit more energy per mm as they travel and therefore cause a greater biological effect.