Lecture 1.2 Unclear Points:

If gamma rays are classified as photons produced by the nucleus, how do annihilation photons count as gamma rays? Is there a more rigorous definition of gamma rays?

Originally the distinction was in energy, but now the distinction is in origin. X-rays are emitted by electrons; gamma rays are emitted by other processes, including nuclear interactions, annihilation, and high-energy astronomical processes.

The lecture notes state that "SI defines no special unit for exposure," so I found question 4 a bit confusing.

No special unit, e.g., Roentgen.

I’m not sure if I understand the sphere and circle example on the slides about Planar Fluence.

Planar fluence – number of particles crossing a fixed plane per unit area – vector quantity, depends on angle of incidence of particle beam

Fluence – number of particles crossing a volume per unit area – scalar quantity

Planar fluence important in dealing with charged particles. Small depths in parallel electron beam, planar fluence remains constant as depth increases, whereas fluence generally increases due to change in direction of electron tracks

I didn’t understand the concept of charged particle equilibrium very well.

CPE allows us to look at only ionizations inside the box, with the assumption that what goes on outside the box is compensated for by what goes on inside the box.

The difference between air Kerma and Exposure, in particular since there is a conversion between the two. It is not clear to me what that conditions are under which this conversion holds true other than the charged particle equilibrium.

From a NIST document:

The Quantities Air Kerma and Exposure

The quantity kerma characterizes a beam of photons or neutrons in terms of the energy transferred to any material. For the calibration service described in this document, consideration is limited to photon beams in air. Air kerma is the total energy per unit mass transferred from a photon beam to air. Air kerma, \( K_{\text{air}} \), is the quotient of \( dE_{\text{tr}} \) by \( dm \), where \( dE_{\text{tr}} \) is the sum of the initial kinetic energies of all electrons liberated by photons in a volume element of air, and \( dm \) is the mass of air in that volume element. Then
The SI unit of air kerma is the gray (Gy), which equals one joule per kilogram; the special unit of air kerma is the rad, which equals 0.01 Gy.

The quantity exposure characterizes an x-ray or gamma-ray beam in terms of the electric charge liberated through the ionization of air. Exposure is defined as the total charge per unit mass liberated in air by a photon beam and is represented by the equation:

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

where $dQ$ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons liberated by photons in a volume element of air, whose mass is $dm$, are completely stopped in air. The SI unit of exposure is the coulomb per kilogram (C/kg); the special unit of exposure, the roentgen (R), is equal to exactly $2.58 \times 10^{-4}$ C/kg. The ionization arising from the absorption of bremsstrahlung emitted by the secondary electrons is not included in $dQ$. Except for this small difference, significant only at high energies, the exposure as defined above is the ionization equivalent of air kerma. The relationship between air kerma and exposure can be expressed as a simple equation:

$$ K = X \cdot 2.58 \cdot 10^{-4} \left( \frac{W}{e} \right) \left( \frac{1}{1 - g} \right) $$

where $W/e$ is the mean energy per unit charge expended in air by electrons, and $g$ is the fraction of the initial kinetic energy of secondary electrons dissipated in air through radiative processes. The value currently accepted by the NIST for $W/e$ is 33.97 J/C. The currently accepted $g$ values for $^{60}$Co and $^{137}$Cs beams are 0.32 % and 0.16 %, respectively.

When defining exposure, the word "air" keeps coming up. How do you define "air"?

"Air" actually means a mixture of 78% nitrogen and 21% oxygen. It’s not really that precise.

The concept of charged particle equilibrium is not yet clear to me. How is this explicitly used to find exposure? Pg. 18 of the lecture says "when we have charged particle equilibrium we need to measure the ionizations that take place inside the box, count those ionizations and use that for measurement for exposure." I don’t understand fully how this calculation process works.

CPE allows us to look at only ionizations inside the box, with the assumption that what goes on outside the box is compensated for by what goes on inside the box.

How do you find the CPE (in experiment/measurements)?
You need to make sure that you have a sufficient amount of air surrounding the collection volume to achieve CPE.

In the definition for exposure, when it says "all electrons liberated by photons," I assume this is referring to only the primary electrons (excluding the secondary electrons). Is this correct?

Includes all electrons, since you can’t tell the difference between primary and secondary electrons.

On pg. 31 of the lecture, you say $1.6 \times 10^{19}$ eV/Joule, but shouldn't this be $6.24 \times 10^{18}$ eV/Joule, since $1\text{eV} = 1.6 \times 10^{-19}\text{J}$?

Yes.

On pg. 44 of the lecture, what is a "critical structure?"

Any anatomic structure that, if overirradiated, would lead to unacceptable morbidity

In the discussion of the proton beam on the same page, it seems to say that there is so much uncertainty in RBE at the end of the range that we don't aim a proton beam directly at a critical structure. However, I thought the advantage of the proton beam came from utilizing the high, abrupt Bragg peak at the end of the range. Then how is proton therapy working, with respect to the problem arising from the uncertainty in RBE?

The uncertainty is not that great so we leave a large margin distal to the beam.

I am unsure of the units on the equations for and units of the mass attenuation coefficient (MAC) and the mass stopping power (SP). MAC = $\mu / \rho = (dN/N)/(\rho * dl)$ ? with unit of m/kg ? SP = $dE/(\rho * dl)$ with units of J*m/kg ?

Units of mass attenuation coefficient are $m^2$/kg, units of mass stopping power are $J \ m^2$/kg

When would we use RBE dose vs. Dose Equivalent?

We use RBE dose when we deal with radiations that are not photons or electrons

Every quantity with units of $1/(s*m^2)$ that I have seen in both physics and engineering has been referred to as a flux instead of a fluence rate. Do other fields use this convention as well? If not, why did ICRU 60 adopt a convention different from most fields? It seems like this would promote confusion rather than clarity of communication.

Flux and fluence rate are the same thing, just called differently in different disciplines.

Absorbed Dose- is the accounting for all radiation interactions (primary and downstream) –and the key quantity for looking at clinical effects of radiation. Kerma and Cema account only for the primary interactions. - When do we see Kerma and Cema being used? Is it calibrating equipment?
Absorbed dose is directly related to clinical effects, but is more difficult to measure, since it includes primary and secondary radiation. Kerma and cema are used more in microdosimetry. Conceptually, they are much easier to understand, but more difficult to measure, and are used more as a handle to connect fluence to dose.

Planar Fluence – I didn’t grasp the geometry on that. Looked at this in Attix... I’m not “seeing” it...

Fluence - number of particles incident on a sphere of cross-sectional area

Planar fluence - number of particles crossing a plane per unit area (depends on the angle of incidence of beam)

In which case should particle fluence be used and in which case should planar fluence should be used?

In this case, planar fluence is same on both sides of scattering medium, but fluence is greater downstream. Dose measurement downstream in spherical detector will be greater than upstream. Dose measurement in flat detector will be the same.

The idea of cross-section is a little unclear.

View cross-section as a measure of probability of interaction per unit particle fluence. Has units of area. Can be viewed as “area” of target particle. Used more for neutrons than any other radiation.

The cross section is defined as the probability of an interaction for a given target when bombarded with a given particle fluence. Does the energy of the given particle change the cross section? If so, are cross
section values then tabulated for a given target with a given particle fluence at a particular energy fluence?

Cross-section is energy-dependent.

The definition of charged particle equilibrium using box example and its connection to exposure was not very clear to me. Not clear for me why we cannot measure the exposure for higher than 3 MeV using the box concepts (If we’re going to try to measure exposure at energies of about 3 MeV, we are going to need a box with dimension of 3 to 4 meters. We need a large volume outside the measurement volume to ensure that any electrons that are produced inside the box are stopped inside the volume of air outside the box. Conversely, electrons that are produced outside the box that can reach the measurement volume will reach the volume).

Mainly practical reasons. 4 m box hard to carry around, hard to get uniform radiation field. Setting of 3 MeV as upper limit for exposure somewhat arbitrary. If we could compress the wall of box to form “solid air,” we could measure exposure for higher energies.

In practice, how do we take into consideration the failure of Charged Particle Equilibrium near interfaces when calculating the dose? What are the corrections that need to be made and how were these determined?

Generally, we ignore failure of CPE near interfaces, unless we do Monte Carlo calculation.

Can relative biological effectiveness be defined for all other radiation sources given the dose equivalent and their effect on tissue, or is it dependent on the individual patient, therapy and intended outcomes?

Generally defined for population.

What do you mean when you say "Quality factors" are "empirical” quantities?

Quality factor is not a well-defined term that accounts for the observation that equal doses of different types of radiation have different effects. The values we use for quality factors are those obtained by general consensus and are approximations.

What are the beta and delta rays you talk about on slide 8?

Beta rays are simply electrons ejected from a nucleus as a result of a nuclear interaction. Delta rays are high-energy electrons that result from interactions of a secondary electron with a charged particle. The energy of a delta rays is high enough so that radiative interactions can occur.

The production of ions when a photon interacts with matter is a stochastic process. But is exposure a stochastic quantity or a deterministic quantity?

Exposure is deterministic. It can only be determined in a finite volume.
The definition of particle flux in the lecture seems ill-defined. "The number of particles that go by you" in what direction, and in what physical area or volume?

That was kind of sloppy. Generally we look at particles emanating from a source and moving in the same direction, but a more precise definition would take a fixed boundary and look at particles crossing the boundary.

The topic of planar fluence is still unclear to me. I don't understand the diagram used to explain the concept.

Number of particles per unit area crossing a fixed plane rather than a sphere.

I also do not understand how exposure can be calculated from air kerma since kerma only relates to primary interactions but exposure relates to primary and secondary interactions.

In a small volume of air, only primary interactions take place; secondary interactions take place in air wall outside chamber.

It seems as if there is quite a bit unknown about particles such as photons and electrons. What is a professional's opinion on this? Obviously, we (physicists) have developed enough information to implement successful treatments for patients, particularly those with cancer, but how confident are we in these treatments? Is the thought that these particles have been explored enough to be used at their maximum potential or does science point to a plethora of information yet to be discovered?

There are still some unknowns about particles, but more in the area of biological responses to these particles, e.g., RBE for protons and other heavy particles.

In the example given on planar fluence, the planar fluence did not change, yet you mention that there are cases where it might be greater on one side of a barrier. Can you expand or further explain the definition of planar fluence? And a related question, why do we define fluence based on cross-sectional area of a sphere, rather than simply a plane that is perpendicular to the incident radiation? (I suppose that there are definitely cases where radiation is incident from many directions.)