Today’s lecture is on Radiation Quantities and Units.

During the last session we spoke about measurements, about different kinds of quantities, and about different kinds of units in general. Today we are going to restrict ourselves to a discussion of quantities and units that are specific to radiation.
We are going to define and identify a whole series of units related to radiation. The units we will discuss today include quantities of radiation measurement such as exposure, kerma, cema, absorbed dose, dose equivalent, relative biological effectiveness, and activity.

Lecture Objectives

• Define and identify units for the following:
  – Exposure
  – Kerma
  – Absorbed dose
  – Dose equivalent
  – Relative biological effectiveness
  – Activity
We’ll also discuss quantities that address radiation on a more microscopic scale, such as particle number, radiation energy, particle flux, energy flux, particle fluence, energy fluence, and planar fluence.
Finally, we will discuss quantities that address radiation interactions, such as cross section, linear attenuation coefficient, mass attenuation coefficient, and mass stopping power.

That’s a whole lot of quantities that we use in radiation.

This is going to be an introduction to some of these radiation quantities. We will be talking about these all through the semester.

You may find this lecture to be very boring because we are going to go through a series of quantities and talk about their units and talk a little bit about their implications, and you’re not going to have a huge amount of context yet. Later on in the course we are going to start developing the context and the relationships among these radiation quantities. A lot of what we introduce today will then make some sense, so you might want to refer back to this lecture from time to time during the course. In fact, in some of the concluding lectures in this course, we will return and revisit some of these quantities. By that time you should have a much better appreciation and understanding of them.
Let’s begin by explicitly identifying the topic of this course, and that is ionizing radiation. This is a course that deals with ionizing radiation, which is a form of radiation with sufficient energy to excite and ionize atoms of matter.

What follows is a very brief introduction to the types of ionizing radiation we encounter in medical physics. We’ll go into a lot of detail about each form of radiation later in the course.
Let’s begin with gamma rays.

Gamma rays are a form of electromagnetic radiation that is emitted as a result of nuclear interactions. There are two major sources of gamma rays.

One way in which gamma rays are emitted occurs when a nucleus moves from an excited energy level to a lower energy level. Energy from the transition is given off in the form of gamma rays. The other way gamma rays are produced results from the annihilation of positrons when they interact with electrons. When this event occurs, two gamma rays, both of energy 511 keV, are emitted.

The energy range of gamma rays is in the range of a few thousand electron volts to a few million electron volts.
A second form of ionizing radiation is x-rays.

X-rays are a form of electromagnetic radiation that is emitted as a result of electronic interactions. X-rays can be emitted when there are changes in electronic energy levels and an atom goes from an excited atomic energy state to a lower energy state. We call these x-rays “characteristic x-rays.”

X-rays can also be emitted when charged particles decelerate, either by slowing down or by changing direction. These x-rays are called “Bremsstrahlung,” which means “braking radiation.”

X-rays energies can range from a few electron volts to several million electron volts.

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**Types of ionizing radiation**

- **X-rays**
  - Electromagnetic radiation emitted as a result of electronic interactions
    - Changes in electronic energy levels – characteristic x-rays
    - Deceleration of charged particles (usually electrons)
      - Bremsstrahlung (“braking radiation”)
  - Energy ranges:
    - 0.1-20 kV Grenz rays
    - 20-120 kV diagnostic x-rays
    - 120-300 kV orthovoltage x-rays
    - 300 kV-1 MV intermediate-energy x-rays
    - > 1 MV megavoltage x-rays
Another class of ionizing radiation is electrons.

Electrons come from several sources. They can be emitted from a nucleus as a result of nuclear decay. They can be ejected from an atom as a result of a collision of another charged particle with the atom. They can also come from an accelerator, either in the form of a continuous beam or a pulsed beam.
Heavy charged particles form another class of ionizing radiation. Heavy charged particles include protons, deuterons, alpha particles, heavy atom nuclei, pions, etc. They are differentiated from electrons because their greater mass results in interactions that are somewhat different from those of electrons. We’ll see that later in the course when we look at charged particle interactions.

We also have uncharged particles, namely neutrons, that are produced as a result of nuclear interactions involving high-energy charged particles or photons.
We can divide ionizing radiation into two categories: directly ionizing radiation and indirectly ionizing radiation.

Directly ionizing radiation includes all charged particles. These particles interact with electrons through long-range Coulombic charged-particle interactions, and deliver energy to matter directly.

Indirectly ionizing radiation includes x-rays, γ-rays, and neutrons, all uncharged particles. They will typically interact via a transfer of energy to a single charged particle, and it is the secondary charged particle that delivers energy to the absorbing material.
Let’s now begin our discussion of radiometric quantities by looking at quantities that are used to measure the amount of radiation.

An important quantity that we deal with when we describe ionizing radiation is exposure. Here we see a definition of exposure. Let’s read the definition and then we can talk about it.

The definition: Exposure is the absolute value of the total charge of ions of one sign produced in a small mass of air when all electrons liberated by photons in air are completely stopped in air, divided by the mass of air.

\[ X = \frac{dQ}{dm} \]

We denote exposure by the capital letter \( X \) and we define exposure to be \( dQ \) divided by \( dm \), that is, exposure is charge divided by mass of air.
Let’s now clarify this definition.

First, what do we mean by “absolute value of the total charge of ions of one sign”?

When radiation interacts with matter it causes ionizations to take place. So we get electrons, and we get positively charged ions. The total charge is going to be zero, because we have as many positive ions as we do electrons. We are only going to look at ions of one sign and we are going to look at the total charge of these electrons.

So that’s what we mean by “absolute value of the total charge of ions of one sign.”
Next we have the phrase “produced in a small mass of air.” How small is a small mass and why do we need to talk about a small mass?

Let’s ask this question in a slightly different manner: Why must we talk about ions produced in a small mass of air and not ions produced at a point?

The answer is that the production of ions is a stochastic process. If we see a photon entering a box of air we have no idea when or where an interaction is going to take place, or if an interaction is going to take place at all. We can only speak of a probability of an interaction taking place. But, the only way we can determine this probability is to look at a large number of photons.

With a large number of interactions we can now determine a mean value.

So we need to have a small mass of air that is large enough to have a reasonable number of interactions in order to obtain a mean value. We’ll defer the question of just how large this small mass must be for a little while.

What do we mean by “air”? That’s a mixture of 78% nitrogen and 21% oxygen, but we need not be too precise.
The devil in the details

- “all electrons liberated by photons in air are completely stopped in air”
  - Aren’t we measuring photon exposure?
  - What do electrons have to do with this?
  - How does this make things complicated?

Next phrase: “all electrons liberated by photons in air are completely stopped in air.” What do we mean by that?

Let’s look at what happens when a photon ionizes a target. The photon comes in and interacts with a target atom or molecule. We are going to spend a lot of time on these interactions in subsequent lectures, but for now, let us just say that there is going to be an interaction. The photon interacts with the target and produces an electron. The electron that’s produced travels beyond the point of the interaction and causes additional ionizations to take place. So we also have to look a little bit downstream of the initial interaction to follow that electron. We not only have to count the ionization that takes place at the point where the photon interacts, but we also have to somehow count all of the ionizations that take place because of the production of secondary electrons downstream. That causes a lot of issues in how we are going to measure exposure. Keep that on hold for a while.

We need to look at the initial ionization in a small volume of air, and we need to look at all of the subsequent secondary ionizations produced by that first ionization that take place until that electron gives up all of its energy through ionization processes. And then we divide the number of ionizations by the mass of air because we want an intensive property, that is, one that is independent of the amount of air present. If we have more air, more ionizations will take place. We don’t want to say there is more exposure because there is more air so we divide the number of ionizations by the mass of air.

So that’s what we mean by exposure.
We have said that all of the electrons that are liberated by the photons in the air have to be completely stopped in air. What do electrons have to do with this and how does this make things complicated?

Photons interact with the absorber, and give rise to secondary electrons. These secondary electrons interact further with the absorber.

A single ionization due to a photon yields many ionizations due to electrons downstream.
In fact, you can look at this table and see what the path lengths of electrons produced by photons of various energies are.

<table>
<thead>
<tr>
<th>Photon Energy (MeV)</th>
<th>Maximum Electron Path Length in Air (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>3.0</td>
<td>12.2</td>
</tr>
<tr>
<td>10.0</td>
<td>40.9</td>
</tr>
</tbody>
</table>

If the photon energy is 0.3 MeV, the path length of the secondary electrons is about 0.3 meters. If the photon energy is 1 MeV, the secondary electrons can travel up to about 3 meters. Now what happens when we go up to photons of energy 10 MeV? Secondary electrons can deposit their energy by producing ionizations for a distance of up to over 40 meters. Whatever sort of measuring device we use to measure exposure in air must be able to stop all of these secondary electrons.

If we’re trying to measure exposure from 0.3 MeV photons, that shouldn’t be too bad. Our device needs to be about 0.3 m large. On the other hand, if we are trying to measure exposure from 10 MeV photons, we’re going to need a pretty large room to house our device. Don’t even think about moving this thing around.
The range of the secondary electrons is one issue; we’ve got individual electrons being produced and they are producing ionizations downstream. But, we’ve also got more photons coming downstream. How do we know whether a particular ionization measured at a point is due to a primary photon or due to a secondary electron that was the result of an interaction involving a primary photon somewhere upstream? An electron that’s produced is an electron that’s produced. We can’t say that secondary electrons produced by the secondary electrons are green, the ones produced by the primary photons are red. That would be wonderful but it just isn’t so.

Because we can’t tell the electrons apart, we don’t know where they are coming from, so we have to introduce a concept known as electronic equilibrium, also called charged particle equilibrium, to help us sort things out.
What does charged particle equilibrium mean?

There are a lot of different definitions of charged particle equilibrium. The definition that I am going to use is that the energy deposited by the charged particles that are produced inside a volume, but deposited outside a volume is equal to energy deposited by the charged particles that are produced outside the volume and deposited inside the volume.

So, I’ve got a box, I’ve got primary ionizations taking place inside the box, and some of the secondary electrons are depositing energy outside the box.

But, I’ve also got some primary ionizations taking place outside the box, and some of the secondary electrons produced by the primary ionization are depositing their energy inside the box.

What I am saying is that if we have charged particle equilibrium, what occurs outside the box is equal to what occurs inside the box. The energy going out of the box is equal to the energy going into the box. Therefore, all we need to do is measure the ionizations that take place inside the box. Ionizations taking place inside the box due to primary electrons produced outside the box are compensated for by ionizations taking place outside the box due to primary electrons produced inside the box.

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 our measurement for exposure. That makes life a little bit easier.
The working definition, of charged particle equilibrium, then, is that the number and energy spectrum of the charged particles that we see in the box is constant. Most of the time when we are in a radiation measurement situation we have charged particle equilibrium. Fortunately, charged particle equilibrium occurs more often than it does not.

We find two major violations of charged particle equilibrium. Violation number one occurs when we are close to a radiation source. We know the intensity of the radiation is inversely proportional to the square of the distance from the source. That’s the well known “inverse square law” that you will be dealing with forever. As we go further away from a source, the intensity of the photons emitted decreases as $1/R^2$. When $R$ is small, small changes in $R$ cause large changes in $1/R^2$. If we are close to a source we may not necessarily have charged particle equilibrium or we may not have charged particle equilibrium over a large enough region to have small mass of air.

The second problem, which is even more of a problem for practical measurements, occurs when we are near the interface of two materials. When we are near such an interface, the production of secondary radiation is going to be different in one material from that in the other. So if we are real close to the interface, the secondary radiation that’s going out of the volume may not necessarily be compensated for by the same number and energy spectrum of charged particles coming into the volume. When we’re near a material interface, we have to worry about CPE, and we may not necessarily have it.

Where is this going to be a problem? If we’re trying to do, for example, radiation dose calculations inside a patient. For example, if we look at a lung/soft tissue interface or a soft tissue/bone interface, our dose determinations may not be as accurate as we would like them to be. We will have to be careful with those places.
So, for the last time, I’ll present the definition of exposure and hope that you now have some feel for the complexities involved in implementing this definition.

**Exposure**

- **Definition** – Exposure is the absolute value of the total charge of ions of one sign produced in a small mass of air, when all electrons liberated by photons in air are completely stopped in air, divided by the mass of air.

  \[ X = \frac{dQ}{dm} \]
Now we need to talk about the limitations of the definition of exposure.

The first limitation of exposure is that it must occur in air. We cannot speak of exposure inside material media other than air.

Second, exposure is only defined for photons, that is, x-rays and gamma rays.

Finally, exposure is not defined for energies greater than 3 MeV. The reason for this limit is the need for charged particle equilibrium. 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.

It just isn't practical to develop a device that’s 3 to 4 meters in dimension to try to measure exposure or try to do an absolute measurement of exposure so that restriction places a practical upper limit on the energies for which exposure can be measured.

So, we've got to keep in mind these three limitations: Exposure is only defined in air, only defined for photons, and only defined for energies less than 3 MeV.

These are severe limitations. We treat patients; we don’t treat air. We treat patients with electrons; we treat patients with protons, in addition to treating patients with photons. We also treat patients with photon energies greater than 3 MeV. Exposure was a relatively important quantity in the early days of radiation medicine when all we had were lower-energy photons. It is still used now in imaging where we use photons with energies typically less than 3 MeV, and measurements are done in air. However, we don’t use exposure in radiation oncology physics.
What’s the unit of exposure? It is a unit of charge divided by a unit of mass. The unit of charge is the Coulomb and the unit of mass is the kilogram, so the unit of exposure is the Coulomb per kilogram. SI defines no special unit for exposure.

Historically speaking, exposure was one of the first quantities that we used to describe the amount of radiation. The old unit of exposure was the Roentgen, named after Wilhelm Roentgen, who discovered x-rays in 1895, and was defined to be $2.58 \times 10^{-4}$ Coulombs per kilogram.

Isn’t that a strange number? Why was the Roentgen defined to be such an off-the-wall quantity? The explanation is rather simple. The Roentgen was originally defined to be one electrostatic unit of charge, an old unit of charge, per cubic centimeter of air at standard temperature and pressure. Converting this quantity to SI units gives us $2.58 \times 10^{-4}$ coulombs per kilogram.

Will Hanson, who taught this course for many years before I did, would always say with regards to exposure and the Roentgen, “You can outlaw the unit, but you can’t outlaw the quantity.”
Another quantity that we use, which has replaced exposure, is kerma. Kerma is an acronym that stands for “kinetic energy released in matter.” When we want to look at ionizations rather than energy deposited we talk about kerma. We will talk about kerma, for example, to describe the strength of a radioactive source used for implant therapy.

Kerma is defined as $dE_k$ divided by $dm$. The quantity $dE_k$ is the sum of the initial kinetic energies of all charged particles liberated by uncharged ionizing particles in material of mass $dm$. 

**Kerma**

- Kinetic Energy Released in Matter

\[ K = \frac{dE_k}{dm} \]

- $dE_k$ – sum of initial kinetic energies of all charged particles liberated by uncharged ionizing particles in material of mass $dm$
What do we mean by the sum of the initial kinetic energies of all charged particles? An x-ray or gamma ray comes in, causes an ionization to take place, and produces an electron. The initial photon energy can go in various places. Some of the energy may be transferred to kinetic energy of the electron that is produced, whereas some energy may be transferred to a scattered photon. That’s something we will be able to calculate later in the course. All we look at in determining kerma is the energy that is transferred to charged particles.
Notice that we are now talking about a local phenomenon. We are not interested in how this electron deposits energy downstream. We are not interested in the ionizing events that follow this initial photon interaction. We do not have to track the electron until it deposits all of its kinetic energy in the absorber. Nor do we need to be concerned with where the electron is going. All we are interested in is how much kinetic energy the electron has as a result of the immediate interaction with the photon.

Since we are talking about a local phenomenon, we don’t need to worry about charged particle equilibrium. We don’t have to worry about whether or not we are in air. We could be in any type of material, although there is a specific quantity that we call air kerma. The concept of kerma has much more generality that the concept of exposure.
The unit of kerma is the unit of energy per unit of mass. The unit of energy is the Joule, so the unit of kerma is the Joule per kilogram. Because kerma is important in radiation studies, SI has given kerma its own unit, the Gray, defined to be one Joule per kilogram.
What are the limitations of kerma? There aren’t any. Kerma is defined in all absorbing materials; it’s defined for any kind of uncharged ionizing radiation. I guess that is a limitation. We don’t talk about kerma for charged radiation, only uncharged x-rays, gamma rays and neutrons. Kerma is defined at all energies and you can measure kerma any way you want to measure it. As long as you can measure the kinetic energy of the electrons that are giving off then you can measure kerma.
Air kerma actually turns out to be a very important quantity. Air kerma is the kerma in a mass of air when radiation interacts with air. This is what we use to measure, for example, the strength of a radiation source that we use for implant therapy. How do you measure air kerma?

The easiest way is to measure exposure. Multiply the exposure, which is the charge, the number of electrons, per unit mass of air, by the energy transferred to the medium per ionization, and make the units make sense using conversion factors.

It is important, however, to correct for re-radiation, when the secondary electrons can cause production of tertiary photons. We’ll deal with that at a later time, and in many cases re-radiation can be ignored. When we talk about electron interactions, we will address the issue of re-radiation.
Let us calculate the air kerma that corresponds to 1 Roentgen exposure.

1 Roentgen is \(2.58 \times 10^{-4}\) Coulombs per kilogram. First we must determine how many ion pairs are produced. We do that by multiplying by a factor of \(1.6 \times 10^{19}\), which is the number of ion pairs per Coulomb.

We do the multiplication, keeping track of units very carefully, and we find that 1 Roentgen is \(4.128 \times 10^{15}\) ion pairs per kilogram.
Example of Measurement

- Multiply by energy transferred to medium per ionization – 33.7 eV/IP

\[ 1\text{R} = 4.128 \times 10^{15} \frac{\text{IP}}{\text{kg}} \times 33.7 \frac{\text{eV}}{\text{IP}} \]

\[ = 139.1 \times 10^{15} \frac{\text{eV}}{\text{kg}} \]

Next we determine the amount of energy that corresponds to that number of ionizations. It turns out that the average energy deposited in air per ionization is 33.7 electron volts. That’s one of the numbers you’re going to wind up writing on your shirtcuffs, you will be using it that often. Multiply 4.128 × 10^{15} ion pairs per kilogram by 33.7 electron volts per ion pair, and we get that 1 Roentgen corresponds to an energy transfer of 139.1 × 10^{15} electron volts per kilogram. That is the air kerma corresponding to 1 Roentgen, the energy transferred to charge particles per unit mass of air.
Example of Measurement

- Divide by $1.6 \times 10^{19}$ eV/J

\[
1 \text{R} = 139.1 \times 10^{15} \frac{\text{eV}}{\text{kg}} \times \frac{1}{1.6 \times 10^{19}} \frac{\text{J}}{\text{eV}} \\
= 86.9 \times 10^{-4} \frac{\text{J}}{\text{kg}} \\
= 0.869 \text{ cGy}
\]

We would like, however, to express this energy in Joules per kilogram, or Gray, so we need to divide it by a factor of $1.6 \times 10^{19}$ electron volts per Joule. Doing the division, we find that 1 Roentgen corresponds to an energy transfer of $86.9 \times 10^{-4}$ Joules per kilogram, or $86.9 \times 10^{-4}$ Gray.
Example of Measurement

- Air kerma corresponding to 1 R is 0.869 cGy.

We also like to use the unit of centigray, which is 1/100 of a Gray, so 1 Roentgen is equal to 0.869 centigray.
What do we do about charged particles? We have a quantity called cema, which is the kerma equivalent for electrons. Cema is an acronym that stands for charged particle energy imparted to matter. Kerma is energy transferred from uncharged particles, and cema is energy transferred from charged particles. Kerma is used for interactions of uncharged, whereas cema is used for charged particles.

Cema is defined to be $\frac{dE_c}{dm}$, where $dE_c$ is the energy lost by the charged particles in electronic collisions. This energy lost includes energy expended against binding energies and any kinetic energy of the liberated electrons (secondary electrons).
It turns out that cema is not used as much as kerma. Kerma is a quantity that we are going to be using a lot in this course. We are not going to be using cema very much.

Similar to kerma, the units for cema are units of energy per unit mass, joules per kilogram, or Gray.
In some ways cema is similar to kerma because we only count the energy that we lose at the time of the collision. We don’t care what happens to the secondary electron down the road. It goes out of the box; it’s lost, so forget it. Just like kerma we are only looking at where the collision occurs.
There are some differences from kerma, however. Cema accounts for the binding energy of electrons, whereas kerma does not. Most of the photon interactions are high energy interactions with outer shell electrons. So the amount of the energy of the incident photon that goes into overcoming the binding energy of an outer shell electron is negligible, typically a fraction of an electron volt compared to incident photon energy of around 1 MeV.

The electron interactions are low-energy interactions so the binding energy of the electrons is significant. Cema accounts for binding energy of the electrons, whereas kerma does not.
In summary, then, kerma is the energy imparted to the medium by the uncharged particles. Cema is the energy that is lost by the charged particles.
Now we get to a quantity that is even more important in radiation medicine, and that’s absorbed dose. We talk about dosimetry, which is the measurement of dose. Absorbed dose is really the key quantity when we are looking at the clinical effects of radiation.

Absorbed dose is defined to be \( \frac{d\varepsilon}{dm} \), where in this case \( d\varepsilon \) is the mean energy imparted by the ionizing radiation to the absorbing material of mass \( dm \). The energy here is the energy that is actually transferred from the radiation, whatever the radiation is, to the absorbing material. It doesn’t matter here whether it’s primary radiation or secondary radiation. Thus there is a big difference between dose and kerma. Kerma deals only with primary interactions, whereas dose deals with all the interactions that take place.
The unit of dose is, again, the unit of energy divided by the unit of mass. That is, the Joule per kilogram, or the special SI unit, the Gray, equal to 1 Joule per kilogram.

Units of Dose

- Units of energy per unit mass
  - J kg⁻¹
  - Special unit – Gray
    - 1 Gy – 1 J kg⁻¹
Previously we spoke about limitations of the definition of exposure. What are the limitations of the definition of dose? There are none.

Dose is defined in all materials; it is defined for any kind of ionizing radiation, and is defined at all energies. So whether we’re using x-rays, gamma rays, electrons, protons, negative pions or carbon nuclei, whatever it is, in water, in patients, in air, and whatever energy we want, we can always talk about dose.

Measuring dose is another issue because of the need to account for secondary radiation. We will worry about that later on in this course. Measuring dose can be a little tricky, but at least conceptually we have a definition for dose that is a fairly rigorous definition.
Not all ionizing radiations are created equal. Different kinds of ionizing radiations have different effects on tissue. So, if we want a measure of the effectiveness of a dose of radiation, we need to introduce something called dose equivalent. For example, neutrons, or alpha particles interacting with cells cause much more severe damage per unit of dose than do x-rays or electrons.

For radiation protection purposes, we use a quantity called the dose equivalent, defined to be the physical dose times a quality factor that weights the dose for biological effectiveness times any other weighting factors that might occur, and normally we say there aren’t any other weighting factors.

When you are doing radiation protection calculations, you need to worry about the quality factor. Quality factors are empirical quantities. The quality factor for photons is 1; quality factor for electrons is 1. Quality factor for neutrons depends on the neutron energy. You’ve got to look those values up.
Units of Dose Equivalent

- Units of energy per unit mass – weighted
  - J kg\(^{-1}\)
  - Special unit – Sievert
    - 1 Sv – 1 J kg\(^{-1}\)

The unit of dose equivalent is energy per unit mass, but now we are going to weight it by a weighting factor. Consequently we have a special SI unit for dose equivalent, called the Sievert. The Sievert, like the Gray, is defined to be 1 Joule per kilogram, but it is weighted by the dose equivalent for the particular radiation. Expressing a quantity in Sievert rather than Gray identifies it as a dose equivalent rather than a dose.
Analogous to the quality factor for radiation protection, there is a quantity called relative biological effectiveness or RBE. We use RBE in radiobiology and radiation oncology. Similar to the quality factor, this is a quantity that accounts for differences in biological effect among radiations. So we determine the RBE dose to be equal to the dose times this RBE factor. The RBE, too, is an empirical quantity and it is specific to the radiation spectrum, the organ of interest and the end point of interest. What are you going to use as the end point? Either cell death or tumor control or whatever. The difference between RBE dose and dose equivalent is the application.

We use dose equivalent and quality factor when we talk about radiation protection. We use RBE dose and RBE when we talk about radiobiology or radiation oncology.
Here’s a very interesting application of RBE. Protons have an RBE that we believe is slightly greater than that for photons. Photons have an RBE of 1; we believe the RBE for protons to be about 1.1 or 1.2. But, we also suspect that the RBE for protons increases as the protons lose energy. At lower energies more interactions take place so there is higher level of interaction density. But, we’re not sure exactly what it is. So we really can’t predict what the biological effect of a proton beam is going to be when the protons are almost at the end of their range.

As a consequence we have sort of a rule of thumb when we are doing proton treatment planning and it says do not aim a beam directly at a sensitive organ unless we are confident that the critical structure lies beyond the range of the protons.

One of the nice aspects of protons is that they stop in tissue and do not deliver dose beyond their range. However, combining the uncertainty in RBE with the uncertainty in range gives us concern when we aim a proton beam directly at a critical structure, so, at least for now, we don’t, unless we are sure that the organ that we want to spare lies beyond the range of the protons.
Activity

- Amount of radioactive element in a particular energy state at a given time that will decay to another state in a given time interval

$$A = \frac{dN}{dt}$$

- \(dN\) – expectation value of the number of spontaneous nuclear transitions from a given excited state of an isotope in a time \(dt\)

Let’s move on to radioactivity.

Activity is defined as the amount of radioactive element in a particular energy state at a given time that will decay to another state at a given time interval. So, it’s the change in the number of radioactive nuclei. Activity is \(dN\) divided by \(dt\) where \(dN\) is the expectation value of the number of spontaneous nuclear transitions from a given excited state of an isotope in a time \(dt\). Notice \(dN\) is an expectation value. Why is that so? Radioactive decay is a stochastic process. We don’t know when an individual radioactive nucleus is going to decay. What we do know is that if we have a couple of million or a couple of billion of these nuclei sitting here that within a time interval a certain mean number will decay. That’s what we mean by an expectation value. So the mean value of a stochastic process is a measurable quantity and that’s what we use in determining activity.
Activity

- Activity represents source decay rate only
- Net value of $dN/dt$ may be affected by
  - Production of radioisotope nuclei
  - Alternate disappearance mechanisms, e.g. biological removal
- Activity does not represent emission rate of radiation produced in decay
  - Given radiation may be emitted in only fraction of decays

Keep in mind that the activity represents the decay rate of the source only. The net value of the change in number with respect to time, $dN/dt$, may be affected by other factors as well. Some of these factors may include, for example, the production of a radioactive nucleus, or alternative disappearance mechanisms, such as biological removal.

Nor does the activity represent the rate of emission of radiation produced in radioactive decay. A given type of radiation may be emitted in only a fraction of radioactive decay events. In such a case, the rate of emission of the specific radiation will be less than the rate of source decay.
The units of activity are those of a number per unit time, so an example of a unit of activity would be reciprocal seconds. The special unit of activity is the Becquerel. 1 Becquerel is 1 disintegration per second.

There is also an older unit of activity called the Curie. 1 Curie is $3.7 \times 10^{10}$ disintegrations per second.

That’s a strange number. Why did we pick $3.7 \times 10^{10}$ disintegrations per second to be equal to 1 Curie?

Because 1 Curie was originally determined to be the activity of 1 gram of radium and measured to be $3.7 \times 10^{10}$ disintegrations per second. Later it was determined that the activity of 1 gram of radium was a bit different from $3.7 \times 10^{10}$ disintegrations per second, but the definition of the Curie stood.

Many of the old timers in the radiation medicine field are still more comfortable with using the Curie rather than the Becquerel, so you will probably need to be able to work with both units. If you’re going to publish a paper, though, you need to express activity in SI units, that is, in Becquerel.
Specific Activity

- Activity per unit mass of radioisotope
- For pure (“carrier-free”) sample

\[
\text{specific activity} = \frac{\lambda N}{NM/A} = \frac{\lambda A}{M}
\]

- \( M = \text{molecular weight} \)
- \( A = \text{Avogadro’s number} \)

A related quantity is the specific activity, defined to be the activity per unit mass of a radioisotope. The activity is equal to the transformation constant \( \lambda \) times the number of nuclei present, whereas the mass is the number present times the molecular weight divided by Avogadro’s number. The number of nuclei cancels out in the numerator and denominator, so the specific activity is equal to the transformation constant times Avogadro’s number divided by the molecular weight.
We have completed our discussion of dosimetric quantities, that is, measurements of macroscopic quantities. We now turn our attention to radiometric quantities, measurements of microscopic quantities.

We are going to look at radiation beams, whether they be photon beams, proton beams, or electron beams, as beams of particles. We will look at the particles and their energies.

Incidentally, we will often look upon a photon beam as a beam of particles with zero mass, just carrying energy.

So, let’s examine some quantities that can be used to describe these beams.

The first quantity is the particle number. Well that makes a lot of sense to begin with the number of particles. \( N \) is the number of particles emitted, transferred, received, etc. How do you know how many particles there are? You count them. Or you can hire a physics undergraduate to count them for you. Have the student sit by the beam with a counter and count the number of particles.

Sounds impossible? Well, as an undergraduate, you thought you could do anything, even count particles.

What is the unit of number? Number is dimensionless. It’s just … a number.

Each of these particles carries some energy. So if we multiply the number of particles times the energy of the particle we have the radiant energy of the beam. When we talk about energy we talk strictly about kinetic energy and we don’t include rest energy.

Units of radiant energy are simply units of energy. The SI unit is the Joule.
The particle flux is the change in number of particles per unit time. That is, how many particles are coming past you per second? That’s the particle flux.

To determine the particle flux you count the number of particles that go by you in any time interval. If our undergraduate physics student counts 180 particles flying by in a 1-minute interval, the particle flux is 3 particles per second.

Here is an example of particle flux. Take a break from the lecture and watch this video. There’s a link to it on the website.

http://www.youtube.com/watch?v=4wp3m1vg06Q

I’m sure all of you measured the particle flux of chocolates, but if you didn’t let’s suppose that 1000 chocolates passed Lucille Ball by during a time period of 500 sec. Then the particle flux would be 1000 divided by 500 or 2 particles per second.
Now each of these particles carries some energy, so we can determine the amount of energy passing by in any time interval. This quantity is the energy flux, and its units are units of energy divided by units of time.

In our previous example, if each of the particles our student measured had 10 Joules of energy, then the energy flux would be 10 Joules per particle multiplied by 3 particles per second, or 30 Joules per second.

I won’t ask you to calculate the energy flux for the chocolates in the Lucille Ball television sketch.

Counting particles and counting energy is fairly straightforward. One of the things that we are going to do later on in this course is try to relate these quantities to dose or to kerma. It’s going to get a little more complicated as we go along.
Particle fluence is our next quantity. This is really a measure of the particle intensity, the intensity of the particle beam. So we are looking at the number of particles incident on a sphere of cross-sectional area. This is represented as $\frac{dN}{da}$. So particle fluence is number per unit area.

For example, if we have $10^6$ particles incident on a sphere of radius 1 cm, what is the particle fluence?

The cross-sectional area subtended by the sphere is $\pi$ times the square of the radius of the sphere, or $\pi$ cm$^2$, so the particle fluence is $10^6$ divided by $\pi$ particles per square cm.

Let’s now compare this beam with a beam of $10^6$ particles incident on a sphere of radius 10 cm.

The particle fluence is now $10^6$ particles divided by $100 \pi$ cm$^2$, or $10^4$ divided by $\pi$ particles per square cm. The particle fluence is much lower now because the beam is spread over a larger area.
Comment on Fluence

- We need to have radiation interact in some volume or pass through some cross-sectional area. We define a cross-sectional area so that the beam is always perpendicular to a great circle of area $da$.
The next quantity we will look at is energy fluence. Energy fluence is the energy that’s incident on the sphere. To determine the energy fluence we multiply the particle fluence times the energy per particle. If we have a polyenergetic beam, that is a beam consisting of particles of many different energies, we will have to weight each energy component by the number of particles at each energy.

\[ \Psi = \frac{dR}{da} \]

- \( dR \) = energy incident on sphere of cross-sectional area \( da \)
- Unit: energy per unit area \([J \, m^{-2}]\)
Radiometric Quantities

- **(Particle) Fluence Rate**

  \[ \Phi = \frac{d\Phi}{dt} \]

  - Unit: number per unit area per unit time
    
    \[ [m^{-2} s^{-1}] \]

Fluence rate is the fluence per unit time, or the number per unit area per unit time. So again, if we have more particles going through this area per unit time, the beam is going to be more intense than if we have fewer particles per unit time. Although if the beam is kept on for a longer period of time with a lower fluence rate, then the fluence could be the same and ultimately the dose is going to be the same. But, here we are talking about fluence rate, which ultimately will convert to dose rate.
Finally, we have energy fluence rate which is the energy per unit area per unit time. So we have particle number, particle energy, number per unit time, energy per unit time, number per unit area, energy per unit area, number per unit area per unit time, and energy per unit area per unit time.

There’s kind of a neat symmetry in all of this.
Some engineering applications define quantities differently from how they are defined in radiation physics. Energy fluence has been called flux, particularly in engineering. Fluence rate has been called particle flux density. ICRU 60 discourages this use.

Note

- Energy fluence has been called flux, particularly in engineering. Fluence rate has been called particle flux density. ICRU 60 discourages this use.

Some engineering applications define quantities differently from how they are defined in radiation physics. Energy fluence has been called flux and fluence rate has been called particle flux density. The ICRU says don’t use those terms. Use energy fluence to mean energy incident per unit area. Fluence rate is number of unit particles per unit time. The definitions that I am giving you are the ICRU Report 60 definitions in order to provide accuracy in communication, which is what ICRU really strives to do. Please use the ICRU definitions as much as you can.
In addition to particle fluence, we also need to consider a quantity known as planar fluence. The planar fluence is defined as the number of particles crossing a fixed plane per unit area of the plane.

How does planar fluence differ from particle fluence?
Planar Fluence

- The planar cross-section retains the same planar fluence, which suggests that the fluence of the total beam has not increased.
- However, the cross-section of the sphere reflects the increase in the fluence through a given $dm$, which results in an increase in the dose rate.

Consider a case in which we have a beam that’s incident on both a sphere of some diameter and a circle of the same diameter. In the upper part of the figure, the number of photons crossing the sphere is the same as the number of photons crossing the circle. In the lower part of the figure, the beam has been scattered. As a result a greater number of photons crosses the sphere, whereas the same number of photons crosses the circle. So, even though the planar fluence remains the same, the total fluence has increased; consequently the dose delivered to the sphere, which is related to the total fluence, will be greater.
We see this effect sometimes when we have a broad beam of radiation passing through a thin layer of attenuator. Because the photons are deflected, the planar fluence behind the attenuating layer may be greater than the planar fluence incident on the layer.
Because this is a course in radiation interactions, it is appropriate that we conclude this session by introducing some quantities that describe interactions.

First, let us define what we mean by an interaction. An interaction is an event that changes the energy or direction of the incident radiation or both. We will be covering many such interactions during this course.

A cross section is defined to be the probability of such an interaction with a target divided by the fluence of the incident radiation. If we multiply the cross section times the fluence we will wind up with the probability of an interaction. We will be talking about both probabilities of interactions as well as cross sections of interactions. They are very closely related.
Because fluence has the units of reciprocal area, the cross section, which is the probability per unit fluence, has the units of area.

High-energy physicists like to use a special unit for cross section called a barn. One barn is equal to \(10^{-24}\) cm\(^2\).
A very important interaction coefficient is the one called a linear attenuation coefficient. Linear attenuation coefficient is a quantity we are going to be talking about a lot when we talk about photons. The linear attenuation coefficient is the fraction of particles that interact in a given path length \( dl \). The unit of linear attenuation coefficient is the unit of inverse length, fraction per unit length \([\text{m}^{-1}]\).
However, the number of interactions that are going to take place will be directly related to the number of particles that are available for interaction. We can generate an intrinsic quantity called the mass attenuation coefficient by dividing the linear attenuation coefficient by the particle density. This quantity is more characteristic of the nature of the material than the linear attenuation coefficient. We will be using both mass attenuation coefficients as well as linear attenuation coefficients. The mass attenuation coefficient is the fraction of particles that interact in a density-weighted path length, $\rho$ times $dl$.

The units of mass attenuation coefficient are the units of length squared divided by mass. In SI units that is m$^2$ per kg.

Note that the cross section multiplied by the density weighted path length has the units of mass, which is the $dm$ in the definition of dose.

We are going to be using these interaction coefficients as the tool to connect quantities such as particle fluence, for example, how much radiation there is, to dose, which is how much energy is being deposited. A little bit later down the line we will show you how that connection is made.
In the world of charged particle interactions, we have a quantity that is analogous to linear attenuation coefficient, called the stopping power. Stopping power is the energy loss per unit path length for charged particles. Its unit is energy per unit path length and we also have a density independent stopping power called the mass stopping power. We will be using mass stopping power probably a lot more than we use stopping power.

The units of mass stopping power are units of energy times units of length squared divided by unit of mass, for example, J m\(^2\) per kg.

If we want to know how electrons deposit energy in a medium, we connect the electron fluence with the stopping power to get the energy deposition.
So, mass attenuation coefficient and mass stopping powers are analogous quantities. Mass attenuation coefficient is used to describe interactions involving photons, whereas mass stopping power is used to describe interactions involving charged particles, such as electrons and protons. Mass attenuation coefficient is the fraction of photons interacting per density-weighted path length. Mass stopping power is the energy loss per density-weighted path length. Mass attenuation coefficient connects photon fluence to dose. Mass stopping power connects charged-particle fluence to dose.