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MICHAEL SHORT: So, before we begin today's bit on dose, dosimetry, and background radiation, I promised you guys a story about how to use 22.01 to get out of Apartheid, South Africa. So, I got told this story when my cousin was about to get married because he needed a diamond and he was going to go buy one and his dad said, don't.

So back in the 70s, when my uncle and his family were living in South Africa, anyone who wasn't Dutch white, so that would be blacks, Jews, including us, anyone else was considered second-class citizens by the Apartheid Government. And you were allowed to leave, because they didn't want you there, but you had to surrender all of your funds to the government in order to leave, which gives me everything you have and then you can leave the country penniless is not a winning proposition.

So, my uncle and his brother devised a pretty brilliant idea to get their funds out of South Africa unnoticed. They were both dentists or radiologists or some sort of medical doctor that requires x-ray reading. So, one of them gave the other one all of his money, then reported bank statements to the Apartheid Government and said, I'm pretty much penniless. My practice went broke. I want to leave the country. And they said, OK, get out of here.

So he went to the US, established a dental or radiological or some other sort of practice, I forget which one, and started requesting his brother, back in South Africa, to send him x-rays to read to help boost his business. Because that was their actual business, it was pretty legit. So then my uncle would send him packets of x-rays to interpret and send back. Except that there would be 10 x-rays on the front and 10 on the bottom, and the middle 80 would be hollowed out.

AUDIENCE: Oh!

MICHAEL SHORT: Now that would have ordinarily have tripped off alarms because any change in density would trigger a change in x-ray contrast. Because these packages were being inspected by x-ray, and if it looked like these x-rays were hollow and you were smuggling something out, they'd be

caught and confiscated. So what sort of materials are valuable that you find in South Africa, that are pretty similar in x-ray contrast to other light media like film?

AUDIENCE: Diamonds.

MICHAEL SHORT: Diamonds. So the remaining brother went and converted all of his life savings into diamonds, which is something that you can do in South Africa because this is where diamonds come from. He then slowly, over a period of months or years, sent packets of hollow x-rays full of diamonds to his brother in the states, knowing full well that the mass attenuation coefficients of soft tissue and carbon are pretty similar and so are their densities. So their total attenuation coefficients are pretty similar, to.

Let's pull those up so we can check it. Carbon graphite. I'm going to add a new tab and bring up soft tissue and we can compare them. Let's see, what's the most similar-- so long as you can see it-- thing to film? What should we call film here? X-ray film?

AUDIENCE: I don't even know what X-ray film [INAUDIBLE]

MICHAEL SHORT: Photographic emulsion. How about that?

AUDIENCE: Kodak.

MICHAEL SHORT: Is there something Kodak? OK. Kodak, standard nuclear. I don't think that sounds right. Let's go with polyethylene and plastic. Carbon, plastic. Carbon, plastic.

AUDIENCE: [LAUGHTER]

MICHAEL SHORT: Carbon, plastic. Basically identical. So this is a way they were able to smuggle wealth out of the country without x-ray contrast tripping off the guards. And once all of the slave savings had been converted into diamonds, he then went to the government and said, I'm penniless. My practice went broke. I want to get out of here. And they said, good riddance.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Yeah. So they were able to restart their life in the states with all of the money that they had had in South Africa. And when my cousin wanted to get married and said, I'm thinking of buying a diamond, my uncle just said oh, don't. He's like, what, don't get married? He said, no, don't buy a diamond. Here, let me take you to the diamond drawer.

AUDIENCE: [LAUGHTER]

MICHAEL SHORT: Yeah. Because there was some leftover. So he said, pick out an extra diamond. And that's the story of my cousin's engagement ring, as well as why part of my family's here in the States.

AUDIENCE: [INAUDIBLE] That's like a very cool diamond story.

MICHAEL SHORT: Yeah, very, very nuclear diamond story. Diamonds aren't forever, as the finish have shown us, but they can get you out of repressive regimes. OK, back to the dose stuff.

So today, and for the rest of the course, we get into biological and chemical effects of radiation. As soon as this pops up. And so in the first slide is everything you need to know about dose and units. Don't worry, it's not up there yet. I know that different units of dose are a common point of confusion. So I wanted to put everything on one slide so you can refer back to it like a cheat sheet.

So, you've probably heard of the roentgen before. You've definitely seen the roentgen as a unit because you've all looked in those pen or pocket dosimeter that you actually had at the nuclear reactor, when you guys took a tour of it and controlled the control rods. The roentgen is not really a unit that we use much anymore for very careful calculations because you have to do some tissue equivalency stuff in order to go from ionizations in air, which is what it actually measures, it's the amount of charge dissipated or built up in air, to some damage to soft tissue.

And the way you actually calculate roentgens from first principles, linking the physics and the biology part, is remember this equation here? Stopping power, which is some energy transfer, divided by the energy required to make an ion. Each one of those will give one electron unit of charge towards [INAUDIBLE] coulombs. And so this is the direct link between the physics and the chemistry/biology in this course.

It's not something that's done that carefully in any of the readings, which is why I'm going to harp on it here in lecture. These two parts of the course are often taught differently. And they're actually totally related and everything's all the same, which is kind of nice. You don't have to just relearn a whole new lingo and field.

Then there is the SI units of dose. The ones that, when you do calculations in the homework and the rest of your life, I recommend that you use whenever possible because they're in units that we're familiar with, in standard units.

The one where you start with all along is the gray. A gray is the simple measure of absorbed energy in joules per kilogram of whatever. And so calculating it is fairly straightforward, too. For example, if you want to know what sort of dose you would get in gray from absorbing gamma rays, you can use this old equation from the first third of the course.

And if you integrate this from, let's say, over the range of whatever object or person you happen to be irradiating, you'll get some fractional difference in intensity. That, multiplied by the original intensity of gammas, which could be given in maybe gamma rays per centimeter squared per second, maybe times time to get total number of gammas per centimeter squared. All that multiplied by the energy of each gamma, divided by the mass of whatever is doing the absorbing, equals your dose in gray.

So you can use all the old stuff from the previous parts of the course directly to calculate dose in gray. And this is the starting point for any calculation. If you don't know what tissue was exposed, what type of radiation provides what biological effectiveness, it doesn't matter. You just start here.

Then the other unit you may have seen is a unit, not of energy absorption, but of increased risk for something going wrong in the biological sense. It's called the sievert. For simple things like whole body dose from gamma rays, sieverts equals gray, because sievert is multiplied by this quality factor, or this effectiveness factor.

That Q factor is actually a couple of factors. There's a Q for the type of tissue and there's a Q for the type of radiation. And the total quality factor for whatever you're trying to calculate is just the multiplication of these two.

And so it's fairly easy, if you're ever dealing with whole body gamma dose, gray equals sieverts. If you're dealing with pretty much anything different, gray does not equal sieverts. There'll be just some factor to add in, which can be looked up from a lookup table but, as I've told you before, I don't like that explanation, look it up on a table. We're going to explore why the lookup tables are constructed the way they are.

And then there's the CGS units, the ones that are based in centimeter-gram-second, instead of kilogram-meter-second. The rad is a simple measure. It's, let's say, 100 rad is just 1 gray. Where the rad actually comes from is, it's defined as 100 ergs absorbed energy per gram, where an erg is 10 to the minus 7 joules and a gram is 10 to the minus 3 kilograms. And so,

you can do the mental math there to make sure these all work out. And then a REM, a roentgen equivalent man, is just a hundredth of a sievert.

So there's historical basis for this. Back in the day, more folks used CGS units. There's been a push to SI units, which I happen to like because everything works out and you don't have to remember things like 10 to the minus 7 joules or whatever like that. So I'd say, when in doubt, for equal comparisons always use the SI units and always start with the gray because that's something where you can take a physical calculation of energy per kilogram and go into some increased cancer risk by using the dose quality factors.

So let's take a look at how these appear. First of all, gammas, x-rays, electrons, positrons of any LET. LET, as I mentioned before, is linear energy transfer. And to put this mathematically, you've actually seen this before, which would be some change in energy over some change in distance. It's the stopping power. It's not like the stopping power, it's the stopping power.

So with the formulas you got in the second half of this class, you can calculate linear energy transfer. Now, why are these things given in, let's say, discrete tables, or now what's currently recommended is these functions? Does anyone have any idea? How many of your Core Seven friends know the formula for stopping power, or could parse it even, or understand it? You don't have to, not everybody has to.

So, for the rest of us, there are simpler empirical relations or relations that get the numbers right that aren't necessarily based on physics. So a simple lookup table, for those who don't have time to take 22.01 or something beyond, is the easiest thing to do. And in most cases it works. It's not exact, but it's probably close enough. Given uncertainties in the amount of radiation that one could absorb or the weight of a certain organ or the energy of some x-ray tube, I think these empirical things are pretty much good enough.

And what this tells you is that there is some effectiveness of different types of radiation and different energies of radiation at imparting energy to the parts of cells and organs that cause damage. To say that in a little smaller sentence, different energies of radiation can have different effects biologically, and these tissue factors account for that.

It's also a table. I want you to keep in mind because you're going to have to do a calculation about it. The principle elements in soft tissue in unit density, otherwise known as number density, which you've seen before. If you want to calculate the dose using a stopping power formula to a human, you have to know what this human is made of and this is a pretty good

assumption.

And this is something you'll be doing on homework number 8, is finding the dose that you're giving to each other in a particular situation. If anyone's seen the particular situation, check OCW for last year's course and you'll see what that situation will be. Has everyone gotten your whole body counts at the EHS Office? If anyone hasn't, do them in the next week because you'll need that data for the homework. You'll also need this table. Because if you think about it, if you want to say, well, what's the damage by electrons to soft tissue? And you want to calculate this from scratch. You have these four number densities, so we'll keep those in account.

And let's put up the formula for ionization stopping power again. Comes out with 4 pi, k not squared, little z squared, big Z, number density, e to the fourth, over MeV squared, log. Let's see, what goes on top again? Oh, yeah, 2MeV squared, over the mean ionization energy. The nonrelativistic form.

Which of these terms vary depending on the atom that an electron or whatever would strike? Let's circle them, there's a couple.

AUDIENCE: Big Z.

MICHAEL SHORT: Big Z, what the electron's hitting. N, the number density.

AUDIENCE: Ionization potential.

MICHAEL SHORT: Yes, the mean ionization potential. So these three terms are the only things that change when you're doing a stopping power to dose calculation. So if you want to get the total dose in gray to a human, you have to sum over these four different isotopes. Actually, wait. Let me put all the other junk in front to make it quicker.

So the 4 pi k0 squared little z squared e to the fourth over MeV squared is just a constant, times the sum over all your isotopes of zi, the number density of isotope i, which inside there has the element fraction of that, times the log of 2 MeV squared over the mean ionization potential of isotope i.

And in this case, notice there's no isotopes given. They're just given as elements. Why do we do that? Why don't we care for humans? How many isotopes of hydrogen tend to exist in you? One, pretty much one, to about five significant digits.

You all have a little deuterium. Something like 1 in every 20,000 atoms of hydrogen is deuterium. But it's not a lot. I think it's even less than that.

Carbon is just carbon-12, except for the tiny amount of carbon-14 you use for radio carbon dating. Oxygen, it's oxygen-- think what, 16? Nitrogen is nitrogen-14. So as long as you know what isotopes to use, you'll know what z's, what i bars. And the number density is given here.

So this right here is how you calculate dose in gray to a human over some distance. Then all you'd have to do is integrate that over your-- let's say thickness of the human, whatever that happens to be. And you get the total amount of dose imparted to them.

So a lot of questions came up in last year's class. How do we actually do these calculations? Well, this is how right here. First, separate out everything that's a constant. Because you only have to calculate it once, as I hope problem set 7 and 6 taught you guys, is separate out whatever you can first, and don't repeat yourself.

Then sum over all the things that are unique to each isotope. And inside this number density is the fraction of that isotope in every human. So it's all built in. So these calculations aren't that bad. Since you know how to do stopping power, you can take out 2/3 of the terms. I don't know why I still have this. It's not terrible.

Can anyone not see through how to do this? Or yeah, have a question?

AUDIENCE: Where do we find the ionization term?

MICHAEL SHORT: The mean ionization potential can be usually approximated as about 10 electron volts times z. Except for the very light isotopes like hydrogen, it's somewhere between 10 and 19 eV. I would say one, you can just look them up. Or two, you can use this empirical relation to get a good approximation. And empiricism definitely enters into the biological world, because uncertainties abound. And it's not always worth being ultra crazy exact, although it can't hurt. Any other questions on how to actually carry out a dose calculation using stopping power? Hopefully it's pretty straightforward. Guess we'll find out on the homework.

The other quality factors to mention-- there are some different ideas about these quality factors. Notice the scales are fairly coarse. So again, there's a lot of uncertainty or slop in these values. But notice that for, let's say, X-rays, gammas, betas of all energies and charges, the quality factor is 1. Why do you think that is?

Let's go for the case of X-rays or gammas. What tends to be the attenuation coefficient of any photon in soft tissue of considerable energy? Pretty low. And the amount of energy that can be transferred by those photons is variable, anywhere from pretty low to pretty high. And so the resulting electron cascade isn't going to be that damaging. And it might not even be that localized.

So let's say if you really want to know how much damage is it going to go do to the DNA of a cell, where it could mutate and cause cancer, not that much. Most of the gammas pass through you, and the ones that do get absorbed can have rather long energy deposition tracks.

Neutrons, however, interact nuclear stopping power. Or let's say they just interact with the nuclei of you, or whatever they're irradiating. And so when you knock out a nucleus, it can then slam into other atoms, causing a huge and dense cascade of ionization. If that cascade happens to be near the nucleus of a cell, you better believe it's going to cause a lot of damage. And that's why these more energetic neutrons have a much higher quality factor, because they're much better at causing damage until you reach some sort of threshold. Why do you think it goes down at higher energies? Yeah.

AUDIENCE: Well, because there's less of a probability that it would actually interact with [INAUDIBLE].

MICHAEL SHORT: Absolutely. Right around 2 MeV or 1 MeV, these cross sections tend to go down. If we look at the cross-section for neutrons in anything-- let's look at hydrogen. [INAUDIBLE] still got to do the screen cloning thing again. Bear with me.

Let's look at any old cross section for, let's say, neutron scattering in, I don't know, oxygen. We've looked at hydrogen enough already. Cool. You can see that. Oxygen-16. We have incident neutrons, elastic scattering, the bouncing off. Let's look at the form of this cross-section.

Right around 1 MeV, things start to dip. And so yeah, the probability of any sort of interaction is going to go down. In addition, the atom that struck has a much higher energy, and therefore a higher range. So chances are, even if the neutron strikes an atom near the nucleus, it will have a higher range and can travel farther before that secondary cascade ends up depositing most of its damage at a lower energy.

So if you remember for the stopping power for ionization or nuclear stopping power, they both look the same. So I'm not going to label which one. It's fairly low at high energies, peaks at a rather low energy, and then comes down. So it's at the end of the range of whatever particle, whether it be the neutron or the atoms that it struck, that it does the most damage.

So you can kind of think like all forms of radiation-- except for photons-- as armor-piercing bullets. They don't do damage right where they enter. They do damage right where they stop and explode. In the case of armor-piercing bullets, it's a literal explosion. In the case of neutrons, electrons, protons, heavy ions, it's at the end of their range they have the most stopping power. And that's where the dense cascade's going to be.

So chances are, again, if a neutron happens to interact with the nucleus of a cell-- that's the simplest cell I can draw-- if a neutron comes in and strikes another atom, it may move far away before its armor-piercing explosion.

Let's see the other ones. For protons, depending on which book you go to, you get a different effectiveness. It's higher than that of gammas and X-rays and electrons, because you get a big cascade at the end. And alpha particles, really, really, damaging. And energy is like even a few MeV, they have a very short range. They tend to deposit a ton of energy. And that's why they have a huge effectiveness.

This is also why alphas are the-- that's the one cookie you don't want to eat, if you guys remember this, the four cookies problem. Never eat the alpha. It's not going to get in through your skin, but if it gets into your body and incorporated into the material directly surrounding your nucleus, that's how things go really bad. That's why smoking's so bad.

Did anyone end up getting into a smoke shop to do that measurement? I did check the one by my house, and they just put up a sign that said no one under 21. So you guys are right about that. Weird law. Whatever.

Now let's look at the tissue weighting factors. We've talked about the factors for different types of radiation. It also matters what tissue it enters. So for things like skin or bone surface, you think of these tissues as not that critical. If you get a scratch and you lose some skin, it's not that bad for the body. Same thing if a little bone chip flakes off. You might get shin splints, but it's not so bad. Not for the same reason.

These tissues aren't dividing very fast. The surface of your bone, the hard part, is basically

standing still. It's just calcified minerals with some osteocytes trapped in there. Not much happens. What's happening in these tissues constantly-- gonads, bone marrow, colon, lung, stomach?

AUDIENCE: [INAUDIBLE] cells.

MICHAEL SHORT: Yep. This is where stem cells and fat-- rapidly dividing cells-- tend to be found. So there's been some theories and some papers saying whatever cancer you're going to get, you probably already got it in the first few years of life, when you're just a big rolling sack of stem cells. This is part of why occupational hazards for infants and pregnant women are much, much lower, because they are giant sacks of stationary stem cells. And you don't want to irradiate something that's dividing really, really fast.

And so the older you are, the more OK it is to get more and more radiation dose, because a lot of these effects take a long time to manifest. Because they all start with a single cell. And it takes a long time for that single cell to exponentially grow and divide over a longtime scale into a mass that be considered a tumor. So it's a little worrying to think, OK, probably most of the cancer I'll get I got when I was five. But then again, it means, don't worry about it. What can you do? There's what?

AUDIENCE: It's free.

MICHAEL SHORT: Yeah, it's free. It's done. Not all of it. You can still limit your dose, because well, one, any acute radiation exposure will have short term health effects. And two, your cells are still dividing. As we had a seminar speaker say, a biological organism at static equilibrium is not very interesting. It's dead. It's not dividing anymore. So your cells are still dividing. It still means you should minimize radiation exposure. But a lot of what happened already happened.

And if you can see here, the pattern is the more rapidly the cells are dividing, the more it has this tissue quality factor. Because the more quickly these effects would manifest themselves, and the more quickly the cells may divide with that mutation before these cellular repair mechanisms fix that mutation before a division. We'll get into a lot of that when we talk about biological effects, probably next week.

So now, how do you do a calculation of dose in Sieverts? First you can take the dose in gray, like we have over here, multiply by these radiation weighting factors, and you get a total amount of dose to that tissue, where that tissue may be a certain organ, a part of your muscle,

whole body if it was a broad blast of radiation from a bomb far away or something like that.

And you get these single doses to tissue, where each of these radiation equivalent factors can be equated to this average quality factor, where you integrate the quality factor as a function of length times the dose at that length. This is where the stopping power formula comes in, is you'll have a stopping power as the energy decreases, as the particle moves through the material. And its stopping power will change. So then you have to integrate that stopping power times some constants and stuff over that distance times the quality at that distance to get the simple weighting factor.

You then take these weighting factors, plug them into your dose to tissue, and sum up all the exposures to different tissues. So each tissue will have its own dose in Sieverts. It'll have its own tissue weighting factor. You sum up all the tissues exposed, and you get the total effective dose to the whole body. This means that some organs incur dose faster than others for the same radiation exposure.

So the whole body dose should sum up to 1. And I believe-- I remember doing this calculation, but it may be worth your while to just try it. These numbers should sum up to 1, because all of these individual organs plus the remainder of your body should constitute the whole body. And so this is, in a nutshell, how you do these dose calculations.

So let's take an example from the actual reading. Let's say a worker gets 14 milligray of uniform whole body dose-- this would just be from background radiation, cosmic rays, food, whatever-- plus a targeted dose of 8 milligray to the lung from alphas, plus 180 millgray from betas in the thyroid. Anyone know why they chose alphas in the lung and betas in the thyroid? What's the most likely sources of those?

AUDIENCE: Iodine and nicotine.

MICHAEL SHORT: Iodine and let's say smoking. Yeah. Yeah, exactly. As we saw, a lot of the radon daughter products tend to be alpha emitters, and you tend to inhale those through the lungs. And iodine is a beta decay with about an eight day half life, and that gets preferentially absorbed in the thyroid. So this is a pretty realistic scenario.

And we'd say, how much effective dose did this person get? To do this calculation, you first-- well, let's go through those steps. You look at the dose to each tissue times the effectiveness for that type of radiation. So the dose got 8 milligray of alphas.

So you multiply by 20 for that quality factor. And the lung gets 160 millisieverts. You do the multiplication for the thyroid, the multiplication for the whole body. And then you do a summation of these single tissue doses here, here, and here, times the tissue weighting factors, which you then look up from that table or calculate from the cell division rate here, here, and here. And you get a total dose of 42 millisieverts.

So I want to point something out to you guys. His thyroid got 180 millisieverts. He got 42 millisieverts. Interesting. Sounds a little counterintuitive. But in this case, these doses for each tissue are calculated for that tissue. So if you have a probability of organ failure or mutation, you can now then know how much increased risk he may have of thyroid cancer specifically, or sum it up to an equivalent whole body risk.

And it just so happens you're only allowed about 50 millisieverts of exposure. So he'd only be allowed another eight. But we'll get into limits and what this ICRU whatever whatever means. I'll actually show you the document. It's also posted online. This International Committee on Radiation U. I forget what the U is. But this is the whole document that has the basis for these recommendations, the numbers, and the reasons. And that's all online for you guys to check through. So anyone have any questions on a example dose calculation? Cool.

Let's look at some of the ways that you'd actually measure dose. One of them we looked at the first day of class, the old Chadwick experiment. Send radiation through a fixed amount of area so you know the flux. If you know the total amount of gammas is produced by this X-ray tube, you know the area, then you know the solid angle. You know the flux.

Then you have just a free air chamber with a high voltage to suck up those ions before they recombine. And that's how you can calculate things like dose in roentgens. You also have pocket versions of these things, sealed tubes with two electrically insulated electrodes. And that cannot discharge unless ions in the gas allow them to.

And this is the basis behind these civil defense air wall chambers, one of which I happen to have right here. So I want to pass this around and let you guys take a look at it. Like the ones you saw in the reactor, you can look through and see a little needle that will tell you the-- not dose, but the amount of ionization this thing has received in roentgens, which can then be equated with some calculations to dose in soft tissue.

And also there's the base for the civil defense dosimeter. I want to tell you guys how it works.

It's a battery. That's it. If you open that thing up, there's a couple of big T cells in there and a voltage divider. And you just turn the knob-- which sounds complicated, all you're doing is turning a potentiometer-- to decide at what voltage this wire end inside of the tube will be. And that voltage deflects the wire a little bit by just coulombic attraction or repulsion, bends it, and gives you the dose.

And it stays there. Nothing can get in or out of that sealed chamber, except penetrating radiation. When gammas or neutrons get through, they can cause ionizations in the gas. Those gas ions can move to these electrodes, partially neutralizing them, making the needle tilt a little farther and a little farther.

So the interesting thing is when that needle read 0 roentgens, it's fully charged. And as the detector discharges from radiation interactions, the needle moves higher on the roentgens scale. Because you can paint whatever scale you want on it, as long as the physics works out. So it's kind of neat to think that the charge is highest when the dose is lowest. Because all the charge is doing is deflecting that little needle.

Quite simple design, and quite robust. These things were designed by civil defense in case the Cold War became a hot war, and they'd have to last for a very long time. So having had this one for about 10 years, I can tell you I've not yet filled the meter, which is probably a good thing. And I took that on flights across the world and hiking in Nepal, where the background dose was considerably higher. And the needle moved like half a roentgen for the entire three weeks up at elevation and plane rides. And I got more dose on the plane ride than I did on the hike. Interesting fun fact.

That's pretty much exactly what you should see. And so Alex tells me these things are starting to get kind of rare on eBay, and that's a shame. Because this is the best possible teaching dosimeter there is. If you understand 8.02 and a little bit of radiation, you know how these work and can predict what the dose is actually going to be.

Now, how do you do things like detect neutrons? If you want to detect neutrons, you want a good moderator. Because well moderated neutrons deposit all their energy in the detector instead of bouncing off, transferring a little energy, and leaving. If you want to know how many and what energy neutrons you have, you can fill a similar chamber that's got a high voltage. It's got a wire on the inside. But instead of air or some other gas in there, you can fill it with things like ethylene or propylene or some sort of very hydrogenous hydrocarbon gas,

something full of hydrogen to act as a good moderator.

That hydrogen ion then becomes a proton, which then damages a lot of other ions, causing an ionization cascade, and leading to some current pulse, just like any other detector. There's going to be some movement of current, which is picked up as damage. You might then ask also, why is that alpha source there? Anyone have any idea? That's your calibration source.

So as the gas in this chamber is attacked by neutrons, you will be blasting some of the hydrogen atoms out of the ethylene or propylene or whatever gas you have. The gas will change in effectiveness over time. The energy of the alpha particles will not. So that is your absolutely fixed energy calibration source. So you know exactly-- if, let's say, 3.72 MeV alphas make a current pulse of a certain height, then you can equate that to a 3.72 MeV neutron that would strike a hydrogen atom. And because the gas degrades over time, you have to recalibrate with that built-in alpha. And any sort of shutter-- like a little piece of foil-- will block the alpha so that you can use it as a neutron detector. Quite clever design, in my opinion. It accounts for the degradation of the gas and the detector.

Anyone seen one of these things before? Then there's the Geiger counter, which is an ionization counter run in avalanche mode. You can use these free air ionization chambers or other counters as an energy proportional counter, where a higher energy particle will impart a bigger ionization cascade. And you can then use that to get energy resolution. Or you crank up the voltage like crazy, so that any count of any energy causes an intense ionization cascade and a huge current pulse. And this is the basis behind cheap Geiger counters, like the ones we build in our department.

Those old Soviet SPM 20 tubes that have actually been survived being stepped on and crushed. As long as the electrodes don't short out, they still work. So there's a few folks in the department that have clearly bent Geiger tubes. One of them looks like they've been chewed, but they still work. Because any sort of anything interacting with a gas will cause an ionization cascade, which is immediately sucked into the electrodes by a high voltage and collected as a current pulse

And that's just a cutaway of what it looks like on the inside. And this is the circuit for a Geiger counter. There is a voltage, a resistor, a capacitor, and a tube. That's all you need.

Everything else in the MIT Geiger counter is there to make lights and sound. It's just for fun. But the actual Geiger counter itself can be made incredibly . Compact the bigger the tube, the

more radiation it will catch, just because of its size but otherwise, as long as you get the voltage high enough to cause this ionization cascade, it works. It's really, really robust.

So I want to skip ahead for some of that stuff, and then talk about how do you measure dose in humans. Who here has seen one of these TLDs, or Thermoluminescent Dosimeters before? Our reactor trainees have. And you've worked on nuclear stuff too, right?

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: You've got one in the vault. Wait, Kristen, what about you, since you've worked--

AUDIENCE: We had one with a little crystal in it.

MICHAEL SHORT: That's exactly what this is.

AUDIENCE: [INAUDIBLE]

MICHAEL SHORT: Yeah. And you can shake it. It rattles, right?

AUDIENCE: Yep. [INAUDIBLE]

MICHAEL SHORT: Exactly. So this is how these work. This stands for a Thermoluminescent Dosimeter. And converting from Latin to English, that means if you heat it, it produces light proportional to the dose that it gets. So these little crystals, aluminum oxide or some sort of assault or whatever have you, something that creates permanent ionized defects, they will relax when you heat them, giving off light. And then you use a light counter to tell how much dose this crystal has received. And by putting different filters in the way for different pieces and looking at the light coming from different parts, you can tell different types of dose. So one works for betas, because betas can get through the little hole in the detector, whereas this may help you figure out gamma rays or neutrons of different energies.

And who here has seen one of these ring badges? Yeah, so again, the reactor trainees. Great. If you shake them, you hear a little rattling. Try it next time. They're usually pretty loose. It's a cheap plastic crappy casting with a thermal luminescent crystal in the inside. So again, shake it. It should rattle. If it doesn't, the crystal might be missing, and you should probably get a new one.

So when you read a TLD, you use this fancy machine, all it does is heat it very carefully, and allow the electrons that are trapped at a higher energy to jump back down, emitting visible

light. That's it. We've seen this process before. What happens after the photoelectric effect? Electrons fall down an energy and release light in the form of X-rays or visible light. Same thing.

And then let's talk about, how can you use dosimeters for dosimetry in medical applications? And let's take the example of proton beam therapy, the new and more upcoming replacement to X-ray therapy. It relies on the fact that the stopping power of protons is extremely low, until they reach the end of their range, like we talked about here. So again, we use protons as armor-piercing bullets to get through the person, drilling a little hole in the process, and exploding once they reach the tumor. It's a nice quirk of physics. It's really an elegant use of the stuff in 22.01 to do damage where you want it to.

There's all sorts of other methods of cancer treatment. Let's say you're simple, and you can just go with excision, which means cutting it out. Chemotherapy, which is a pretty nasty process, and is usually used as a backup for radiation therapy to catch whatever else might be floating. X-ray therapy, which is still used a lot, but hopefully will get phased out a bit. Brachytherapy, where you implant a little seed of a beta emitter into an area near where the tumor is.

Let's say you have an easy route of entry, like that way. Then you can implant one of these seeds right where the tumor is. But if you can't have an easy route of entry, that's where proton therapy comes in. And as we've talked about X-ray therapy, if you want to damage the tumor more than the rest of the brain or the rest of the person, you have to come in from different angles so that the sum of all the dose to this target is less than anywhere else. And X-ray therapy tends to do a lot of damage. Well, you hear of X-ray therapy causing hair loss in people. Well, yeah. You're going through the head. It's not good for your hair follicles, either.

And then there's proton therapy. We've talked about it before, but not in the strict medical sense. And actually I'm going to reveal to you guys an invention that we've got out of our department that might help this go a little better. The way it works is you start with a cyclotron, which I've already explained, something that accelerates charged particles to about 250 MeV. And we have one of these across the river at Mass General Hospital.

Send them through bending magnets, and bend them up so that they hit the patient. Then you move the patient on this gurney or table so that-- and the entryf can rotate anywhere, to come in from any entry point, minimize the dose to the rest of the patient, while frying the tumor.

AUDIENCE: Is that a scale diagram?

MICHAEL SHORT: Yep, quite big. Yeah. It's pretty to scale, yeah. So time on this instrument runs in the thousands per hour. If you go through the back door and know the folks that run the thing and no one is not being used for cancer treatments. Proton therapy can run in the hundreds of thousands of dollars. This is one of the millions of reasons we have medical insurance. It's because when you need it, you want it. And these cyclotrons aren't cheap.

The way they work is pretty simple. You inject ionized particles through these D magnets, and they go faster and faster and faster every time they cross this electric field. They bend at larger and larger tracks through these magnets as their energy increases. Than they exit out the other side, getting delivered to the patient.

And why protons versus X-rays? Well, I made it quick Desmos graph. To say, let's say you started off with a equivalent dose of protons and X-rays, and you're trying to get to a 40 millimeter deep tumor. This is why. This is the amount of dose that the X-rays would give compared to the protons in this highlighted tumor region. Then you look at the dose where X-rays and protons give to the rest of the person. It should be graphically obvious.

And you can do some tricks with proton therapy. If you have a lung tumor, you can vary the energy and time at each point, such that you give a uniform dose to the tumor. So you can move that [? Bragg ?] peak by degrading the proton energy, by putting filters in line with the beam. You don't tend to like to change the energy of the beam.

So you can put things in the way of the protons to slow them down. And because when the stopping power is very low, the proton speed's very high, and forward scattering is preferable, putting things in the way of the beam pretty much just slows them down, but doesn't change their direction. That assumption breaks down when the energy gets low. But when the energy gets low, you better be in the tumor anyway. And you want them to change direction and explode out and blast everything in sight.

The problem with proton therapy is that humans are not biological organisms at static equilibrium. In other words, they're alive. They tend to move. Breathing is something I like to do every few seconds. Swallowing, maybe once every couple of minutes. And most of your organs move around and dance without you controlling them.

It's really hard if you're trying to hit a tumor on a moving target. That is the main problem with

proton therapy. The solution right now, I like to call it spray and pray. You fire into the person, hope that things don't move. We know that they do though. Those proton beams are very narrow.

And let's say, for abdominal patients, let's say you happen to be digesting something. Your intestines will just go krschlock like that and get lunch where it's going. This is one of those reasons that they say don't eat anything before these procedures. If you're not actively digesting things, then your abdomen won't be moving as much.

Thoracic patients, better known as the lungs or your thorax, if you're from France. My wife likes to make-- I like to make fun of my wife. That's right. Because she still refers to this region as the thorax. And I was like, I am not a giant beetle. But it is the medical term for this.

You tend to breathe. And if you actually measure how much you move when you breathe in and out-- let's say you're trying to fry a lung tumor. That's a tricky proposition. So how do you keep the protons on track? Ideally, some dosimeter would be able to determine absolute dose, and it would be able to-- where on this list of things is-- oh, there's even more things I'd want here.

So ideally, if you'd want a proton dosimeter, you want it to be able to measure things, provide some data, not be orientation dependent, and things like not be toxic, be cheap to build, but also be able to turn on and off if the tumor moves out of range. And this problem hasn't been solved yet.

Existing dosimetry methods include making calculations and hoping, which is what we do now. We do complex Monte Carlo calculations based on scans of the patient, try and map out how much energy is going to be lost and where to go in. There's conventional port films, which means you put a film on the entry of the patient, which gives you an idea of where the beam is, but not necessarily where the organ is. Let me get into some pictures of these things so you know what they look like.

Anyone ever put one of these in your mouth before? The sort of electronic dosimeters, the X-ray imagers that you get at the dentist, you bite down on one of these, and you get X-rays of your teeth. That's great if you have a place to put them, but doesn't quite work for proton therapy.

There are tissue equivalent gels, where you can cast a person in gel, fire in the proton beam,

and see how deep it goes, and then hope that your tissue equivalent gel is equivalent to the tissue. Usually it's pretty good.

There's silicon diodes. You can implant a tiny little diode or other semiconductor device near or in the patient, and measure the change in band gap, or the voltage required to turn on conduction in the semiconductor. The problem is you can only use them once. Once you irradiate a piece of silicon, it's irradiated. And then you would have to take it out and stick another one in with a big needle to keep going.

There's optically stimulated luminescence, which means protons hit stuff. Stuff creates light. Light can be measured in real time. So you could implant a little crystal like this TLD or Thermoluminescent Dosimeter, attached to a fiber optic cable. And in that way, you can measure the amount of light and preamplify it. PM means-- what is it-- Photo Multiplier tube. And use electronics and software to calculate that light and turn it into dose. Problem is, this scintillation, it's not very strong. There's a lot that can go wrong between where the radiation is done and where it can be collected.

Also implanted MOSFETs are these metal oxide semiconductor field effect transistors. Same problem. You can look at the change in difference-- I'm sorry, the change in band gap as you irradiate these things, or in the MOSFET voltage. But again, you can only use them once. It's not like you can reset them.

So the problems with all of these is we don't know what dose the tumor gets. If we know how much we need to fry it, but we don't know if we fried it, the cancer could recur. Or it may not respond to the radiation. These are liability terms to say it didn't work, but you can't sue us, because we don't know why. And you don't know why.

Or you may apply too much dose to the surrounding tissue and induce secondary tumors. This is one of those things that's not talked about very much, except in medical circles, and my entire family happens to be in medical circles. So they confirmed, yeah, this is true. We don't know how many times, if you treat a tumor, or do you induce another one that will pop up five years later in the same site.

All you may think is, OK, it recurred, despite being dead for five years. It might not have recurred. It might have made a new one. You don't know the dose rate versus time. The existing *in situ* methods haven't worked very well.

So we had another idea, that I'll go in the last negative 1 minutes, what we call the integrating F-Center Feedback Dosimeter. We just got the patent filed on this. Not accepted, but filed with the US Patent Office.

It's pretty simple. You send in calibrated light into a little crystal of something that creates these color centers, or F-centers. When it's irradiated, look at the light coming out. See what's absorbed. You know how much dose you've received.

And so look at these three parts. A is just an alkali halide salt, better known as table salt, sodium chloride. B is some biocompatible casing so your body doesn't reject it. Calibrated white light source, fiber optic connection cables, and a spectrometer to read the absorption. These can be little compact USB spectrometers.

And it relies on what's called F-centers. When you irradiate ionic materials, they change color. These defects produced by, let's say, blasting out a chlorine ion or a sodium or potassium ion are optically active. Because you get differing regions of electron density. And you absorb certain wavelengths of light changing their color. If you then send calibrated light through it, you can tell what happened, how much dose there was.

And F-center creation versus radiation is extremely well known. We've actually done some preliminary tests on the Dante accelerator here to show that the amount of dose that you give in a fractional cancer treatment on the order of a kilogray or so does cause the salt to respond very strongly and produce a color. And the best part is, they relax on their own. After anywhere from 5 seconds to a few hours, the color just disappears. Because the atomic defects relax. So you don't have to implant, remove, reimplant, remove.

And you can enable dose rate information by putting multiple salts in a row that have different response levels to these protons. So by looking at the amount of absorption in each wavelength, you can tell not just the dose, but the dose rate. Calibrate your beam current.

And I'm going to skip all the way to the end to say how this would work. So let's say you had one of these IF2D dosimeters implanted in your tumor, and your heart was beating, or your lungs were breathing, or you were digesting something. You could then feedback this information to the proton accelerator to shut the beam off when the tumor moves out of range and send in tiny little pulses to say, hey, are you there?

Little micro second pulses to say, microsecond of protons isn't going to do much. But if it

senses the IF2D back in range, it then blasts continuously. And as soon as the IF2D says no more dose, it starts just putting those wake up pulses back on. So this would be the first feedback way to apply proton therapy without screwing it up.

You could also install IF2D dosimeters near the tumor, outside the tumor, and play the world's first game of radioactive proton Operation. Don't hit the sides. If you wonder if your beam's on target, you then steer it until it doesn't hit any of the IF2Ds, and you know you're right through the gates on the tumor. Very important for certain sensitive tumors, like chordomas, spinal cord tumors, which tend to happen in infants and young children.

There's various ways of treating those, other than removal of the neck, what you don't want to do. They're extremely difficult to operate on. You don't want to give radiation therapy. So highly targeted proton therapy like this, making sure that you fry the tumor without the surrounding spinal cord and medulla, would be probably the way to go for this.

So I'm going to stop there, because it's exactly 10. It's also the perfect stopping point. And we'll pick up with background radiation tomorrow. I also want to let you guys know that we'll be doing our nuclear activation analysis irradiations Friday at the beginning of recitation, and we'll finish up recitation by doing the exam review.