

For those that haven't figured it out, my name is Melissa Martin. I am one of your AAPM liaisons, and sometimes I actually do real work. I am a consulting physicist in Southern California for about the last 15 years, and what the topic I am going to go through on this presentation is, one of the items we were requested with is what in the world is really involved in these PET scanners that you're seeing come in to your facilities that you're asked to inspect. So this is the discussion of basic, the basics of positron emission tomography. I want to give acknowledgements to many of my colleagues. I did get a collection of information so you will see a variety of models of these PET and PET/CT scanners come through here. Phil Vernon from GE, John Anderson from UT Southwest in Dallas, Tim Turkington from Duke, Don Fry from South Carolina, Fred Fayhe, and then from Siemens. I just wanted to make sure that I gave the correct acknowledgements to all these suppliers of these pictures and information. So this is the basic level, it doesn't get much more basic than this.

What is a positron? What are we actually detecting in these scanners. A positron is basically, it's an elementary particle. It's an electron with a positive charge. It's probably the easiest way to think of it. You learned about electrons when we went through school, some of you a few years ago, some of us a few years ago. But the charges equal and opposite to an electron, and basically where do these come from? Well, the positrons we use for PET imaging come from radioactive decay. A positron is basically an antiparticle. In other words, it's going to interact with an electron. When a particle and the antiparticle interact, it's sort of like Star Wars. They annihilate each other and both are destroyed. So it's sort of like little boys playing games, and you know you crash in these things everything and knock each other down. Well they knock into each other and destroy themselves. In the process, what you're going to create is two photons, and that's what we are going to detect. We are going to detect the gammas that are produced in this annihilation process. The photons are emitted along a straight line. That is actually critical information.

This is what you want to remember. The two gamma rays are produced in a straight line in this annihilation process. Each photon that has the energy of the particle that it has destroyed, and so at this point, what you want to realize is that that the positron-electron annihilation is going to release two gamma rays, each of which has five hundred and eleven KEV. This is significantly higher energy than the hundred and forty KEV of technetium, which is what you're used to using and most people are used to seeing in a nuclear medicine department. So you are dealing with 511 KEV stuff, not 140 KEV energy radiation. Where do we actually get these radiopharmaceuticals? The positron emitting radionuclides uh have several unique features, one of which is they are very short-lived, so at least for PET imaging, you are not worried about long-lived isotopes, which are going to create a long-lived contamination problem. These things have a very short life. There is one, the strontium 82 rubidium 82 is a generator system. That is the only one that is a generator system. The gallium is what we use as a calibration source, and the bulk of what you will find is most people are using fluorine-18. We think of that in terms of having a long half life because it has a 110 minute half life. One of the comments earlier in the day was cleaning up contamination. The nice part about PET is if you spill the whole thing all over the hot lab, if you close the door, by tomorrow morning, you can come in and it's all gone. You don't have to worry about it. So clean up is actually rather easy with these. But these are the different isotopes that we

actually use for PET imaging. Again, the bulk of what out in most of the community hospitals at least are using the F18 with the 110 minute half life.

In some of your research facilities that have cyclotrons on site, you're going to see them using other isotopes, particularly the carbon 11. With a 20 minute half life, the carbon 11 has a fair a half life long enough to be useful for some studies too. Obviously what you're after is anything that is involved in the metabolic process. You are looking for, and that's why the carbon is a real good isotope to test with also. The nitrogen 13, oxygen 15, and rubidium 82 are obviously very short-lived isotopes, and they would completely require you to have your cyclotron on site. You will have different options like at UCLA in the new med center. They have the cyclotron on site. One of the physicians doing research there wants to obviously get his isotopes quickly and did not want to wait for someone to walk them over from the cyclotron to the 6th floor of the med center, so they have installed a pneumatic tube system so they can put the isotopes in, let the cyclotron shoot them through a parking lot and up 6 floors to the med center. I am just waiting for it to get stuck. But that's when we will call Cassie and keep her entertained.

Imaging concepts, conventional nuclear medicine, this is what we we've dealt with for years and this is what you are used to dealing with. Technetium 99, each gamma ray is emitted independently. The detectors, what your detectors are going to pick up each one of these gamma rays. They cannot tell where the gamma ray came from. All they can do is detect it as a count, and so therefore, we have to have collimators. In annihilation detection, obviously you're looking for coincidence counts. You are looking for the two photons that are created in an opposite line from each other. What you want to do in coincidence counting is you only want to count the events in which both detectors register the photon. So you basically set a very narrow window on these of a few nanoseconds to make sure you're only detecting true coincidence counts. If you do not detect both photons, then the coincidence is not recorded. Where was the event? That is the question. Both of these, if the event happened here, or if the event happened here, both of these photons would be counted, or did it happen out there. So what we wind up using, this is a picture, it looks sort of like a CT scanner. Again we are using a ring technology. We are detecting the events that happen across from each other, 180 degrees apart. What we are going to use in the way these scanners work is they basically have rings sort of like a CT scanner, if you are used to looking at CT scanners, with lots and lots of detectors. The same thing applies for a PET scanner. It is a ring with lots of little detectors. The detectors have to have a good stopping power because again you are picking up 511 KEV photons. The detectors should be fast because you want to pick up the very accurate counts of coincidence events. The two that you see out, BGO are bismuth, germanium was the first one out, and LSO is the second one out. Those are your two detector materials.

Just realized there's two systems out there, and depending on which brands you encounter, you will find the two different detectors used. I am going to go through in some of the later slides, some of the positives and negatives of each one of those detectors. Basic PET scanners lack conventional collimation because one of the things you want is to have a high geometric efficiency. In other words, you really want to make sure you detect all of these counts so you want a high efficiency. On the other hand, you want to be able to find out where those counts happened. So if you're going to do what

we call 2-D imaging, they actually do use septal rings to reduce the cross-top, and we'll go through some pictures of what we are talking about. But when you're when we talk about 2-D imaging, 2-dimensional imaging, we are going to talk about the collimator rings in. When we talk about 3-D imaging, we are going to have the collimator rings out because you're going to go for high sensitivity. That's a picture of the GE scanner. Again, it's lots and lots of these little rings, little detectors in a ring formation. If you look at it, it looks no different or very similar to again an MR scanner or a CT scanner. It's nice for the patients because most of these patients have had CTs or MRs before, so they're actually sort of familiar with being told to lay on a table, you know, lay down on the table, we're going to scoot you in to this gantry. It's not the first time they've encountered most of this type of exam, and that's actually a bonus because they don't find it so intimidating if they've been through this kind of exam before.

So what are we actually detecting? Again you're detecting what we call a true coincidence event. That's the good stuff. Unfortunately you can also detect what are scattered coincidence events. That's the bad stuff. It's like x-rays. You would like to have only your primary beam form your image, but that's not reality. What we would like to have only true coincidence events recorded, that's not reality either. What scattered fraction are we actually looking at? In 2-D, you're looking at scattered fractions of somewhere between 10 and 20%. With 3-D imaging, you are looking at scattered fractions of somewhere with 30 and 80%. If you use 2-D imaging, you're going to reduce your random rate, because again, you're going to have collimator rings so you won't pick up as many random events. One of the factors you may hear people talking about, or if you study these, is what we call correction factors or corrections. And how do we, it's it basically attempts to eliminate the scatter, the scatter factor. So in other words, we are truly counting true coincidences. So we can use basically a window system, so in other words, again a timed window system that will eliminate some of the scatter counts. The other way we'd count for randoms is to measure what we call a coincidence rate, and you find out if it's truly random, then that's how you subtract that then from your trues. As far as image reconstruction, it's very much like a CT. We basically do what we call image reconstruction. It's filtered back projection. It's _____ process is what I want you to realize. You basically take a trial image, if you decide it's not good enough, you can collect more counts, and it keeps going back and forth until it basically gets enough counts that we have predetermined if it's an adequate count for that type of image, and you say basically you're done. One factor that goes in, if you've worked in nuclear medicine at all, is obviously we have a problem in nuclear medicine with attenuation corrections. Any photon that's emitted here has a fairly good chance of being attenuated, and so what you're trying to do is correct for images so that you have a uniform picture regardless of where in the body that the photon was emitted, and there's different ways of getting these attenuation corrections.

Obviously with PET, you're going to have, because it's a high energy isotope, you're going to have less attenuation than you do with traditional nuclear medicine scanning using 140 KEV technetium, but we still need to make sure that we do this attenuation correction. There are several methods of doing this attenuation correction, and if you notice, each one of them has sort of a positive and a sort of a negative that what we call the purely calculation, the calculated factor where we don't have any measurements on this, there is no noise, and it's probably inaccurate, but, you know, you

can calculate it. Measured is the way a lot of your well, the measured factor is what if you have a straight PET scanner, that's going to be the method we use. You're going to measure it, but you do have noise in it. There is one we call it segmented that has less noise and takes less time. The best one and 95% of the sale are now PET/CT units, and you're using the CT scanner to get your attenuation correction for that particular part of the anatomy of which you are interested in. But what you're correcting for is the attenuation through the water or brain, and then another correction obviously for the skull or the bone. That's just like doing attenuation corrections back in x-ray. If you're going to do a measured correction, you basically just do it. You count how long with no person in there, in other words, no phantom, no body, how long it takes you to get 100 counts, you put the body in there, and you can only get 15 counts, and so you do a corrected emission factor there, so you know for every 15 counts you detect, you actually had 100 that were occurring. That's your attenuation factor. The PET/CT is the best way to go if you have that option. Obviously, you're going to scan for that particular slice through that particular patient and get a very accurate attenuation correction based on the CT value of the Hounsfield number, the CT number of that effective slice. So that is why, for one reason, they are selling the PET/CTs. You get the great images. If you have a straight PET scanner and don't have the CT option, what you usually do is you wind up using a germanium or cesium a germanium 68 or cesium 137 radioactive rod, and these are the sources that with these PET scanners these are your "long-lived" standards that come in with your sources. So anybody that has a traditional PET scanner is going to have a radioactive source associated with that which allows them to measure their attenuation factors, and these get replaced on a regular basis, that's part of their service. So yes, they will have radioactive materials. They will have these sources in addition to the isotopes that they will use for the patients. These are the two isotopes that they will use for their machine, basically QA.

Now, what is the best technology? This is more information than you may want to know, but this is what is being marketed out there and what the physicists and physicians are trying to use to decide what is the best technology for this imaging modality. How important are, the four factors we use to evaluate these scanners are resolution, sensitivity, the scatter fraction, and what we call the count rate performance, and this is what NEMA has actually set standards for as far as describing the physical performance of these detectors in these scanner systems. Resolution has a different definition in PET imaging than what you're used to in measuring x-ray systems. Resolution is defined for a PET imaging system as how big does a 1-mm source appear to be. That is very different than what you're used to doing in x-ray systems where you're putting metal bars and we're measuring line pairs. You're not measuring it that way, you're basically saying how big does my 1-mm image appear to be. Because resolution is obviously what limits your ability to see edges, it's going to determine what your ability is to define and detect the shape of small objects. In other words, is it a true metastasis? That's what you're using these scanners for. Sensitivity is another aspect of this, and that is defined as basically how much information is collected per unit time. In other words, for a given amount of isotope, how fast can I collect the data? Obviously if you're the facility that has invested these multiple thousands or million dollars into these machines, you want to be able to put as many patients through there as possible, and it sort of comes down to the how fast can I get this patient through, and the big question is, if I give them twice as

much dose can I get them through in half the time, and that's going to be the question. I think we've sort of ah the community is establishing what are acceptable doses for patients but that's what I think we have to be careful of is that we basically don't get dose-creep in the future. In other words, can we give if we give them 20 millicuries instead of 10 can we get the data in half the time. That's not necessarily the case. But that's what we define as sensitivity, how fast can we detect per unit time for a given quantity of tracer. Obviously the faster we can get our counts, the faster we get through with that patient.

Again, what is our scatter fraction, just means what fraction of the data collected is scatter, or in other words bad data, and that's important because your scatter degrade your signal to noise ratio. For those that have gone in to study the digital radiography, you know that signal to noise ratio is really a factor that we're using to define image quality now. Count rate performance. As the tracer dose is increased, how much more information is collected? Okay, what is continuing to answer that question, what is the best technology for resolution? Realize on a 1-mm object on this is going to average 5.5 to 7.5 is how mm is how that's going to appear. So your resolution is not what you're used to in a CT scanner. Again, a 1-mm object looks like it somewhere between 5.5 and 7.5 mm in size. Sensitivity is going to vary by a factor of 3. So these units and systems do have a large variation in them. Scatter fractions are going to vary anywhere from roughly a third to a half without the rings in what we call 3-D imaging, where we're simply collecting all the data. About up to half of that numbers that we collect are going to be scattered. With 2-D imaging, you get a much cleaner view, but it's like using a grid in x-rays. You're going to have a lot fewer counts. The most meaningful measurement you can get is what we call the count rate performance. The most meaningful measurement and will, I'll show you some pictures of this is what we call the noise equivalent count rate, and it's the total count rate, corrected back for scatter and random events. In other words, you're taking the noise out. You want to know what is my actual count rate for true events.

Okay, spatial resolution, again, at 10 cm is where we typically see this. They don't vary that much so we've just kind of averaged it out. These are different systems. If you notice, most of them are coming out about 5.5 mm. That's how big a 1-mm source looks. So this is this is very nuclear medicine level, it's not x-ray level. How are we actually detecting these? It's the crystals, we are using we're using typical scintillation crystals like we've used in nuclear medicine before, except the crystal has to be thick enough that it can stop a 511 KEV gamma ray. That's different. We're used to detecting these low energy gamma rays, and we can get away with thin crystals. If you go back, thin crystals give you sharper images. So we're back to the days of thick crystals so that we can actually stop these 511 gamma rays, and then we just basically have photomultiplier tubes on the back of the crystal array and that's what you're counting as how many events come through into the photomultiplier tubes. That's just what these look like. You have banks of these photomultiplier tubes onto the back of the crystals. That picture is actually from Siemens straight out of their brochure just so I thought that would at least give you a picture of what you're dealing with on the inside of these scanners. Okay, what in theory this is the marketing information. Okay, if you really want GSO as Phillips, BGO as GE, and LSO as Siemens, we've got the same big three players out here having fights with each other as to what is the best system to use. Relative light

output, if you just go with theory, the LSO crystal that Siemens is marketing has far and away the best relative light output. In other words, more light means we can improve our energy resolution and reduce our scatter, or if you could have more crystals per photomultiplier tube, the cost is less. The money is in the crystals.

So what else you're looking for is decay constant, the faster that crystal decays and is ready to count another count, then you get a higher count rate per crystal. Again, you can do things faster so you get the patients through faster, you reduce the number of random counts, and you get a higher more accurate count rate. The one where the one aspect of "pure scientific measurements" that the LSO doesn't come out on top is the photo fraction or the stopping power. The higher sensitivity means you get more counts actually the B, the bismuth, germanium, that GE uses would come out on top. I liked that quote. "Theory and practice of PET scanners is sort of like that envision by Yogi Bear." In theory there is no difference between theory and practice, but in practice there is. Because what really happens is the performance in clinical scanners when you actually put into practice they aren't that significantly different. Both systems work. So it's not a matter that any of these are the ultimate perfect system, I'm not sure what's going to be the ultimate perfect system, but all three of these systems are out there, and they are all doing fine. Relative light output, actually the energy resolution is very, you know you are not going to see this difference between 16 and 17% in a clinical situation. They are a wash. All three, 16, 17, 16%, they're equal. The decay constant, the LSO is definitely the fastest system so it will, you know, it still comes out ahead. On the other hand, the net count rate, the GE system comes out, so Siemens wins that one, GE wins that one. They're all good systems, but you can't evaluate these systems strictly on their scintillators. It's not all crystals. It's like evaluating a CT scanner on the detector. That's part of the system. Obviously the rest of the system is software and image merging and all the other aspects that makes these things work. Sensitivity is defined again as the amount of information per millicurie of tracer injected that I am going to detect. Can you go back one, did I goof it up? I can't go back with this thing, I discovered on Friday.

What I wanted you to realize is for 3-D, again, you don't have your rings, so it's the effect of taking out a grid, you don't have your rings so your count, your sensitivity is much much higher with what we call 3-D imaging than it is with 2-D imaging. So you definitely collect your counts and your images faster if you're doing 3-D imaging. Next. Okay, counts determine image quality. This doesn't matter if it's x-rays or nuclear medicine. Counts determine our image quality. The noise in the images can be reduced by filtering, and the noise in PET images is dominated by the counting statistics. These are different filters. But look at the difference, it's just like, you know, you want to get rid of that noise. At 10 to the 5 counts, you really can't get a good picture there. Ten to the six, this may come back to what Keith was showing. Is ten to the sixth adequate, or do you need a ten to the seventh count rate. You know, do you need that other factor of 10 to get that crystal clear image or will this level of counts give you a perfectly acceptable image. That's going to come out in your different clinical studies. If this image is good enough to see, then you may not need to inject more tracer, or you may not need to count longer to try to get that image.

So we have an argument going on out there as to what is the best way to do scanning, whether it's 2-D or 3-D. The difference is these are theories. In theory your 3-D gets to your net equivalent count rate much faster. Your 2-D can actually go higher.

Reality is this is that short range is the small area we're actually using. So if you look at your count rates, this is actually what we measure. For 2-D, you're going up to about 80,000 net equivalent count rates, 80,000 counts per second. In 3-D, you will not get up to the 80,000 counts per second. The difference is this is what all the manufacturers like to sit and argue about is to which one is better. Reality is we're working down here in this end of the scale. So you have to when you look at this, this is why even in theory if you go up, say the 2-D in theory, would get you eventually a higher count rate for the area that we are actually working. For a 15 millicurie injection with a 45-minute uptake, you're working in this range. So you're going to again get your counts faster with a 3-D system. That's just another picture of the optimal clinical performance. Again, we're working in this range here where 3-D will give you, without the grid, about 50% more counts. So if you can see it adequately with a 3-D image, you get it a lot faster, or you can get it with less dose.

So again, this is the discussion, what is the best way to acquire the data. 2-D acquisition gives you a much cleaner picture. It's all events that are used to reconstruct that slice actually happen within that slice. In other words, you have your rings. You have your collimators. So you're only going to detect those events that happen within that slice. Events that cross the slices would be rejected. For 3-D acquisition, you're going to detect all the events that happened within basically that volume. So events that cross slices would be counted. And that's just the picture of the 3-D. Both scatter and random counts are significantly reduced when you use the 2-D images, but you suffer on your count rates. Only if you're doing 2-D imaging do you have the equivalent of having your collimators in there. So this is if you come back to the different techniques that we're using, 2-D versus 3-D sensitivity, 3-D is obviously better because you don't have those collimators taking out your counts. The resolution, the pure resolution is no different. The way we define resolution is no different. The scatter fraction 3-D is worse, random obviously 3-D is worse, and the counting rate because you get more scatters of the true. You get all your scatter and random factors built in so the 3-D is worse. This is just a picture of what, just to show you. I'm going to have Mr. audio visual man toggle back and forth here in a minute. This is a 2-D image. When they started the acquisition, it was with 11 millicuries, but this is pictures from MD Anderson, and see it's a relatively clean looking nuclear medicine image. That's as good as it gets.

Next, when you go to a, ... no advance it one more. This is the 3-D image of the same patient. This was with 10 millicuries but basically that's just the way it was when they started the counts. See it's not as crisp. Toggle back to the 2-D. See it's like which one do I really have to have. So what you actually see is a lot of the people that are strictly doing PET scanners, they like to the 2-D version because it is a cleaner image. Go to the 3-D. When they go to the 3-D, it still may be adequate. That's really a clinical decision. Is that image good enough. Because what you really find is most of the 3-D scanners or at least a lot of the 3-D scanners, going next. This is the different count rates for those pictures in the trues. In the 3-D, your trues are like 24%, whereas in the 2-D, your trues are 79%, so you almost have a 3 to 1 fraction between the true counts on your 2-D versus your 3-D. That's why you get those crystal clear pictures on the 2-D images. On the other hand, people like the 3-D because it is fast. It gets you your counts quicker. You have a 4 to 5 times increase in sensitivity. On the other hand, you're also getting an increase in scatter of about 40%. Some devices actually give you an option. What they

are doing typically is 3-D in the brain and 2-D in the whole body. So those machines are out there. I think you will eventually see them.

This is just a picture of what we are going to. This is the type that are selling. I do a lot of shielding design for these, and I would say I have I've done one pure PET scanner in the last 3 months, and I've probably done 15 PET/CTs. Ninety-five percent of the sales now are PET/CT units. What you've got is a PET unit in the front and a CT unit in the back. Now, the main difference is these CTs can be as good as any other CT on the market. Siemens is actually now selling a 6 slice CT. GE is going to be selling their 16 slice CT. That what you don't get that the reason these probably won't be used a lot for true diagnostic, is you can't tilt these scanners. If you think about it in normal CTs, they usually tilt the machine so that you can get parallel cuts through the head, you can't tilt these scanners. So to a certain extent, they're limited. On the other hand, these are very very popular for radiation/oncology because for radiation/oncology setups, those patients are on a flat table top. So most of these scanners come with a flat tabletop, and these are terrific units for setting up radiation/oncology patients. Again, that's what most of this is, is cancer patients, so these simulate and can be used for CT simulations for radiation/oncology purposes very very effectively. Because again, a linear accelerator doesn't tilt, so the CT doesn't tilt. That's not a problem. This is the Siemens biograph unit, it's called, has again you have your PET in the front, CT in the back. So it's a coupled all of these. The patient does not move. The patient is on the table, you're imaged in one mode, imaged in another mode. You do not move that patient, so you get both of your metabolic information, your physiologic information on the uptake and the PET, and it's immediately correlated with the anatomical information from the CT, and so the merging of these images is what makes these units so valuable, but in the talk I will give on Tuesday for the whole group, you definitely have different shielding requirements when you go into these systems than you do for a normal CT scanner. But these work. They have a coupled x-ray scanner to acquire the transmission image for attenuation correction, and you have auto automatic registration between your anatomic CT and your functional PET images. So you get faster scans through reduced transmission time, and that's the type of image that we're working with now. You basically have the CT scan for your anatomic information. You marry this with the PET images and you come out with a merged image, and most have gone to color monitors, but in other words here, it's very hard to define and get an accurate necessarily very accurate location of where that tumor actually is. When you marry it with the CT scan, you get wonderful delineation of the exact location of that tumor. You put an axial image up there, and you can use it for treatment planning purposes, and that's where and what this whole process is going to, and that's why these images are so that's why this technology is getting so popular, particularly in cancer centers. So yes, if you like merged modalities, if you haven't got one of these, you probably will have.

So that that working group that's trying to develop what do you do with these, I hope it goes very quickly, and I will take questions. That's the last of the pictures that I have. I'll take questions if you've got any for a few minutes. Thank you!

Q: Thanks for your presentation on the basics, but wanted to get your ideas for the future of the modality with perhaps gated or the use in cardiology with the rubidium 82

generators and quality assurance for both fluorine and rubidium, perhaps an imaging phantom. Is that something that can be standardized or is it specific for each unit?

A: No it's not well it is... and it, it is sort of specific (inaudible). I have not done the rubidium. I don't have any of those, so I can only speak from the, where I'm coming from is the ACR accreditation program from PET scanners used as obviously it's a different base put onto a JASAC imaging phantom. So it's a generic phantom for regardless of which model scanner you're using. So that phantom is existing out there and the whole accreditation program is already set up. So it is a generic phantom. I haven't, I don't have any experience on the cardiology end of it. I don't know if anybody else does or not. I've taken GE's, Siemens's, and there is another one out there, Hitachi, I think it is, is bringing in one that has gone through with the PET phantom, and they all work fine. I mean, you can image the protocols, you can image it with the adequate, you know, you use a patient dose and for that testing, and it, all three brands can work just fine on them. Any other questions?