We're going to be discussing applying Monte Carlo to IMRT, so we take one complex technology and add it with another and have a little bit of fun with it. Basic outline of what I'm going to be covering here, is first I'm going to be talking about what is different about IMRT, hopefully most of us realize that there are some differences with respect to IMRT and why, in fact, with IMRT conventional dose algorithms can be inaccurate and once we discuss why conventional algorithms are inaccurate, the answer to the next question should be obvious of why Monte Carlo is better, then we'll discuss the applications of Monte Carlo to IMRT specifically to the process of quality assurance and to the future where routine IMRT optimization will in fact be done using Monte Carlo algorithms. So, what is different about IMRT? Well, hopefully we all know that in

IMRT we typically have an iterative planning process; we have an iteration loop where the dose calculation occurs within the optimization loop. The result of this is that we need to compute dose often and fast so in the optimization loops, typically a pencil beam algorithm is used. These are the algorithms which are, they use an equivalent path-length correction, so they're less accurate than for example, superposition. So, one thing about IMRT is the algorithms that are used during optimization are not the most accurate algorithms, they're not even the second most accurate algorithms, they're almost the third class of algorithms and if we take a look at the speed here of why pencil beam is used because they're fast as a rabbit where Monte Carlo, at least some people believe is slow as a turtle, but the new Monte Carlo codes are now getting much quicker. Another nice

or another difference about IMRT is that it involves leaf-sequences. Within this optimization loop, after we have some optimized intensity for beam, we need to convert that into some type of leaf sequence and this leaf sequence is going to go on through and this is actually how we deliver an IMRT plan, with the sliding window technique and this is actually, note there's all these small little areas which are coming on through, passing through to deliver the beam and this actually makes dose calculation a little bit, a little bit fun. So, before we talk about Monte Carlo with IMRT, we should first understand how we include a time-dependent multi-leaf collimator in a conventional IMRT dose calculation algorithm. Well, if we take, if we start out with a view of the accelerator, then the patient down at the bottom, what's done in conventional algorithm is the multi-

leaf collimator is actually replaced with a matrix, an intensity matrix or a fluence modification matrix, as you will. And as rays are cast through the accelerator onto the patient, as we pass through a fluence element, the energy fluence of the particle, the initial energy fluence is multiplied by the matrix element which it uses to pass through to give you the final energy fluence. So we can do this for a few more particles and, but what really happens with the MLC for IMRT, well the first order effective of course is to produce our desired intensity modulation but the MLC also introduces other effects into our field which such an intensity matrix does not account for. It adds MLC scatter, so we have particles that interact within the MLC and scatter within the field and also, particles that are transmitted through the MLC, there is, you will get, your energy spectra

transmitted through the MLC will be harder, so this will be beam hardening and that can cause for example, about a five percent difference at depth within the phantom for the beam transmitted through the MLC. Now, we all do good quality assurance processes to actually make sure that things are good and what we do is we are using this actually predicted to check our predictions of fluence. Now if we compare this with a conventional algorithm, this is a convolution algorithm using an intensity matrix compared with a measurement here for the beam hitting the film, if we compare, I hope we can see this since the screen is a bit low, that we have the measured in black convolution in red and in profiles, things look pretty good. If I subtract these two images and histogram the differences however, I get what's in the second panel here and this shows that there is quite a spread in the dose difference with the mean dose difference of about minus three percent and if we get a little more tricky and we actually plot the

absolute value of this dose difference, versus what's termed the distance of agreement, that is if I take a given point in one image and say how far do I have to travel in the other image to get the equivalent point, you get this third panel and we actually see that only, that didn’t, that only in this case only about 90, about 50 percent of the points actually fall within two percent or two millimeters. So in general conventional algorithms, they can be inaccurate, either due to their fluence prediction for IMRT or due to the transport in patient and it’s, can actually be inaccurate for small fields, regions of dose gradients or radiation disequilibrium in heterogeneous conditions. Now this pretty much explains how we’re delivering IMRT, that we typically delivering using a sequence of static fields, small static fields or dynamically moving aperture, and we have a lot of dose gradients.

So this is why we expect conventional algorithms actually, to have these challenges. So of course, we know Monte Carlo can be better for IMRT. The reasons for this is that Monte Carlo makes no assumptions regarding radiation equilibrium so it can be accurate for very small field sizes and in regions of disequilibrium. Also, Monte Carlo will transport directly in the patient materials, therefore directly is accounting for the patient heterogeneities rather than trying to do it through some correction scheme. Finally, the Monte Carlo can actually transport directly through the multi-leaf collimator, even in moving multi-leaf collimator, on the fly during the calculation. Now, how do we do the multi-leaf collimator for Monte Carlo? Rather than watching the movie, we’ll get to the point. Well first of all, we can actually use the same intensity matrix that we use when

we do conventional algorithms such as convolution or pencil beam algorithm where we cast rays through and we actually take the weight of a particle, the statistical importance or statistical weight of a particle coming in, multiplying it by the intensity of the statistical, by the intensity of that element to get the final weight of the particle and transport that into the patient and score the dose of the patient that way. If we do that and actually take a look at the fluence, using the same quality assurance procedure as before, using the Monte Carlo now on a water phantom, we actually see results which are nearly identical to the results of the convolution algorithm. So all we've changed here is the algorithm underneath but used the same fluence which is telling us something that we all should know, that a convolution algorithm, pencil beam algorithm, Monte Carlo algorithm, they all should be exactly identical if they're fed the same fluence in the water phantom, and they're properly commissioned. This shouldn't be any surprise and that's because in this case we're using the same intensity matrix and the effects of the multi-leaf collimator are actually being approximated and it's ignoring the scatter of the multi-leaf collimator and beam hardening. Now another thing we can do in Monte Carlo, is we actually can directly transport particles through the multi-leaf collimator as it's moving and we'll show you the results of doing that and the advantage of this is then the geometric details of everything about the multi-leaf collimator included; the leakage, the scatter and any beam hardening effects are actually completely taken into account. So if we take a comparison here, same as before, film within a phantom, measurement and

calculated with Monte Carlo but this time transporting through the multi-leaf collimator, what we see is profiles agree very well, the dose difference panel showing a very tight distribution centered around zero, the width in here is actually due to the fact that of the statistical imprecision in the Monte Carlo and take a looking at the number of points within two percent of two millimeters, we see that we have 97 percent as opposed to about 50 percent agreeing. So much better agreement, and this is the ability of Monte Carlo to help us better predict the fluence for IMRT, nothing to do with actually transporting the patient since we're just going through a water phantom. Now let's take a look at the application of Monte Carlo to IMRT. First, what we're going to look at is verification basically of planning systems and that is taking plans from a planning system

and recomputing Monte Carlo. This is the result from Todd Pawlicki from Charlie Ma's group which shows a comparison between Monte Carlo and a pencil beam algorithm, the Monte Carlo in fact uses an independently developed intensity matrix rather than transporting through the MLC so it's not using the same intensity matrix as the treatment planning system, it's using an independently developed intensity matrix that includes a empirical correction to account for scatter from the multi-leaf collimator and what you see is the pencil beam algorithm predicts nice, this was the initial dose calculation, Monte Carlo re-calculation predicts a nine percent lower mean dose and it predicts a higher cord dose by quite a bit in this case and here are the dose, the isodose Profiles and you actually can see the difference with the isodose lines encroaching on the target on the

Monte Carlo case. Another result from Memorial Sloan-Kettering, where they used Monte Carlo to compute five lung and five head and neck plans, this is comparing Monte Carlo to pencil beam, using in fact the exact same intensity matrix for here and when you first, the first thing you notice is that on average, everything looks pretty good. The Monte Carlo and the pencil beam algorithm agree and this is what's mainly reported in the paper. But the other thing that I note of these, on two of these plans have actually fairly substantial differences, this difference being about eight percent high and the D95 and the V95 on this patient being about 20 percent low. So even when we use Monte Carlo using the intensity matrix in the treatment planning system, we can find substantial differences in the patient plans. Now if we go to a case from our institution, where we

actually compare Monte Carlo compared to convolution where the Monte Carlo is actually going through the multi-leaf collimator, the initial convolution optimized IMRT plan had nice coverage of the PTV, but the Monte Carlo initially showed two things, it showed a hot spot for the 66 gray, and it also showed encroachment of the 57 gray line. So we're seeing actually two effects, one effect is actually due to heterogeneities in the patient and the actually the second effect is due to fluence. I should point out that this is actually for the patient, which I was showing the earlier film dosimetry results for. If we look at the dose value histograms, for example, for that patient, comparing the super position convolution algorithm dose value histogram, which is in red, in blue, I have the dose volume histogram for the Monte Carlo using the same intensity matrix, the fluence modification matrix as the convolution. In the flat phantom you show the same results but what you see in the patient is you actually a bit a hot spot in the PTV whereas when

you use the Monte Carlo including the multi-leaf collimator, you actually see the PTV is cold and then getting hot. So you have both underdosage and overdosage shown by the Monte Carlo. Now, what about, so this is actually checking out planning systems with the previous stuff was showing, was checking out planning systems with Monte Carlo, what about using Monte Carlo for IMRT patient Q, quality assurance? Well, at our institution in addition to doing the film dosimetry that I showed earlier, for every IMRT patient that we have, we recompute the plans using Monte Carlo. So the plans were initially developed using the treatment planning systems algorithm and then we recompute the beams using Monte Carlo. We in fact use the multi-leaf sequence files that are sent to the accelerator to generate the intensity modulation during the calculation

and what we do is we then compare the dose volume histograms with the treatment planning systems convolution calculation. And if you're going to use something in a quality assurance process, of course you should know what you're going do with it once you have the results otherwise it's not much of a purpose to have it in this part of the quality assurance process. So what we actually do is, this is our flow diagram, we start with, we have an acceptable IMRT plan, we copy the plan within the treatment planning system and recompute it with Monte Carlo. We then ask the question, is there greater than a three percent difference in the dose volume histogram at the points in which the IMRT plan was specified? If there are no differences greater than three percent, if everything is less than 3%, we print and sign the dose volume histograms, include it in

the patient chart and we're done. But what if there are bigger than three percent differences and we do see this. The planning team is actually notified. They then actually ask the question to the physician or the entire planning team, is our, are these differences acceptable, do you care? And if they say, if they don't care, if the differences are acceptable, they just go ahead and treat anyway. But if they're not acceptable, they actually modify the plan based on Monte Carlo. Then after they modify the plan based upon the Monte Carlo dose calculation, then they proceed with putting the dose volume histograms that they believe the patient will get into the patient chart. Now, a typical result we see from this comparing the dose volume histograms, solid line being the convolution calculation, straight from the treatment planning system, the dash line being the Monte Carlo recheck, of course a physicist has signed this because in this case there are no differences greater than three percent, this is a typical very good result. There's a little note over here, the dose grid doesn't include the entire contour for the convolution calculation, indicating the reason for the difference between these two dose volume histograms. But this is a typical result. Well, sometimes you see results that are a little bit less typical, but very important nonetheless. This is another patient case showing Monte Carlo and the convolution, Monte Carlo being the dash line and this case indicating a ten percent difference. So in this case, we actually change the patient plan based upon the Monte Carlo. Now we have performed this quality assurance on over 300 IMRT patients at our institution where we also have to realize that a number like 400,

which I think is probably closer to where we're at, is greater than 300. Now what about using Monte Carlo for optimization in IMRT? Using it for quality assurance is good, but how can we use it to actually improve our plans? We're now starting to actually do this at our institution and if we go back to that plan I showed earlier, the head and neck treatment plan, where we had the convolution optimized plan over here, and we're back up, here we have to convolution optimized plan, and here we have the plan recomputed with the Monte Carlo including the effects of the multi-leaf collimator and we have the hot spot and the 57 gray not covering the PTV. So here's that convolution plan again, that's the approoved plan that was initially approved by the physician but did not agree with the Monte Carlo, so this could not be achieved in the patient with leaf sequencing as

specified, but when they re-optimized with Monte Carlo in this case, we actually see that the isodose lines come out very similar to the convolution, in fact, almost identical and taking a look at the dose volume histograms, you actually can see that the Monte Carlo optimized which in this case is in blue, pretty much directly overlay that from the initial convolution optimization indicating that when we use Monte Carlo within the IMRT optimization process, we come up with a excellent plan in this case. So let's get to the quick summary here. In summary, let's see, Monte Carlo, what about Monte Carlo? Well, we know for IMRT that it will do a very good job for the small field sizes, because it doesn't make any assumptions regarding the radiation equilibrium, Monte Carlo's well suited for IMRT, it's also well suited for IMRT quality assurance and it may in fact

eliminate the need for quality assurance measurements. Indrin asked me to put something controversial, so there's a nice controversial point for you. But probably more important, is we shouldn't be using our better algorithm for a quality assurance tool. We should actually be using it for dictating our plan and instead be using it for IMRT optimization. I'd like to thank you for your attention.