

Thanks Steve, thank you all for being here. First I'd like to acknowledge my co-authors. The people who've actually contributed, I would say the, the lion share of what I'm gonna be talking about. I just get to, kinda kibitz, on the side to a large degree. We'll be talking about high resolutions 3D, but I have a lot of background in regular good old low resolution 3D, for vascular. And so, there's going to be a little bit of a mix, but basically the things that I'm saying, any time you see something that looks like there's a low res, it's really high res, because I have Steve's micro angio in my back pocket. So, just that you know that. Okay, so we're gonna be talking about 3D and my big thing is that you don't have to have multiple views for a 3D, I think you can do 3D from single views, there's a lot of information in a single view. Two views is nice and that's where I have most of my background, multiple views is something we've been working on

recently and, and CT everybody knows, we can get 3D from CT. So from, the 3D from single views, you have an angiographic system that you have to acquire the images with somehow. You have to do the calibrations. These are really, really important. Then you do vessel sizing using various techniques that you want to be using, and you do the lumen construction, again, from a single view. So, what do you have? You have an x-ray system, with x-ray source here, passing through the patient that's on the table, then you have the II, usually, now a days, they're detectors or one K by one K, with pixel size on the order of a hundred to three hundred microns. And the calibrations you have to do are the calibration curve, which is the relationship between the exposure and the pixel value, resolution getting the modulation transfer function or that type of thing. And then magnification, you have to use some kind of calibration objects, oh catheters

or something like that, stents are also a possibility. Now, one of the things when you're talking vessel sizing, accuracy really depends upon the resolution. The error goes up with the full width half max of the resolution function. What we have here is a graph of some simulations that we did using a derivative technique. And what we see for the full width half max down here at .5, .7 and even at the .3, as the vessel size goes down below 1 mm, you start getting significant deviations whereas, if you go into the high resolution range, which is what we're talking about here, you stay very nice and low, in terms of the accuracy or high in terms of the accuracy, low in terms of the error, in the actual measurements. So, how do you get 3D from a single view? Well, everybody knows that if you've got x-rays coming down through a healthy vessels or circular cross section, you get a projection profile that's also basically circular or elliptical, if you will,

depending on what your attenuation coefficient is. If you have plaque, there's a distortion of that nice elliptical or circular profile. And if you go and you fit that distorted profile, with some kind of circular elliptical function, then you can get back and reconstruct a circular cross section and then if your really clever, you go and say "Oh, well I know what the difference is between my fit and the actual profile, so I've got this distortion, the asymmetry in the profile and I take my circular one and eat back out, using a little Pac Man idea and you can come back to getting the distortions or the asymmetries or the plaque, the intruding plaque, in the actual vessel. So, with high resolution on the order of 50 micron pixel, I really think that 200 micron or below diameter vessels, if they're semi healthy in terms of circularity and ellipticity, they may be reconstructed.

However, it's not the end of the story. Single view is we've been, but two views has more information, at least and

therefore, again, we have the angiographic system, calibrations and lumen reconstruction. So now, we have two x-rays sources and we have two image intensifiers for the clinical systems. You have the standard calibrations that we talked about before, but now another one comes in, called pincushion, which we'll see in a minute. The imaging geometry has to now be calibrated. You have to know where those objects or those sources and image intensifiers are relative to each other, to do the proper reconstruction, and for that you either need calibration objects or a self-calibration techniques. And it turns out that you can also, from the two views, calculate the attenuation coefficients, there's something that's down in the poster section that I believe is still up, since I haven't taken it down. Okay, pin-cushion is a, I'm sorry, pin-cushion distortion, you need the corrected image. What you have here is a little bit hard to see, because of the quality of

the distortion, or of the tube itself, but if you look really carefully here, there is a slight bowing out here, at the edges, the periphery. They're not really straight lines, whereas over here, after correction, you see it's very clearly a straight-line image. We have to take care of that. The next thing is the imaging geometry; you have to know where one imaging source is relative to the other, because you have to bring everything back into the same coordinate system, when you're doing all your re-projections and reconstructions. And so, a lot of investigators have proposed using a calibration objects with objects like lead beads or something like that at known relative positions and they basically solved the set of equations. Dennis Parker did some of the early work in this area, and I believe they still got a number of algorithms out there being used by

various investigators. And Mike Potel, coming from my home university, over at University of Chicago, did some initial work as well, using a cube phantom, but there also helix and helices that one can also use for this. You can also use something called self-calibration techniques and basically those techniques require no calibration object. That is, you use the images themselves, and this is actually something within our group, we tend to like to do, because we don't want to have to pull the patient out, put the calibration object in, and then put the patient back in, etc. What we do is, we use corresponding points, such as bifurcations. I use vascular images, so coronary bifurcations, or in the neuro domain, the bifurcations of the various vessels and the cranial vessels, and I only minimize an objective function. And basically the basic concept is shown here. Here we have a right coronary system with two bifurcation points indicated and

what's nice in the two dimensional system and the two view situation is, a point over here, if you think about it, going back to the focal spot, becomes a line in the second projection and these are called epipolar lines and if your geometry is good, this epipolar line lies right on top of that bifurcation, the corresponding bifurcation, in the other view. It's similarly down here for the other one, if you geometry is good. However, it's not always that good, especially what you get from the gantry. Here we have an uncorrected

view, 3D reconstruction and a corrected. And now, you can look and see and they look very, very similar. There's some differences, that you can pick up. So, the bottom line is when you're looking at this, why should we correct? Well, the answer lies, when you start looking at the true 3D. You end up seeing that there's pieces of the vasculature missing because the epipolar lines haven't been properly lined with all the

corresponding points and what ends up happening is, the correspondences are wrong, not only for completing the vessel trees, but also for corresponding points within the vessels for reconstruction. And you're reconstructing the wrong thing. So, if you got two slices and you're going back and you're doing the wrong reconstruction with the wrong pieces of the vessel. So, you need to align those things to do accurate reconstructions. Okay, so now, we got the geometry right, now what do we do? Well, we can now reconstruct elliptical as opposed to circular cross sections. You have two views and you can reconstruct very trivially, by measuring the sizes or using the profile data to get back a 3D or actually two slices, so then you can do the 3D for along the entire length of the vessel. And Anant Gopal has done the work here. Now, in the same way that you have with the 1D, you can pull off the asymmetries, well you can also get

the asymmetries, again, in the 2D and project those back and eat inappropriately here. And what we have here is some results that he has from, I believe, the original projections and an SNR of about 10. Here's the original simulation and here's the result that we have, using the reconstruction algorithm that he's developed, using this asymmetry concept. And the deviations that you're seeing here are in the order of a 100 microns, these are the vessel size here was about 3 mm. So, with high resolution again, 50 microns, we really can reconstruct 200 micron diameter vessels. So, we can get the 3D back out. However, if you got multiple views, you can even do more, cause you got more information. Again, you have a angiographic system. Now, it turns out that single or good old fashioned bi-plane that everybody is used to and I've been, I've been touting for the last 10 or 15 years of my career, we can get away from. We can use anything that the clinician obtains, we have to obviously calibrate and know where everything is,

relative to each other, but then we can do the lumen reconstruction. So, again, the calibrations, all the standard ones you gotta do plus the imaging geometry is now a little bit more complicated, because you got a lot of use. When you use a calibration object, but basically, we don't like doing that, so we always fall back onto self-calibration techniques and over the last year, Peter Noel, also in the group, he's presenting here at the AAPM, is optimizing the 3D data that we get from the two views... or the multiple views. What we see here is, if you just do a single biplane, you get one of these curves. And then if you do another biplane set, you get this curve. So each of these curves represent a second, a separate biplane pair and what you noticed is that these guys vary on the order of 1 or 2 cm, relative to each other in their Z position, along the entire axis. Plus, not only that, the shapes are different. So, we're doing something wrong in terms of, we don't have everything aligned and correlated properly. The variations from the average central

line we would get from this is on the order of 1 cm, okay? That's just doing good old fashioned standard biplane. That's how reliable a standard biplane with our self calibration technique, with biplane, would be. However, what Peter has done, is he goes and he correlates all the information from all the different views and aligns everything along the Z and also along the axis. So, we now have the proper correlation for each view, along each vessel along this entire length and as a result, his variations along the center line are now in the order of 1 mm. And as you can see, the shapes are fairly similar. Now, what's really neat though is what I consider a head to head. We have a multiple projection set of data, and we have a cone beam, that we have now taken and fused to see the differences between the two. Now, one of these is the multiple projection and one is the cone beam. I'd like you to choose which one you like better as this thing

rotates. Now, the average difference that we have between these two reconstructions is only 1.1 mm, or 1., sorry, 1.7 mm, okay? Now, hopefully you've all chosen which one you like, I'm going to tell you the answer of who's who. The multiple projections was the red, the cone beam was the yellow. In all honesty, I had to ask Peter and he told me that I was wrong. I thought the yellow was the multiple projections for reasons that maybe some of you will see. Anyway, bottom line is a head-to-head with, it was 10 projections that are used, with standard cone beam with about 180 projections, would do a nice head-to-head and getting very, very similar shapes, curvatures, etc. So, with multiple views, we can optimize the consistency of the 3D data sets that we get back out from the multiple views. We can then combine the results for the multiple pairs of images, and, I haven't told you about the reconstruction because we haven't done that yet,

we've only managed to do the center lines. However, if multiple views is not sufficient, you can also now, go off to the cone beam. So, there's your graphic system calibration reconstruction. You should know this by now. Here we have detectors, 1K by 1K, pixel sizes, 100 to 300 microns, the detector rotates 200 degrees about the patient. This is standard II angiography. This is not high res, at least in, in my sense, but it's what's being used clinically and available now. However, you can go and use a micro CT system using a rotary stage, where the source and detectors are stationary. The object rotates so you're this guy is rotating on a rotary stage as opposed to the x-raying source and the high resolution detector rotating about it. It's easier to construct one of those babies. And here we have one from Marquette University, this is probably, I don't know, maybe Dennis would even know, the first micro-CT system that I know of that was

being used for angiography at Marquette and they have a three micron focal spot. They were using an image intensifier with a 1K, by 1K CCD, 12 bits per pixel, 60 frames per second. Now, what we get, this is our system again, this is what the UB is, so everybody knows. The high resolution detector is a 2K by 2K, pixel size 43 micron, voxel sizes, we got our choice, we can go anywhere from 10 or below, for that matter, but it's not computationally, it's too expensive to go down here, too hard, too much below that, up to a 100 micron, which is more or less what we usually use, somewhere between 25 and a 100 is what our standard reconstruction voxel size is. Our x-ray source is a 100 micron

focal spot, and what we have here, is that same slide that Steve showed you earlier, but it's blown up and you can see very clearly, the stent wires, those are easy. But what's visible here, are the stent and wire, and the mesh wires, which are about 60

microns in diameter, and the gap between those, is a 140 microns. This is the quality of the images that one can get, with this microangi camera. Now, you feed that into a CT machine. So, now, what are you gotta to do? You got the calibrations again, you gotta take care of distortions, pin-cushion and now there's something called the S-distortion, which comes in because the earth's magnetic field. And again, we have to do the imaging geometry. You always gotta know where everyone of those x-ray sources, imaging systems are relative to one. You have to define a coordinate system and you always have to know where everything is and therefore, you always have to calibrate. Every one of the manufacturers has a periodic calibration they have to perform, but again, we have self calibrations techniques, because we're basically lazy and we won't want to do the calibration all the time. We want to do it on the

images. So, what we have here, this is now the image, you can see changing, the reason it's changing is, the images actually of the, the image intensifiers rotate in the earth's magnetic field and the change of the field, because of the, the x-ray, the electrons moving through the II, and actually, you can see an S-shape, that's where the S-distortion name comes from. The image on the right, though it's not really contrasting enough, and the lines aren't perhaps big enough, but basically what you see are the paths of the various points within the image, as the image intensifier moves from the 0 degree to the 200 and what you can also possibly perceive is that the various path, paths that are being taken are different, depending on your location, within the II. So, this is again, something that has to be taken out and taken into account or not taken into account, but taken out, removed, before you actually start doing real 3D. So, again, you can use

calibration objects, Fahrig and Holdsworth back up in the University of Western Ontario have done stuff with helical phantoms and but, again, our group likes to use the images themselves and Ravi Chityala just presented in the adjoining suite, his technique for the calibration of the Micro cone beam CT System, using the images themselves, And basically he lines the reconstruction axis along with the rotation axis in his algorithm and what you see is, if you take a slice through the data set, there's a reconstructive data setup error. You take a slice through. If you don't do the calibrations or if you're misaligned in terms of your reconstruction axis, and your actual axis rotation, you get artifacts like rings for the high contrast objects and you get double boundaries that you see in here. However, after you align everything properly, you get nice sharp points here, and the double boundaries basically disappear. So, types of images you get? This

is a aneurysm phantom that we're just moving our way through. The little black dots are the stent wires and the aneurysm and the vessel wall was shown as we moved down. Here, we have a contrast filled stented phantom. I'm gonna stop it and the little dots that you see here are the stent wires and if you watch carefully there's gonna appear a kind of whiter, brighter region, which is actually the mesh, as we go through. Over here, we have the same one with the microangi, the dots are much tighter, once again, we have

higher resolution. This unfortunately, is not contrasted or no contrast filling, this is with contrast filling, so it makes a little bit more difficult, but basically, I think you get the basic idea. Okay? Now, once you've got that, you can do maximum intensity projections and actually this is a minimum intensity projection, of the aneurysm phantom with the stent in there. And here, you can actually do slabbing where you can extract this region

we're interested in looking at the orifice, to see how much coverage we had, which we'll get to in a minute with quantitation, but using this type of extraction of the information, you get a very clear idea of where things are positioned relative to the objects of infrastructures, such as the orifice. These images here? Are from a cerebral actually it's a vertebral aneurysm. From David Holdsworth and his lab, the rotational Angio System, there's nice vessels out here, but their pixel, voxel size on the order of 400 microns so the vessels that you're seeing are on the probably on the order of .5 to .6 mm in diameter, but rotational angio gives very, very nice images, if every thing is well calibrated. Here we have some images from Anne Clough out at Marquette, with their high resolution micro CT. This is a rat thorax and you can even see the beating of the heart. And then, sorry, over here you can see the vessels, very clearly, moving down, on the, if I didn't

know any better I'd say that was a human thorax, my limited knowledge of radiology. Here we have for reconstruction of a mouse heart using our system, with some contrast and the reconstruction that was rendered, using volume renderer. You can see some of the vessels there, and some of the other vessels, clearly seen there. So the rendering is all nice. You can make very, very, pretty pictures with the current status, but that's not where we're interested in going. We're more interested in the quantitation. Here we have again, some images from Anne Clough, isolated rat lung. They have the perfusion study. Looking at the vessels, you can see all the very tiny vessels, inject the contrast, get the images, look at the time density curves, for each of the, each of the little vessels and vessel regions, and they can actually get microvascular transit times and they're doing some really nice ground-breaking work with regard to what's going

on in the mouse lung, in terms of, of the vessels and the transit times. Here again, shooting from Anne Clough, really nice pictures, down to the third, fourth, fifth generation vessels. Here that you've seen in the, in the rat lung. Here's 2 mm that you get a feel for the quality, all the way down here, you see down to 45 microns, the vessels that they're seeing and the result of when you take it perpendicular, perpendicular versus in a arbitrary axial planes, say, in terms of the quality of the, the vessel lumen. Very high resolution, very, very pretty pictures, but more importantly, these are images that we can now quantitate, we can actually get numbers out of these and start talking about were things are, how much stenosis, whatever, is in the vessel. This is a 3 mm vessel phantom, that we created, so we can get high resolution 3D, of the vessel lumen, and actually Anant, with his two view technique is gonna go head-to-head, before he

graduates with this and my guess is, that he's gonna do a very nice job. Definitely within a 100 microns with the two views, but with a multiple views of the micro CT. Excellent! Really beautiful quality information, at the high resolution, so we're gonna be

able to be looking at what's going on with those vessels, when we do the aneurysm, when we, we create stenoses, etc. Not only that, but we're gonna be able to look at orifice openings. Here I've taken that slab view that we had before, and this is where the white region was, so we can now quantitate how big the orifice is, what its shape is, etc., by doing some simple analysis of the 3D. Not only that, but we can actually calculate the coverage. In fact, it was an interesting story, because Steve went with optical and said "Oh, the stent only had a coverage of about 20%." And we kept coming back with about 33%. It turns out that in our calculations, we were doing the cross stents here, so we

were higher. Once we took those out, we were down to 22%, in good agreement with what Steve had measured with his own eye. So, in conclusion, all the way from single projection to cone beam rotational angio, you can get accurate high resolution vascular data. The accuracy depends on the resolution and the calibration. I can't emphasize this enough, I mean the high resolution, you can always get better resolution, but the trick, the trick of getting good 3D is really in the calibrations. There's lots of other stuff going on at the higher resolution and the rotational Angio with regards to hearts and things like that. I think a lot of that technology that they're learning, what to be doing with that, and how to do the things right, in terms of gating and everything is gonna come into the smaller domain. I think high resolution angio and high resolution 3D is gonna change the way we think about doing animal studies and how they're

gonna feed back into the humans. So, and I'd like to acknowledge the various people who supported us, and in addition to the AAPM for their invitation. Thank you very much.