Thanks Jeff. The next few minutes I'll describe to you some of our work in developing robot-assisted 3-D ultrasound-guided brachytherapy system. It follows naturally after Mike Meniere's talk and he describes some of the applications of robotics, needle-guidance and tracking and I hope I'll be able to cover some of those points in this application. For this audience, I don't think I need to dwell too much about current prostate brachytherapy. We all know that it involves multiple steps at those planning phase and implantation phase and in evaluation phase of post planning phase. This company's centers are developing ways and approaches to these steps. Some of them are now intraoperative, in other words, a few of these steps can be integrated into a single intraoperative procedure. I'll describe to you a plan to integrate all of them. But

basically, current brachytherapy involves a procedure that looks very much like this and in fact all systems involve some form of template for which the needles are inserted and the seeds are dropped in the permanent implantation procedure of the prostate and you see the rest of the anatomy. So, basically the ultrasound transducer is used to collect images. The template is used to localize the needles so they are inserted in the right locations. These steps are by and large manual. So, what I'll describe to you is some of our attempts to remove some of the manual components here and develop the automated or semi-automated approaches to producing a complete procedure. One of the issues that we're trying to solve is pubic arch interference. Many patients have enlarged prostates when they come for evaluation and before they can undergo brachytherapy, they have to

undergo prostate reduction and size procedures, some antiandrogen drug therapy which may last quite a few months and in fact in some cases there are some patient's who will not be able to be implanted with brachytherapy seeds because the prostates are too large. From trajectory through a template, the pubic arch may interfere with some of the agents of the prostates. So, this is one of the issues, we're also trying to solve; not only just automating the procedure, but also try to avoid pubic arch interference or at least reduce that effect. So, basically the problem we're trying to solve in our work is avoid or reduce pubic arch interference, avoid multiple imaging modalities, be able to track changes of the prostate through the procedure and reduce the manual aspect of the procedure. And our solution is to develop a complete intraoperative procedure with no **recto**-linear

template and dynamic replanning; continuously planning with automated tools. So if the prostate is changing and swelling for example, the seeds are misplaced and the needle is misplaced, all these issues can be dealt with as fast as possible, at least automatically or semi-automatically. So, our approach is to integrate these components: robotics for oblique insertion to avoid or to reduce pubic arch interference, also for improving the placement of the needles, avoiding this kind of template approach, 3-D ultrasound to be able to collect images very rapidly, monitor the complete prostate, not just a few slices, be able to monitor the needle in 3-D, in 3-D locations, be able to track the needle, guide the needle and track the needle and software tools for segmentation tracking and dosimetry. So, basically software tools to do the segmentation of the prostate and the seeds for post-planning. So, this is our hope or plan and I'll show you where we are in this and some of the components we have developed already. So, this is a blocked diagram. I only show you this because, just to show you that each module involves a graduate student and a thesis. So, my students will be happy to see that their work is actually being shown here; basically, the ultrasound machine mechanical approach to 3-D acquisition, the robotics visualization segment and a lot of software tools. So basically we have all these kind of modules to interface to the ultrasound machine, to control the ultrasound transducer, to control the robot, of course registration, dosimetry, tracking, segmentation and so on. So, I'll describe some of these modules very quickly. The 3-D

ultrasound component essentially, and in this picture where the physician is holding it, but it's actually mounted in the brachytherapy jig. So, basically it's a conventional ultrasound transducer mounted on a motor, essentially, this is the stationary component, which is either clamped or in this case held, and the rotating component is this part. So when the motor is activated, the transducer rotates in the rectum through whatever angle; we want something like 100 degrees or 90 degrees in a few seconds. We collect images at 30 frames per second and build a 3-D image as the images are acquired. So, this is after the images have been acquired. We get a 3-D image, which we can navigate and interrogate the image. We use this for diagnostic applications and in this case, for therapy planning. So, this shows that we can see planes and the image that cannot be seen

in any other view. There is the tumor in the **<u>semi</u>**-coronal section, which can't be obtained from conventional ultrasound imaging. So, this kind of image, we can now obtain in four seconds. So, this can be done continuously and visualized and the next thing of course, is to outline the prostate to somehow determine the margins of the prostate. Well, the fact that we have a 3-D image, we thought it would be more accurate than individual slices or individual approach, so we tested our 3-D image for volumetric measurement and the results are shown here where we can, the fact that have a 3-D image allows us to get quite a precise measure of volume. So, this is a manual tracing technique in which I'm showing you the minimum detectable percent change at the 95% confidence level. So, using 3-D ultrasound you can see intraoperative variability is about 15%. This

is 95% confidence; Non-radiologist, one of the graduate students, but the same as a radiologist. So, the fact that we have 3-D images shows us that we have enough 3-D information for non-trained operators to be able to be as accurate or in this case, as precise as a trained operator in determining the margins of the prostate and this is for volumetric measurements. However, manual tracing is very tedious and we certainly cannot do that intraoperatively. So, we developed a semi-automated approach. It's based on the formable model and our approach is essentially the operator places four points on or five, but typically by four points of the margins of the prostate in one slice or one 2-D image of the prostate. So, by placing four points, we develop algorithm places of boundary, a first guess and then using the formable models, it's essentially, the

boundaries deform to fit the margins of the prostate and this happens very quickly. This is of course in the 2-D image and we have done this, extended it to 3-D, since we have a complete 3-D image. First, we tested accuracy and variability of this approach and basically we are within the variability of a human operator. The accuracy means the mean difference between the algorithm and the human is about 5%, where accuracy is 95%, which is within the variability of the human operator. So based on these kinds of results, we then automated a procedure into 3-D and there is an example. This is the video, a real time video of the whole procedure you saw in 2-D and then propagating into 3-D by serially slicing the prostate. That's the whole segmentation. It's completed and now the operator is checking to make sure that the all the margins are correctly outlined.

If there are any errors, then the operator can edit the margins. All this also took about three or four seconds. So again, this can be done quickly and there are the margins, individual boundaries of the prostate. Again, the user can interrogate them, look at them and decide if they are correct and resample them in parallel slices and again decide whether they're correct or not, and again, these operations take seconds and the next is **explore** this to the dose planning procedure, which of course you all are familiar. There are just a couple of views, but the end result is the plan in which we allow oblique insertions to avoid pubic arch interference. So, there is an example of a preplan based on this kind of segmentation approach with allowing oblique trajectories in two dimensions. So, you can see the needles are splaying out in the lateral direction, as well as in the

vertical direction. So, based on these trajectories, now we can carry out the implantation. So, here are a couple of big examples, in which have inserted needles into the patient, but in this case in cryotherapy approach, just to see what problems we will run into. So, this is combining 3-D imaging and the needle guidance and tracking. So, there is an example where the physician inserted a needle using 2-D ultrasound guidance, using the conventional approach and then we perform the 3-D scan to see what the best practice of the physician, whether the needles are actually inserted in a straight line and in fact in some cases we could see that even though in a 2-D image it appeared that the needle is going straight, in the 3-D image, it was going at an angle and the reason for that is that the ultrasound image has a finer thickness, in fact, the elevation or resolution is relatively

poor. So, if the needle is angled within the thickness or the width of the ultrasound beam, it'll appear as if it's going straight, but in reality, it's at an angle, and one would never know that unless one had a 3-D image. So, in fact, in the cryotherapy procedure when our physician noticed that he's actually inserting needles at an angle without knowing it, he's gone over to a 3-D verification approach in cryotherapy. So in this case, this is one example where it's going at an angle and then he removed the needle and reinserted it and now it's going in a straight line towards the seminal vesicle. So to guide the needle, at least align the needle and guide it into the prostate, we are introducing robotics into that. So, there is the head of the robot, it's a commercial robot, 6 degree of freedom robot used for just testing of our integration, just to see if we have the precision and accuracy of

integrating 3-D ultrasound and robotics and getting needles and seeds to the right locations. So basically, the approach is the use the robot to position the single hole at the right angle and position and insert a needle manually. So, that's the task and there's the phantom and the results of these. I'll just show results without many figures and basically the first issue is 3-D transrectal ultrasound image calibration, in that the collaboration of the image quality of the image distortions are present, of course everything will be incorrect. However, there are uncertainties and basically the mean error is about 0.5 mm with the maximum displacement within the image of 0.7 mm. And the reason for this level of error is due to the lack of, well, the resolution of the ultrasound image, making measurements in ultrasound images is limited by of course the resolution.

Robot collaboration shown here, basically telling the robot to go to a certain location and testing whether it's gone there; again, with this kind of system, it's about 0.56 mm of the robot calibration. So combining the two and placing a needle at the patient's skin; not inserting it just at the patient's skin; so basically we're planning where the needle would go to the skin and then measuring where it is, is highly accurate but 0.15 mm. So, it's not using the ultrasound information. It's just the robotic information and then angulation isn't important, so again, the robot angulation is highly accurate. I won't go through the numbers, but vertical and horizontal angulation is very accurate. So, the next part is then testing the accuracy of implantation with combining all the errors, all the system errors and then localizing a point in a phantom, which involves 3-D imaging causing the robot

to align itself and then manually inserting a needle into the prostate. So, we tested that by these phantoms, **___**-based phantoms, which matched the velocity of sound and tissue and we placed a number of these beads, target beads at different distances from the transducer. In other words, close to the transducer for higher resolution ultrasound imaging and far from the transducer, shallow insertion and deep insertion on all these, because ultrasound images and resolution is non-isotropic and for the one inserts, the greater the chance for needle deflection. And the end result, I'm showing you one of these results and basically what I've plotted here is the scatter plot of where the needle tip ended up in the phantom, where 000 is the target position and the red dots are the actual position. So, basically we get a 3-D scatter plot of the locations of the needle tip relative

to the target, in which you see here and they ellipsoid is a 95% confidence interval, a 95% ellipsoid, encompassing 95% of our targets and projections on the orthogonal access. So, you can see that at a 95% confidence interval is of the order of about 0.7, 0.8 mm. Essentially half, that's at 95% confidence; about 2 sigma. So, combining all the errors, the result is still, well you can see the order is quite good within about one or so millimeters. The next problem we have to address is the fact that if we're inserting a needle obliquely, it'll cut through multiple planes. In fact, Mike Meniere showed that in the CT application one would have to extract multiple planes and see the needle going through each plane and by a form of triangulation, find out the trajectory of the needle, but we want to do this in real time, basically extract the needle entering the patient in an

oblique trajectory. So, here's the schematic, there's the transducer producing images in a sort of a open book fan. As the transducer can be rotated; those are the images, however the needle can go in at an oblique angle to these planes. So, we have developed an algorithm to continuously scan the needle as it's going in and extract the needle and display the needle in orthogonal planes, just as shown here. So, this is an **AGA** where we can see the needle going, these are reconstructive planes, extracted planes. We can see the needle is quite accurate and in an actual patient, we again tested this in a cryotherapy procedure as we insert the needle. The ultrasound transducer is slowly rotated and the algorithm segments the needle and extracts it, displays it to the physician as it's being inserted on the oblique trajectory. So, we see the needle in a coronal plane and a sagittal

plane in a sorta 3-D image with a history of the trajectory going in and the physician can stop and interrogate the volume anytime, as well as volume rendered image. Since we have a continuous 3-D image of the needle as it's going in, we can have a continuous volume rendered image to see the needle and the segmentation. So, the white line is this image of the needle and the yellow line is the segmentation. So, the physician can continuously track whether we have not made an error and see the trajectory of the needle as this is progressing. The last phase of course is a post plan where the seeds, so we're attempting to develop a procedure to segment the seeds from a 3-D ultrasound image. So, this is the way it looks like. You can see the cross-sectional section of the prostate with seeds, but they are the 3-D images. By navigating through the image, we get a much

better sense of the seeds. You can see multiple seeds are laid along lines. So, our belief is the fact that we have high quality 3-D images of the prostate with seeds, we'll have a better chance to segment the seeds from ultrasound images. From 2-D images, it would be very difficult because we see some seeds but we see artifacts and some seeds, well we can't tell if they're seeds or calcifications, for example, but since we have a 3-D image and they're aligned in certain trajectories and certain lengths and so on, our belief, that it'll be easier. So, this is a dynamic view so you see what I mean. There's just a static image, but the fact that we can interrogate the image in various ways, there's a chance for developing algorithm's to extract those seeds. So, we're just navigating through the volume just to give you an impression of how the seeds look like in a 3-D ultrasound

image. So, this is a recent example where we have segmented some of the seeds where this is an incomplete project. We're still progressing; we are segmenting and finding about 80% of the seeds. Our algorithm hasn't been able yet to segment or to find more than, well target is at 95%, but we're about 80% and you can see some cases where visually you think there's a seed, but the algorithm is not found, but we're getting closer to our goal, but not there yet. So, in summary we can see needle placement accuracy is of the order of 0.14 mm. The angle also is very accurate using this kind of approach. Needle targeting accuracy at a 95% confidence interval, we can get a volume described by this ellipsoid, but 1.5 mm by 0.8 by 0.2 mm ellipsoid. 3-D segmentation and accuracy, at least it's different from a human operator by about 5% and as I said, it's

within the variability of a human operator. Needle tracking accuracy, we have tested that and it's where the tip can be tracked with an accuracy of about 0.8 mm and 3-D dose planning with oblique trajectory showing you that, although that has not been validated yet, and the seed segmentation and dynamic replanning, but dynamic replanning is quite easy, but the seed segmentation is in progress. Thank you very much for your attention.