Well, good morning everyone. I’m Tony Seibert from UC Davis Medical Center in Sacramento, California and I’m going to be spending the next hour talking to you, and with you, hopefully, about digital fluoroscopic imaging. This is part 3, of a 4part series on fluoroscopy. In part 1, we actually saw a very nice overview of fluoroscopic imaging from the applications point of view and some of the issues related to how fluoroscopic imaging systems are used. Yesterday, we had the overview of issues related to dose and today, we’re going to talk about some of the digital aspects of fluoroscopic imaging, with respect to real time processing and display, as well as the acquisition part. What I’m going to talk to you today about is, we’re going to look at the introduction to digital fluoroscopy, look at some of the components that we need to be able to digitize the image information streaming from the image intensifier or flat panel display, take a look at analog and digital image characteristics and how they impact image quality and the way in which the images look, image digitization, take a brief overview of quantization and sampling and what the impacts of those issues are on the image quality, go into an overview of image processing from the point of view of being able to do edge enhancements smoothing for specific purposes of improving image quality, as well as quantity, and summarize the overview. In terms of the history of digital fluoroscopic imaging, it’s been around since about the mid-1970’s. I, myself, was very fortunate to be in that time frame, where I was able to get a, or advanced degree based upon the implementation of digital subtraction angiography and the way in which we can quantitate and use the quantitative characteristics of DSA and digital fluoroscopy. In the mid-1970’s, we were a little bit less behind compared to where we are today. There was a modified II TV system, using the analog output and with reasonably fast, at the time, analog to digital converter circuits, one was able to digitize the video signal very reasonably and from that perspective, we’re able to do temporal energy subtraction methods. The individuals that were really important in the implementation of DSA were chiefly from the University of Wisconsin and also, the University of Arizona, at the time. Chuck Mistretta was a superstar and he was one of those that implemented DSA with his graduate students. In the mid-1980’s, we finally reached clinical DSA angiography, in terms of being able to have a clinically implementable digital system and during that period of time, there were many qualitative and quantitative improvements in the ability to use DSA and digital angiography in an optimal way. Subsequently, we’ve had an opportunity to improve image processing, and. as well as implement some interesting temporal and recursive filtering techniques and I will describe some of those as we go through the presentation. In the 1990’s, we’ve seen a lot of quantitative correction of image data rotational fluoroscopic imaging, whereby you can get a three dimensional sense and Phil Rauch did a really nice job on Monday showing some of those images. Microfluoroscopic imaging capabilities, Steve Rudin and others have done some interesting work on being able to improve spatial resolution for the delivery of very, very fine microcatheter materials and stents and the like. CT fluoroscopy is now becoming a reality. Cone beam CT reconstructions using a rotational and reconstruction capability and since 2000, when we look at the historical development of where we are today, the introduction of real time flat panel detectors, which we're going to hear a little bit more about tomorrow, in terms of how these have changed the scope of digital fluoroscopy and what we're going to be doing in the future. Well, I guess the first thing that we need to do is "Well, why digital?" I think there's many reasons why and I've put a list of those reasons on the slide here. Low dose fluoroscopic imaging is achieved by doing temporal averaging; last frame hold types of applications, as Phil nicely showed on Monday. Pulsed fluoroscopy and variable frame rate would not be possible without digital acquisition and, of course, in interventional angiography, DSA has really changed the

scope of the way in which the practice of interventional radiology has been implemented over the last 20 years. Digital image processing and quantitation are certainly aspects that, hopefully, I will show you today; how we take this to advantage and now, as we're moving into an all paperless environment, image distribution and archiving and picture archiving and communication systems interfaces are extremely important and if we were still in the analog world, we would not be able to capture this information. So, let's take a look at the digital fluoroscopy components. This is just one example of the many types of fluoroscopy that can be implemented and Phil went over this in a little bit more detail, but let me just refresh your memory and for those that didn't have a chance to see his presentation. The fluoroscopic system is typically comprised of an image intensifier

coupled to an x-ray tube; the patient in between the x-ray source and the detector. The image intensifier is the mainstay of being able to increase the information content with a huge amplification, so that we can use relatively low exposure rates to the patient to keep the dose low and at the same time, produce a non-limiting brightness image that will provide us with very good temporal resolution, albeit, with a noisy demonstration of information in the still frame sense. The issues are related to dose that Keith (Strauss) went over. We need to keep the dose relatively low and we're doing this in a real time format. If we take a look at the image intensifier itself, and go in at a cross section, if x-rays are coming in to the image intensifier, they're going to impact upon a scintillator phosphor, typically made up of cesium iodide and if we could blow up a small section of

the input phosphor, we would see that the cesium iodide input layer would be coupled to a photo cathode. As x-rays interact with the cesium iodide, electrons are released in proportion. As a result of the electrons being charged, an amplification of the electrons as they stream from the input phosphor to the output phosphor under a potential difference of, typically, on the order of 25,000 volts, will improve the number of, increase the number of light photons coming out at the output phosphor, as the electrons interact and impinge upon the zinc cadmium sulfide output phosphor, so we get a huge amplification of light. That light is then, subsequently, focused on to a TV camera and that TV camera signal is then, subsequently, digitized. In this particular case, we also have a light limiting aperture that will allow us to change the speed of the image intensifier by reducing or

increasing the amount of light that is actually allowed to be directed towards the output system, the TV camera, typically. And that TV camera could be an analog TV camera or a CCD camera. In the analog to digital conversion process is one area in which we're able to digitize very nicely that TV camera output. One of the really nice things about the image intensifier and the flat panels now, is the use of structured phosphors, in which, we can overcome some of the trade-offs that must be made in a conventional sense when we look at the quantum detection efficiency versus spatial resolution. Usually, there's a trade-off; as we want to increase the quantum detection efficiency, we sacrifice spatial resolution. But, with cesium iodide, which can be grown in a structured crystalline format, one is able to keep, as x-rays are interacting, keep the light photons that are produced as a result of the x-ray interaction, pretty nicely collimated, so that the spread of light is minimal, and therefore, we can have high detection efficiency simultaneous to reasonably good spatial resolution. So, when the TV camera produces the output signal, the light coming in to the TV camera target; it being a photo conductive target, one is able to create a corresponding signal in terms of voltage, that is produced by the TV camera, with an electron beam that scans the photo conductive characteristics of the TV camera target and as a result, we can get a continuous variation in video voltage that corresponds to the variable light patterns that are produced during the acquisition process. And, once the analog signal is produced in the conventional sense, without any digitization in this process, one is able to recreate the light image, as a result of a cathode ray tube and an electron beam that is modulated by the video voltage, producing a corresponding variation in light output at the video monitor. With respect to the TV camera, if we look back historically, we've been chiefly been using 525 line TV cameras. This is a low resolution TV camera with the RS170 video format. It was, it is a 525 line interlaced 30 hertz camera. These are now giving way to high resolution, higher resolution, thousand line TV cameras and CCD cameras. In the case of the 1000 line camera, which is typical in today's digital fluoroscopy systems if, in fact, an analog TV camera is used, 1023 to 1049 line 30 hertz operation and there are some digital systems that have 2k (2000) line systems. As we go through the process of converting the image information into a digital format, what we have found, over the years, is that interlaced operation is just totally suboptimal for the acquisition process and progressive scan is a must for short pulse with digital applications. And that's as a result of the fact that, we no longer are limited by being able to produce a 30 hertz signal by an interlacing process that can reduce the bandwidth. We're not band width limited anymore, so we need to use progressive scan so that we can get really nice last frame hold images and the like. Now, when we go from the analog world to the digital world, we see that there are two decades of availability of digital systems that we have now. The video signal is convenient for digitization simply by taking that video voltage variable (signal) that I showed you in a previous slide and just simply, digitize it. And I'll show you how that's done. The low noise performance of II's, really provides a relatively high detective quantum efficiency and high signal to noise ratio as a result of the massive and relatively noiseless amplification of the signal by that process that I described in the previous couple of slides. There are very well developed capabilities now; II DSA digital photo spot and even rotational CT. CCD camera implementations are overcoming some of the limitations of the analog camera implementations and improving the dynamic range somewhat. However, as we're seeing into this new millennium; beyond the year 2000 , the II is being replaced by flat panels and the reason is, that they are big and bulky; it takes a very large device to be able to get that amplification into a reasonably noiseless output. So, we see flat panel fluoroscopy and fluorography coming online and it's based upon thin film transistor erase systems that can store, charge and read out the information

in an active matrix, and I think we're all becoming more and more familiar with these devices. I'm going to give you a brief overview of how they work. The thin film transistor rays have been proven, very nicely, with radiography applications and now they're available in fluoroscopy. There are two different versions of the flat panel for fluoroscopy. Cesium iodide indirect conversion and amorphous selenium direct conversion systems. The way the TFT active matrix array functions is, through the use of an array of photo diodes coupled to a thin film transistor array and in the indirect sense, we have indirect detectors, a scintillator, who's going to convert x-rays into light; the light is going to fall upon a photo diode and the photo diode is going to create charge that's proportional to the incident light. So, if we could blow up this photo diode array,

the individual components of the thin film ……transistor array are the transistor itself, which is a switch, a charge collector electrode and an indirect system as a photo diode and in the direct system, the amorphous selenium is just simply a charge collector, a storage capacitor, which stores the charge that is produced and that's on a pixel by pixel basis and gate switches. The gate switches are used to be able to turn on the transistors one row at a time and then drain the charge, so that we can get an active readout and then the data lines and the charge amplifiers, and the charge amplifiers are ones that will increase the signal relative to the charge that's being captured and then, that signal is then, subsequently, converted into a corresponding digital value. One of the things that must be considered, although there are new

technologies that are overcoming some of these issues; the active area is the collection electrode, in this case, a photo diode, the dead space, which incorporates a lot of the lines and the transistor array and the like, is the dead zone and there's this concept known as the fill factor and the fill factor is dependent upon the ratio of the active area divided by the active area plus the dead zone and you can see that we're going to have a loss of the ability to capture signal as a result of the dead area and the fill factor is going to have a consequence on the ultimate detective quantum efficiency that can be achieved. How does is work? Well, if you expose the TFT to x-rays, there are going to be variations in charge that are produced as a result of the corresponding number of x-rays and, therefore, light photons falling upon each individual charge collector. To read it out, the charge is

stored in the storage capacitor, then we read out the charge by turning on the gates and the gates turn on each of the individual transistors. The charge that's stored in the capacitors will go down each of the individual lines, the drains, to the amplifiers and we do that row by row by row, building up the image into the digital image matrix. And if we could take a look at the cross-section of the amorphous silicon TFD with the cesium iodide, x-rays interact, light is produced, the photo diode converts that light into charge and that charge is stored in the storage capacitor. This is known as indirect x-ray conversion. And in terms of amorphous selenium, which actually can do fluoroscopy quite nicely, as well, one can produce electron whole pairs within a selenium photo conductor and this is a direct conversion of x-rays into charge. The charge is stored on charge collection electrodes and then, within the individual storage capacitors for the individual thin film transistor pixels and in this particular case, we have direct x-ray conversion and because of the way in which these charges are acquired, one can achieve very, very high resolution and have still, a relatively thick photo conductor material that converts (x-rays into charge). If we want to look at the comparison of flat versus, what I call fat (the image intensifier), one of the things, and I'll show you in the next couple of slides is, that with this digital flat panel capability, the dynamic range is increased, because the limitation in the conventional II TV system is actually the TV camera itself. There is no distortion. The detector size is very compact and relatively low weight. The image area is square, compared to the image intensifier, which is round and when we take a look at image quality, they both have reasonably good image quality. The DQE of the image intensifier in, at least, within the high exposure region, is limited by electronic, more by electronic camera noise, where in the image quality, the DQE, with the flat panel detectors is limited by electronic noise at low exposures. Taking a look at the dynamic range then, if we look at the digital flat panel, it has a relatively large dynamic range and a small noise floor, with respect to the II TV system, particularly with analog cameras, and not so much with CCD, but the video signal has to be incorporated over a much smaller dynamic range and the use of a light limiting aperture is very necessary to be able to achieve a reasonable light output. One of the really nice aspects of the flat panel arrays that we're going to be seeing more and more, is the fact that the square array area compared to the circular array; the fact that we have the distortions in the image intensifiers due to a curved input phosphor and a planar output phosphor, which results in pin cushion distortion and geometric non-uniformities, where as the flat panel, is, actually, very nicely non-distortion; doesn't have very much distortion in the output image. Another issue is; when we look at the image intensifier, which does have a circular output; one has to frame the information, the digital sampling matrix, within a compromise situation, where we can get all of the vertical information or all of the horizontal information, and you see we're trying to fit a rectangular or square array into a circular format or we can do over framing. And the bottom line here is; if you take a look at the trade-offs that must be made, which aren't necessary with a flat panel, if we have maximal vertical framing, we are going to be able to record all of the area, but the percentage of the digital digitization of the signal is only 41%, with this particular type of framing of the digital matrix. Maximal horizontal framing is a compromise, where we lose a little bit of the recorded area versus the utilization of the image matrix and if we go to maximum over framing, where we want to make sure that we get everything incorporated into the digital sampling matrix, one is able to have to sacrifice the amount of recorded area that would be used, although you could collimate to within that area. So, the bottom line here is that there is a trade-off of field of view; not necessarily so, or not so at all, with respect to the flat panel detector. Just a couple more remarks about the flat panel versus image intensifier. One of the really nice things about the image intensifier is its gain; five thousand to one and more, in terms of being able to take a very low light, very low intensity of x-rays converting to a non-limiting output image, in terms of a corresponding light value. The flux gain is the chief advantage of the image intensifier as we see it today. And what that speaks to is the fact that the flat panel systems do have a bit of a problem at relatively low x-ray intensity values, where the electronic noise does seem to make it not nearly as nice as the image intensifier. So the gain noise advantage goes to the II. However, in terms of the other aspects of flat panel imaging, as we saw, as we heard about yesterday and the day before, one of the nice aspects of the flat panel is that one can pixel bin and one can use a similar situation with respect to the mag modes and image intensifier by simply doing pixel binning. Do one pixel equals one pixel or two by two area equals one pixel or a three by three area equals one pixel, so that we would have a mag mode, a intermediate mag mode and then, a non-mag mode and then a large field of view, where we would pixel bin, for instance a three by three area. And that would offer improvements in terms of the effects of noise in the output image. It’s predicted, and I think that this is going to happen more and more quickly, is that the II’s are going to go the way of the cathode ray tube, in terms of how we display images. Now, with respect to the interventional system digital hardware architecture; whether we use a flat panel or an image intensifier TV system; there are a couple of key components that we need to know about in terms of how we can acquire an image, convert it into a digital value, into digital values and then do subsequent image processing and then reconvert that into a displayable image. There are various sub components of an interventional system digital hardware capability. The x-ray system, obviously, has to be interfaced to the image intensifier or the flat panel; acquiring images, synchronizing images; having a video memory that will be able to acquire the images in a wide range of different formats. There is going to be a lot of image processing that’s done on the images and I’ll show you some of those image processing techniques as we move forward in this presentation. And, another area is the ability to get the digital image information out, in terms of DICOM interfaces, HL7 interfaces for modality worklist functionality and patient images reconciliation in the PACS and then the subsequent distribution of those images to the clinicians that are going to be reviewing these images. If we take a look at analog versus digital characteristics in the next step of this presentation; the analog image is a continuous brightness variation that corresponds to the differential x-ray transmission of the object. Here is a very, very simple object. The image intensifier area and a lead disc placed upon the central area of that image. In a conventional system, what we would do is use a TV camera to scan the generated light that is focused on to the TV camera target and by doing so; we’re actually discretizing the image, even though it’s in an analog sense. So, if we take a simple line that is going to sample the photo conductor properties of the TV camera target, it’s going to be created. What it’s going to do; is it’s going to create a variable video voltage that is going to correspond to the variations in the light intensity across that particular sample point (line). And in this situation, what we see, is that we have video voltages that correspond to the x-ray incident flux and underneath the lead disc, where there's supposedly no signal, we're going to see that there is some signal due to a phenomenon known as veiling glare and then we recreate the image based upon the analysis and the reproduction of the image using this video voltage signal. There's 39 microseconds that's typically spent across one particular line for an RS170 image output. This is a single horizontal line. So, in terms of how we're going to take that analog image and convert it into a digital image depends upon two issues: contrast resolution and spatial resolution. And as we see, that when we digitize the image information, the ability to maintain that contrast resolution is going to be dependent upon how we quantize the data and the ability to render the adequate spatial

resolutions depending upon how we sample the image. So, we're going to now take a look at some digital image requirements. Instead of looking at it in terms of a raster scan, now we're going to discretize in two dimensions, across the lines, the video lines, as well as within each row, we're going to discretize and sample the data in time. So, we have 39 microseconds to sample. We have a certain video band width; that's output and we have to sample at least twice the video band width in order to ensure that we have the adequate image information in the digital representation. So, when we look at the information display across one line, the integer values are going to correspond to the video voltage signal, which of course, corresponded to the incident x-ray flux in the first place. So, now we have a digitized video signal that corresponds to the information process. So, there's

two things that have to be done in order to achieve this. We have to convert the analog signal into a discrete digital signal, and then, we have to do that by the process of digitization, meaning sampling and quantization. What I want todo now is take you through some of the aspects of how one samples. One of the things that's going to occur when we create a digital image is, we're going to be dealt with some advantages and disadvantages, in terms of the way in which the digital image presentation can be displayed and manipulated. Obviously, with respect to digital imaging, we have separation of acquisition and display and that allows us to do a lot of interesting things. Some of the disadvantages, and this is really not thought about a lot, is the fact that noise and data loss does occur during the digitization process and I'll show you how that occurs

and the issues are quantization sampling and electronic noise, shot noise. The consequences of digitization: losses of spatial resolution, loss of contrast fidelity and aliasing of high frequency signals. Phil showed a really nice example of how aliasing occurs and I'll show you my version of that, as well. Some of the positive aspects are processing, distribution and quantitation. So, let's take a look at the image digitization, which means quantization and sampling. Our acquisition; the fluoro unit produces a continuous analog video signal and we have to convert that into a corresponding discretized digital characteristic (signal) and we use the analog to digital converter to do that. Processing occurs, by which we can use hardware and software algorithms to enhance, to image process the information and then what we have to do is get that

information back out to the human viewer by converting the ~~continuous analog signal~~, the discretized digital signal back into an analog version so that we can view the information. And this acquisition process, display and storage are all separate aspects of being able to do that within a short period of time. So, let's take a look at sampling. Sampling is going to measure the analog signal at discrete time intervals and what we're going to find, is that in order to avoid the concept, or the consequence of aliasing, we need to sample, at least, two times the frequency of the video band width. So, if our video band width is 10 megahertz, we need to sample the signal at 20 megahertz. Quantization is the ability to convert the amplitude of the sample signal into a digital number and that's determined by the number of ADC bits. Sampling is just signal averaging within the detector element

and the cutoff sample; if we look at discretizing, in terms of along the rows and along the columns, we have a discrete area delta x, delta y. There's a concept known as the cutoff frequency, which is just, simply one over the distance (delta x) within either direction. The Nyquist frequency, and this is that factor of two that we need to ensure that we do not have any aliasing, is equal to one over two times delta x. So, that means that we're going to lose some information if we have object sizes that are smaller than this frequency, known as the Nyquist frequency and they're going to be aliased back into the low frequency domain. Let me just show you how one might sample and what are the consequences of sampling are. In the upper column (row), we have a sampling aperture that's quite large. This might be a three by three bin of a flat panel display, for instance.

And the sampling aperture; what's going to happen is, is that within the center of each of the sampling apertures, we're going to measure the signal at that instant in time and the over the sampling aperture, there's going to be one, one digital value that's going to be measured. And then, when we go to the next sampling point interval, we're going to see a step function that occurs as a result of sampling at the next juncture in time, that value of the analog signal. So, what this means is, that if our sampling aperture's of a finite dimension, we're going to, the consequence is going to be, there's going to be some error trying to sample that continuous ramp function. If we decrease the sampling aperture, shown on the lower row; one takes those sampling points, and we see that as we make the aperture smaller, the amount of error that occurs is going to be correspondingly smaller

as well. And of course, the limit would be an infinitely small sampling pitch, or aperture. The consequences are this: if we have objects that are smaller than the pixel size, the output is going to be smeared out over that pixel area and if we have an MTF of the sampling aperture, which is just a sinc function; the sinc function of the MTF falls off as 1 over delta x, the cutoff frequency is 1/delta x. The Nyquist frequency is, remember, is 1 over 2 delta x, so if we have the MTF of the sampling aperture displayed, and this doesn't mean anything about the MTF of the input phosphor or the like, we see that the sampling aperture is going to cause loss of signal and our maximum useful signal is information up to the Nyquist frequency. Everything beyond the Nyquist frequency is going to be aliased. And you can see some examples of the reasons why we do lose information when

we digitize. So, what happens when we have, let's say, a very high frequency test object? If we're in phase on a digital matrix, even though we might meet the Nyquist criterion, some phase variations are going to occur, in which, in one case we might get good signal modulation as a result of how the patterns line up with the digital image matrix, however, by simply shifting the patterns where they overlap in the individual pixels, there could be a situation where we have no signal modulation for the same test object. And one of the factors that we've always heard about is the Kell factor and the Kell factor is one of those issues that takes into account these phase effects, even though we've met the Nyquist frequency. Now, insufficient sampling; Phil showed a really nice example, let me show you an example, too. If we have a low frequency signal, and remember, we're sampling at the center of each of the apertures. If we have a high frequency signal and we do the same sampling, what's going to happen is that the template that the computer tries to match in terms of the variation in the spatial frequency is going to be manifested as the same spatial frequency, so what this means is that the high frequency signal is going to masquerade as a low frequency signal and it's going to be flipped back into the (low) frequency domain. So, using that same analogy that I showed you previously; if we have a frequency that's 1.5 times the Nyquist frequency, what's going to happen is that we

have this high frequency signal, with the output
signal is going to be reintroduced into the lower spatial frequencies as .5 of the Nyquist frequency and if we have the input frequency equal to twice the Nyquist frequency, then that signal is going to masquerade as a frequency which is equal to the Nyquist frequency. So, you're going to get a lot of information that's put back into the lower spatial frequency domain. And that arises as a result of the periodic nature of the spatial domain process, whereby we can capture information in a true sense from zero to the Nyquist frequency. Any band width that exists beyond the Nyquist frequency is going to be aliased back in and wrapped around at the Nyquist frequency content. And here, down at the lower part of the slide, you can see an example of what happens when you do sub-

sampling of an image in an inappropriate way. The correct image on the left and the aliased image on the right, and you can see the effects of what happens when that lower frequency signal or the higher frequency signal is actually manifested in the low spatial frequency domain. So, what is the impact of aliasing? Well, if depends upon how high a contrast is, that is extended beyond the Nyquist frequency and if it's a low contrast signal, sure you're going to get aliasing, but the amount of alias signal is not going to be as important as this particular example shows. But it is something we need to be aware of in terms of digitization of the signal. The clinical impact is likely to be minimal. What are some of the issues that are going to affect resolution in the digital image? The light spread in the phosphor, the

geometric blurring and magnification and focal spot. And of course, we always try to optimize the signal output, so what we want to do is match the detector element with anticipated spread. So, the detector element size in fluoroscopy can be, actually, relatively large compared to a corresponding system that would be used for radiography. And the example would be; in radiography, we might use 200 micron detector elements size. In fluoroscopy, typically, it's on the order of 500 microns. And one can do pixel binning of a standard (fluoro) system. And this just explains, and shows you how that might occur in terms of if we wanted to use a fluoroscopic system, we'd probably want to use larger pixels over a larger field of view, but now some of the newer flat panel systems are able to provide an

ability to do pixel binning and we can have a switchable radiographic fluoroscopic flat panel display, by just simply changing the way in which we can bin the output pixel values. And here's some consequence; I wanted to show you a couple of examples of what happens when you sample an image. This is some DSA images of a 1k by 1k system and I just wanted to show you what happens when you change this sample element area as a result of going from 1000 samples to 500 samples to 250 samples and 125 samples; obviously, we begin to lose resolution to the point where it's not useful. This would probably be deemed, still, a useful image (250 samples) and what I haven't done here is do any image processing, such a cubic spline or bilinear interpolation, which would actually make this image look a

little bit better than it really is shown here. Now, the other aspect of digital sampling that we need to be aware of is quantization. And quantization is going to discretize the input signal ramp, in terms of the output digital value; the integer value. And now, I'm going to show you two examples of a two bit and a three bit analog to digital converter just to make it simple. And in this particular example, I'm showing you where we have infinite sampling and in this case, what's going to happen is that the analog to digital converter is going to convert image information, depending upon what the value is halfway between the individual values that the output can actually produce; in terms of a two bit analog to digital converter, we have four discrete levels, so we take and chop up the image signal values in four separate discrete values. If we increase the number of bits, obviously,

we're going to be able to render that analog, continuous analog signal in a much more robust and accurate way and we can reduce the errors. So, not only do we have spatial sampling errors, but we also have the quantization errors. In this particular case; if we had 450 millivolts coming in, the analog to digital converter is just a sequence of individual reference dividers that would allow one to determine if the 450 (milli)volts coming in, in this particular three byte analog to digital converter, we would see that the comparators would be turned off, up until the point where the input video signal actually met and exceeded the reference voltage at that particular point. So, in this scenario, we would have a 450 (millivolt) volt input; we would have a digital value output of four. The typical bits depths that we find in fluoroscopy and angiography CRDR; anywhere from 8

to 14 bits and that's going to, of course, encode anywhere from 256 to 16,000 gray levels and I've obviously showed you that the larger number of bits provide better image quality. In this particular case, let me just show you what happens when you go from eight bits to three bits to two bits, you get, pretty much a cartoon after awhile, because you only have, you have a two bits analog to digital converter, you're only going to be producing four gray scales, whereas, with an eight bit, 256 gray scales. So, contouring is an issue that is problematic and one of the downsides of digital sampling and it really is a problem in slowly varying areas in contrast. So the dynamic range -- obviously, you want to choose an analog to digital converter and the gray scale range corresponding to the issues related to quantum noise, system noise and electronics, as well as the maximum useful dynamic range. As I said before, typical bit depths in digital fluoroscopy now are on the order of 10 to 14 bits. What about resolution and image size? We, in digital fluoroscopy typically, and we’re moving more and more towards 1k x 1k outputs, 512 x 512 matrices are going to be producing, if we’re operating at 30 frames per second, 15 megabytes per second of image information and we can see that in fluoroscopy if, in fact, we want to digitize the image information, there’s going to be an extremely large amount of image information content that we’re going to need to capture and send to the PACS. We typically don’t send all the fluoro images, just typical key images and in angiography, that’s the same situation. In an angiography study, when we consider the issues of storage, anywhere from 200 Mbytes to 1 gigabyte are common at

our institution, so when you do look at some of the implications of digital fluoroscopy and angiography on PACS storage is an important issue. Once we’ve digitized the image, now what we have to do is convert it back to an analog display and that is done by the device known as the digital to analog converter. In that device, one takes the information that has been discretized and tries to recreate an estimate of the original analog signal amplitude. Image fidelity is dependent upon the frequency response, the number of converter bytes and the image refresh rate. Let me just show you the example here; now, we’re going backwards. If, in fact, we had a digital input value of 156 for an eight bit digital to analog converter, we would see that for a input value with a reference voltage of 800 millivolts we would be able to put out for that input digital value range on the

order of 487.5 millivolts. So, we can recreate the image information and that is stored in the information, in the bit planes in the computer as individualized discretized values from the most significant bit to the least significant bit that will be able to render our digital values from the dark to the bright in terms of a corresponding digital representation. Look-up tables are the way in which we can display the information in a non-destructive way by just changing the brightness and contrast values. And this is necessary because of the reduced dynamic range displays that we have. So, in the case of input values, digital input values, one can use a look-up table, a linear transform and choose the minimum and the maximum values that are going to be displayed by the window width levels and then change the brightness in a sliding fashion to be able to

display a certain range of digital values into the output display range. In this particular case, we’re going from 12 bit digital image to an 8 bit output range across a small range of the overall input function. So, we have, and then there’s various different transforms that can be used. In terms of gray scale processing, this can be demonstrated mathematically by just looking at a function; with the input function times a constant contrast (C), thewindow width plus the offset (D) , which is the window level. And this allows us to do this in a nondestructive way and there’s a couple of ways in which you can do it. Histogram equalization is the ability to redistribute the gray scale frequencies over the full output range. And in this particular case, one can see that we can get variations in image contrast simply by changing the way in which those look-up tables

are applied to the input image. In terms of contrast resolution; that’s going to be mainly dependent upon the kVp and also, the speed at which we're operating the fluoroscopic system. If one has a light limiting aperture, one is able to change the speed corresponding to the clinical need and if we need high contrast resolution, obviously we want to shut down the aperture and decrease the speed so that the noise isn't going to be as much of a problem. There's electronic noise, structured noise and those are all going to conspire to reduce contrast resolution, so we need to keep these characteristics of the digital fluoroscopy system at a low value. The useful dynamic range is dependent upon the minimum detected contrast with minimum noise. And one of the ways in which we can measure that in an analog or a digital system is to use a low contrast resolution target and look at variations in entrance exposure by, and taking that, and Phil showed a really nice output of one of the things that can be done in terms of image processing averaging or last frame hold, where you don't have temporal averaging, and you can see a significant difference in the contrast resolution that can be achieved. In terms of noise sources, the digital acquisition is signal to noise ratio limited and the reason I say that is because we can arbitrarily, as I showed you previously, change the image contrast by window leveling and window width changes, conversions, so, what's going to happen is that there are other electronic noise sources that are going to be amplified during that translation process, so in order to get a given signal to noise ratio, we have to ensure that the noise sources and the corresponding signal are, the signal can dominant over the noise. And many times, we can't get, we have to do certain image processing techniques to get rid of anatomic noise, such as structured noise and that's one of the aspects of DSA, where we can eliminate anatomic patient noise (by subtraction) and increase the temporal conversion of, the temporal way in which the contrast flows through the vasculature. The imaging system should always function in a quantum limited range and that is going to depend upon where we set our dose limits in terms of operation. So, for DSA, for instance, we have to use a much higher dose. Image processing; this is the last part of the talk and what I'm going to talk about here is some of the aspects of image processing in order to enhance conspicuity of clinical information, such as the contrast load in the vasculature, optimized image display on soft copy monitors, hard copy film and reduced radiation dose. There's various different types of image processing that we need to be familiar with. Point, local and global types of image processing operators. Let me just show you some examples, in terms of the functionality. Temporal averaging is a way in which we can take a sequence of real time image outputs and simply average them together and that's going to allow us to reduce the apparent noise in the image by the averaging process, and that typically goes as the number of frames to the 0.5 power, or the square root of the number frames. It increases the signal noise ratio, but of course, the lag effects are going to be also introduced in the image. We can do image subtraction, whereby, we have a mask image as a function of location in the image, subtracted from temporal images that are, subsequently, streaming in that have differential attenuation due to the contrast, and in this particular case, one is able to take and subtract images by using the logarithmic means, logarithmic amplification and the reason for logarithmic amplification is shown in this slide, whereby the mask image is the exponential, it's exponentially related to the attenuation of the components and the thickness of the components within the overall image as a function of (x,y). The contrast image has the information that's additive, or actually negative, due to the attenuation of contrast and if we take the log of those signals, we see that the subtracted image is dependent upon the attenuation of the information in the vessel due to the iodinated contrast times the thickness of the vessel. We use a linear-to-log look-up table to be able to do that linearization of the exponential process. Digital subtraction angiography eliminates static anatomy and isolates contrast to get rid of the structured noise. And this cartoon just shows you how this happens. The x-rays are turned on, a mask image, a pre-contrast mask is acquired, contrast agent is injected, the contrast itself is superimposed upon the anatomy, but the subtraction process eliminates the static anatomy and one is able to achieve information that is going to allow us to get rid of the static anatomy. In this particular case, there's a lot of contrast load, so you really don't need to do processing to a great extent, but on the image on the right, one is able to acquire quantitative information as a result of being able to eliminate the static background anatomy. And this just shows you the cartoon of how the time dependent subtraction DSA process occurs. And some DSA examples of a cerebral angiogram. Some of the manipulation and quantitation technologies that are done in DSA; pixel shifting, if the patient moves we're going to have some residual signal that results from the fact that the static anatomy is no longer static, so one can do pixel shifting on a, by remasking or warping the pixels, such that we can get a nicely rendered image. Another aspect of quantitative capabilities is to use video densitometric techniques. Because we've eliminated the variation and the signal and isolated the signal simply due to the contrast, one is able to look at the ability of using an integral value over a region of interest, to simply get the thickness information out (quantitatively). Some other aspects of image processing are illustrated here. This is a, instead of just throwing out all of the information in a digital subtraction angiogram, whereby, each image is just a single subset, one image of a full range of values, one can do a process known as matched filtration whereby, you can place a region of interest over the vessel and by looking at the time dependent increase in the contrast agent and measuring an average value of that output, one is able to get weighting factors that can be used, such that all of the images, based upon those weighting factors are going to be allowing us to use the full data set and then, be able to get a much lower output noise image. This is known as matched filtration, whereby, we can actually take a look at the contrast at a particular area within the image where we get a maximal signal to noise ratio by using a large subset of the images as opposed to just a single subtraction. And here's an example of that. Here's a contrast image where you can very, you can hardly even see the contrast on the left, a masked subtraction image, where you can see some variation background noise, a matched filter image, which uses a large number of images, as I showed you before, and then a landmark image as Phil Rausch had shown in the first session, whereby, you can put a certain amount of the anatomy back into the enhanced contrast image. Recursive filtration is another method in which we can reduce noise and Phil showed a really nice example of how the recursive filter is going to create some lag and it's just a feedback of the information coming in, back in, and you're adding previous frames into the current frame such that you can reduce noise by temporal averaging, but you also implement some lag effects. What about spatial filtration? You know, some of things we've always heard about are convolution filters and what I wanted to show you briefly, in the next couple of minutes, is how one can implement convolution and look at

it and its impact on the spatial domain. And convolution is, simply, a pixel by pixel multiplication and addition with an image, so you have a filter kernel and you multiply the filter kernel by a value within the image. And in this particular case, what I'm going to show you is the impact of what happens when we have a given filter kernel. Here's an.nfinitely small filter kernel with an MTF of one over all spatial frequencies. I think everybody realizes that. If we have a single element LSF, and I did refer and allude to that in the previous characteristics of, previous aspects of the talk, the signal element LSF is going to have an MTF that goes as the sinc of the value delta x. So, this is sinc of x, and we see that the Nyquist frequency and the cutoff frequency are dependent upon the. If we increase the size of the LSF, what's going
to happen is, is that the MTF is going to reduce correspondingly, because the width of the LSF, in terms of pixel values within that kernel, are going to cause a reduction of the MTF, so we have a one element and a three element MTF. would look like the area that I'm showing you on the left; a series of one values. We divide that by nine and the way in which the convolution kernel works, is to take that kernel, do a point by point multiplication and addition, and then, put that corresponding value, four, into that point (in the new image). And then we would move

over and shift to the next area on the (old) image and we would see that that value would equal seven, we put that into that If we want to do variable low-pass filter, we could break it into parts and then we could see what the frequency content of the corresponding filter would be. High-pass filtration does a very Here's our single kernel LSF and our low-pass LSF, and if we do a subtraction of those two, we can get a high-pass filter, and this is how someone and this is how one

might be able to do some edge enhancement. And in this particular case, our kernel would look like a series of negative values, negative ones and a nine in the middle. This would have a gain of one and the difference image would result in an MTF band pass, as illustrated in the yellow line. And in this situation, you'd do the same thing and you'd see that the profile before and the profile after would enhance variations in edge characteristics of the image. And here is an example of an unfiltered image, a smoothed image on the right and an edge-enhanced image on the left by using those filter kernel operators. Now, global processing is another area in which one can actually improve the image characteristics. And global image processing, because it's a much larger kernel extent, it's more efficient to do these types of processing in the frequency domain, by

using inverse filtering and deconvolution techniques, where the deconvolution and the convolution and the frequency domain are a simple product as opposed to a series of multiplications and additions; and some of the things that can be done with global image processing are translation, rotation and warping. An example, that I've shown in the past, with veiling glare and image intensifiers, variations in (glare cause a variation in the signal as a function of) lead disc size, and the glare is going to have an impact on the quantitative characteristics of the image. Glare in flat panels is not going to be much of a problem, but to give you an idea how a global inverse filter would work, the radial distance of the point spread function of the glare is very long and it has an impact on the signal underneath a lead disc, which, ideally, would be zero, but if you could do a two

dimensional Fourier transform in the spatial domain, over this long frequency extent, one can achieve a restored image output, that is going to nicely maintain the quantitative characteristics of the image. And there's various quantitative algorithms, as listed in the bullet points in this particular slide, one can do after quantitative improvement of the image. Some of the limits to quantization within digital imaging; nonlinear, nonstationary degradations, beam hardening, scatter, veiling, glare and non-uniform bolus infusion. So, there's still a lot of research to be done in being able to make these systems more quantitative. And geometric effects, which are going to become less of a problem with flat panel implementation. So, with that very rapid overview, I submit to

you that digital fluoroscopy, obviously, is an extremely important and essential part of the way in which we implement fluoroscopy, now and into the future. There are limitations and advantages of digitizing the images and the knowledge of those limitations and advantages are certainly important for us to know as physicists. DICOM is another area that we need to concentrate on, and it's certainly a must to make sure that we can use these systems in an efficient way. Fluoroscopic and fluorographic image processing can provide a huge number of advantages, so it's important for us to understand these issues of digitization, sampling, quantization and the effects of doing image processing in terms of reduced dose, enhancing image details and extracting information that provides a much more diagnostic capable system. And then finally, there

are some references and further information. I think one of the best sources is the" Summer School" that was done in 2002. This is a really nice book and I encourage all of you, if you need further information on these issues and fluoroscopy, in general, there's a really nice overview by the authors that are included in that "Summer School." With that, I believe we're just about out of time. Thank you very much for your attention. I'm open for any questions that you might have.