We are going to end the series of MR talks this morning, which I am sure there have been three really good ones before this. With a discussion about high field MRI the technology, applications, safety and limitations. Got a lot of bandwidth here so expect a little noise. I just want to give you a general idea of where high field is coming from and why its taking so long to get here and some of the challenges associated with bringing it into the clinic. The promise of high field MRI is basically that you have this increased currency in your signal and noise ratio. You can trade this increased SNR off for higher resolution, or higher speed, or some combination of both. The higher resolution imaging you can either do for in-plane resolution, which is going to impact your imaging time, which is where that trade off is, or you, can do thinner slices. The impact on your time there would be collection of more slices if you have to collect the same volume, but its going to give you more detail and less partial volume averaging allowing you to resolve smaller structures. The faster imaging is going to allow higher throughput for clinical practice. Also, for ultra fast imaging you will have better motion suppression. You should basically have better SNR for breath holds and procedures like that. Essentially as you move to higher and higher fields you will have exploration of newer altered contrasts mechanisms, such as being able to view new metabolic processes, become available to us by looking at new nuclei. Actually the T2 contrast mechanisms are going to shift as we get to higher fields. Not at 3T field strengths, but at substantially higher fields. And there will be other similar types of contrast mechanism shifts. The bottom line is that you have the potential to significantly advance the anatomic, functional, metabolic, and eventually molecular capabilities of MR imaging. (I'm using "molecular imaging" in that lose manner that the nuclear medicine people would likely slap our hands for. Now this currency, this "SNR currency", and you are going to find during the talk and you are going to want to keep note of it that the unfortunate reality is: physics applies a progressive tax on this "SNR currency". You will find that actually, the tax man cometh and so every time you think you are going to have enough SNR, you have to make some concessions. So it is not always as fun and happy as everyone makes it out to be. Now the "high field scanners", currently the 3T whole body scanners, have hit the market with a resounding boom. The whole body scanners have been commercial since about 2002, although there were some specialized small neuro scanners on the market before that. In 2003 they accounted already for about 8.5 of the high field revenue. All the major vendors have one on the market. GE's is the Signa Excite, it's a short bore and so it has about the same foot print, although about double the weight, of their 1.5T's. Phillips has the Intera Achieva; and Siemen's has the Magnetron Trio, which replaced their former neuro specialized 3T unit. Whole body 4 to 8T scanners are currently being evaluated and have been for quite a number of years. 4T whole body scanners have been around for probably about 10 years. 7 and 8T scanners have been out for several years in research institutions and you could probably expect 7T to start to hit the market. Its right around the corner. Probably within the next five years. Whole body 9.4 tesla scanners are also in the queue and have been installed at several sites (although I haven't seen images from them). Here's an example of a 9.4 tesla magnet from the University of Illinois, Chicago. These images came from Joe Zhou who heads up that program. It's a General Electric 9.4 tesla magnetwith a five-inch thick iron cage surrounding it for shielding, dual coil heads (basically a requirement at the higher fields), and patient positioning as you can see from the high tech rails there is kind of a work in progress. It was up to field on May 9th of this year and they got their first FID. Shimming of these larger field magnets has proven to be quite the challenge. And University of Minnesota's Center for Magnetic Resonance Research have several high field magnets, two of which I have shown here. They have one the earlier whole body 7T's, with a 90 centimeter bore and they have a 9.4T. Both of are Magnex Scientific magnets and I think they are running Siemen's consoles. This 9.4T

was installed in April 2004. And you might want to note that MGH and NIH also have 7T magnets. Ohio State University has been very successful with their 8T magnet for research. So these are basically the some of the high-field research centers, and hopefully no one gets mad for me not including one or two of them. They are basically responsible for bringing the next generation of high field to us (beyond 3T). So a brief overview what we are going to look at here. I really want to go over the technical and safety issues associated with the main field and how to bring high field into the market place, what is going to happen with the RF fields as we go up higher in field, and gradient issues Then we will talk a little bit about some of the contrast changes we can expect to see as we get up to higher fields (all the relaxation parameters and spectral resolution)

and then we will briefly touch on some of the applications, time permitting. Everybody, I think, has probably seen this by now, it's the flying frog. As you get up in higher fields you can actually counteract the effects of gravity in diamagnetic materials. This is probably a 16T, 32 millimeter vertical bore and its pretty much why they shouldn't give grad students high power magnets. I think this stunt originally showed up in a Physics Today article (I think). Only they used a 20T magnet and probably a different frog. The main field—Modern Super Conducting Magnet Design. Basically we have solenoidal magnet designs with windings. The windings are Type-2 super conductors, chosen basically because of the higher critical field. We have niobium-titanium windings. The critical field is going to limit how far we can go up in the main field, probably to less than

10T (or so). That's a sketchy number with this particular superconductor type. You can crank a little bit more out of these by super cooling (the windings) below the 4.2 Kelvin limit down to maybe 2 Kelvin. That will get you probably another one, maybe two testla. You can also integrate niobium tin windings in to get even higher fields. Niobium tin, although it has a higher critical field, is extremely brittle and difficult to incorporate into the windings. It makes it very expense, so its very difficult to use. But for fields above 10T, you are going to start seeing interleaving of both, where maybe niobium tin is used in the area in the region of the high field and you fall off and have niobium titanium windings dominate at the edges. Now, increasing the field this is going to be pretty much useless unless we can maintain the same sort of magnetic field homogeneity (we had at

lower fields). Homogeneity in the field is usually stated as the shift in frequency, in

Hertz or PPM (parts per million), across a given diameter of spherical volume (DSV). Homogeneity desired is going to be, more or less, application dependent. For routine imaging, you can probably get by with 5 PPM at 35 cm (although I am sure most people desire more). For “fast imaging”, you want less than 1 PPM at 35 DSV. For spectroscopy, at least 0.5 PPM at 35 cm DSV, although you would like to see that creep down to 0.2 or 0.1 (PPM). So the high field sighting challenge is, with constant homogeneity in the field, as you increase this field your overall magnet size is going to have to increase to maintain that homogeneity. The overall weight is going to increase and cryogen volume consumption is going to be increased substantially. And so, since you are also going to have substantial energy in the windings being increased so you have to think about quenching issues as well. And also the Fringefringe fields are going to creep out further, making siting of these magnets a little bit more difficult. So, the cost in siting concerns can be significant if you are thinking about room size, weight, where you can put the magnet, how you can site the magnet, how much it’s going to cost to upkeep it. Now, the modern 3T scanners, they only weigh about twice as much as the 1.5. And a lot of that has to do with the technology put into the magnets to counteract this before they hit the market. And that is what we are going to talk about for the next couple of slides. But the higher fields right now coming in, they are really research driven, not commercial driven, and so at these higher fields 7T, 8T you are talking about 20 tons with cryogens or more. Plus about 100 tons of passive shielding. So, I would really wait until they have active shielding installed before buying one (unless you’ve got the room). So the high field siting challeng is: how to minimize these costs while maintaining the field homogeneity. A lot of that’s “black box” engineering that I don’t have access to. But the general gist of it is you’re going to have to mess with the magnet winding circuits. You are going to have tighter windings; you are going to have more windings per unit length in order to get the size of the bore down. The reduced length is going to reduce your cryogen volume use. They have to use new conductor formats, they have to use new conductor joining techniques other than what they used at 1.5. There is going to be new films and alloys and you are going to rely heavily on shimming and shielding in order to correct the remainder of the effects. Now, shimming is going to be more important as we get to progressively higher and higher fields. High performing, automated shims are needed to maintain the homogeneity in the magnet. There are several stages. When the main magnet gets shipped to you, well, not shipped to “you”. But the main magnet without anything else, hopefully, will have a inhomogeneity that is less than 125 ppm. The super conducting shims should be able to get this down to 1.5 ppm, even in some of the larger magnets, easily. As we get to the larger and larger magnets the passive and higher order room temperature shims should be able to get most of the magnets, even up to 10 testla, down to less than 0.2 ppm over the DSV's. And this, oddly changed colored photo here, is basically just a real quickie off of our three tesla magnet showing you that, if you look at the color bar, even just throwing a simple little head phantom on there, we get within plus or minus 0.2 ppm easily not using any high order shims. Although, I have to say on a 3T when you put something that is not as uniform as this in … you are probably going to want to use higher order shimming. And everybody just has to forgive me here for putting the knob … the filling knob … in there. Sorry about that. Magnet shielding: Another problem is we want to keep the 5 Gauss line inside the room as much as possible. This reduces problems with sighting the MRI in a confined space so we want to bring that in. The 5 Gauss line using magnetic shielding can be reduced from about 10 to 13 meters down to about 2 to 4 meters. Now passive shielding is where we put in a high permeability material such as iron and it gives you a return path for the flux and it takes the flux away from the magnet. If you use this

exclusively it makes the room rather heavy and expensive, a little difficult to sight. Active shielding which is generally what most of the commercial scanners use now uses secondary set of shielding coils they can be superconducting to cancel the Fringefringe fields produced by the primary coils. And typically these are going to be sitting beside the magnet cryostat. And here is an example of an iso-gauss plot off a 1.5T actively shielded magnet taken from the GE web site. And just wanted to point out here, where the 5 Gauss lines are axially, its out about 4 meters and radially, in this case, transverse, is out about 2 1/2 meters. In on a 3T actively shielded magnet from the same vendor, that 4 meters goes out to about 5 meters; and instead of 2.5 m we have about a 2.8 m (fringe field). And so with the active shield in the magnet, 3T's actually don't see a huge

increase in the 5 Gauss line. And here's just a real quick plot off of those so you can get an idea of how quickly these Fringefringe fields will fall off. So for the 1.5T, it falls down pretty quickly. I guess I should have labeled probably the edge of the bore which is probably somewhere around there. At the edge of the bore magnet after the isocenter and the field falls off rather rapidly as it does for the 3T and it falls off more rapidly for the 3T. And I zoomed in a little bit here so that you could see that as we come out to the 5 Gauss line. Kind of keep that in your head because this becomes a little bit of a "got-you" with regards to safety issues and physiological effects a little bit later down the line. I will bring this plot up again. As far as the FDA is concerned, magnetic field strengths are safe up to about 8 Tesla, and that is in adults and children, and infants more than one

month old. For neonates or infants less than one month they advocate nothing more than 4 tesla. I know in Europe they are reconsidering this. For the time being, these are as of 2003, and the FDA guidelines are available online (see slide). Now the primary safety concern with the increased magnetic field is going to be (obviously) projectiles in the room. Medical devices, translational motion, interference of their operation and hydrodynamic effects increase as we get to higher and higher fields. And you want to be very careful: routine things that may be lying around when you put your new higher field unit in may seem a little bit benign, but once they get into the room those sharp gradients I showed (on the previous slide) you have a little bit more pull than the 1.5T magnets. So things that look rather benign and like they may have come a little bit into the room

before … they no longer do that. This was a laundry basket that really was not MR compatible, and didn't belong by the door, that zoomed into a 3T magnet at an "unnamed institution". The main field safety, torques and force: The torque on an object and magnet field (for those of you who haven't seen it 500 times) goes approximately as the square of the field and the angle that the object makes with the main field. The translational forces on objects in the magnetic field are going to go as the field times the gradient of the field (the spatial gradient of the field). Now these torques and translational forces, they are also going to be proportional to the susceptibility and the volume of the objects that are put into there. So the actual scale can vary depending whether you have a ferromagnetic object if you get to very high fields; whether it's a paramagnetic object like

surgical steel. So for magnetic field safety, the primary I want you want to take back with you forever is: equipment that was formerly designated as "MR Safe" at 1.5T is not necessarily so at 3T. And there has already been at least one article I think by Shellock, where there were several items, I think they are aneurisms clips, that were designated "safe" at 1.5T but failed the deflection tests at 3T. So, you do not want to just blindly use the old 1.5T guidelines when putting patients into the magnet. The force on paramagnetic objects at 3T can be about five times the force at 1.5T (rule of thumb). And the force on ferromagnetic objects can be about 2 ½ times the force at 1.5T (if it's fully saturated). Back to the Fringefringe fields. This is just a plot that I took right off of the plots before, where I weighed off the gradient, so accuracy is probably not there, hopefully the field

isn't really linearly interpolated between those two points. That's what I did, so it's basically going to overshoot it. But if you look at it we're basically looking probably at 3 ½ times the force (3T to 1.5T) as we are inside the bore of the magnet and as we come down because of the sharp gradient (of the fringe field) on the 3T. If we look here over on before we start about 2 meters out from isocenter. That short gradient of the 3T gives it a much stronger force in addition to the magnitude of the magnetic field. So, even when you are out about 21/2 –to 3 meters away, you are talking about five times the force (compared to 1.5T). This has a much stronger pull than the 1.5T … and it's the active shielding that helps you along. Magneto-Hydrodynamic effects-its too early for that. Okay, electrically conducted fluid flow in a magnetic field: basically its going to induce a

current. You have the hall effect going on there (setting up a potential across the vessel) and a force opposing the fluid flow. The effects are going to be greatest when the fluid flow is perpendicular to the field, "non-axial flow". For most people in the position you go into the magnet, that is going to be transverse. Effects are greatest, like I said, when its perpendicular to the field. The potential across the vessels that's going to increase as we go from 1.5 to 3 as the B field as well. And the force that resists the flow goes up as a square of the field. So as we go to 3T it's basically going to be quadrupled. Does that matter? Not really. T-wave swelling: What matters (most) is the potential. Distortions on the ECG that we see during the period of highest flow through the aorta on MRI exams is called "T-wave swelling". The induced potentials are on the order of about five

millivolts per tesla, so they are going to basically scale with field. The effects is going to be exacerbated as you go to higher and higher fields. The bad news is that, basically, the bad ECG's that you see now at 1.5T are only destined to get worse (with higher field strength). The flip side of the Magneto-Hydrodynamic effects is the increased blood pressure due to additional work needed to overcome the force. It really has a negligible effect on blood pressure, and everybody says that over and over again. I think theoretical predictions up to measurements at 10 tesla have it less than 0.2 percent. You need, basically, about an 18 tesla field before you see some kind of significant increase in blood pressure that puts humans at risk (I don't know about frogs.) Transient effects: There have been some anecdotal reports, and now there are a few papers out with phenomena reported in association with patients moving in and out of these high fields. And you want to keep in mind that, particularly with the actively shielded magnets, those field gradients are quite sharp. And so some of these transient effects are generated by moving within that sharp spatial magnetic field gradient. Some of the things that have been reported are: nausea slight, vertigo, headaches, tingling and numbness, some visual disturbances (which are referred to as phosphenes) and pain associated with people who have tooth fillings. (I don't know if that is going to become more of a contraindication of 3T … and just because of artifacts), but you might want to move them in pretty slowly. The end results are all these effects are "transient" … they cease after leaving the magnet. The actively shielded field magnets you have larger spatial gradients and so you might expect these effects to be a little bit worse. The end result is just to move your patients slowly in and out of the field. And tell them not to move their head rapidly while inside the field (I don't know if you can control sneezing.) The Bane of high field Imaging: moving away from the main field now , we'regoing to be looking at the RF field and changes in the RFpulses. First of all, as we increase the main field (up to a certain point) the B1 field sensitivity is going to increase approximately linearly with B0. At around 3 to 4 tesla that (sensitivity dependence) actually changes somewhat. As we get higher and higher the RF propagation becomes increasingly inhomogeneous as a function of the permittivity, conductivity, and the conformation of the patient and how large they are. What part of the body you're imaging is going to change how the RF propagates. The primary reason for this is that the wavelength is getting smaller and smaller with respect to the effects of the permittivity and conductivity, so we have increased dielectric effects, and when that happens the assumption that we have a quasi-static field that is uniform (as far as propagation is concerned), starts to crumble and so you get reduced penetration from higher frequencies. What you get is that, basically, phase and magnitude become a function of position (which results in) some unpredictable shading. And it's going to be a significant imaging challenge, especially as you go beyond the 3-tesla regime. Field focusing: which was named so, I think, to keep people from thinking of it as a purely dielectric resonance. It's basically a hyper intensity artifact that's in the middle of the image volume. Generally, it is seen on the brain images. This is just a typical Brain-O phantom that I threw in there to show it. And it (the artifact) is associated with dielectric effects becoming more significant at higher field. You will not see this in an oil filled phantom because of the change in the dielectric coefficient. So, that is one way to better evaluate the (signal) homogeneity of the system as you get larger and larger tissue bodies and the dielectric constant of tissue. This is going to continue to be an effect to watch out for as it will change the signal homogeneity across the field. It's very difficult with any given object to just randomly model it (for correction). Finite difference time domain methods are being employed, and that will probably help develop things like transmit array coils, which may help minimize the effect. (However) there is not much hope there either. More importantly, in the immediate sphere, especially 3T, is the problem of specific of absorption ratio (SAR). The deposition of RF power into the body can cause

heating. The primary concern is going to be whole body and localized heating. This is going to be a significant concern at higher fields but you don't want to forget also about the heating of medical devices or implants that you may put in there (as they become approved). And that is something to think about that's going to be a bigger issue than it was at 1.5T. Another thing, that I probably didn't put on the slide and people want to think about, is heating of the RF coils and RF burns. Especially as new coils hit the market and haven't been put through the rigors. You want to make sure that you keep the patient padded and separated from the coils, especially these large body array coils that are taking energy from the body coil. The SAR is the RF power absorbed per unit mass (watts per kilogram). It goes approximately as the B field squared, the flip angle squared

and the RF duty cycle (which pretty much is the number of RF pulses you are going to dump into the patient during a given TR, as a rule of thumb). Another rule of thumb is, Basically, one watt per kilogram raises an insulated tissue slab about 1 degree Celsius per hour. And what they are doing with the SAR is trying to predict, on the average, what kind of body heating that they are doing. And they are trying to control that, which is the main reason why the FDA limits it (SAR). So, the current FDA limits, as of 2003, are basically that you want to limit whole body SAR averaged over 15 minutes to be less than 4 watts per kilogram in the head. You want to 3 watts per kilogram or less averaged over 10 minutes in the head. In any gram of tissue in the head or torso, you do not want to exceed 8 watts per kilogram over a 5-minute period. In the extremities you do want to

exceed 12 watts per kilogram in a five-minute period. Now SAR's can influence the operating mode on the new scans that you see out there too. The new commercial scanners coming out actually … they report SAR in real time and they notify users of operating thresholds. Normal mode imaging is if your SAR for the procedure is going to be less than 2 watts per kilogram. That corresponds roughly to a temperature change of less than 0.5 degrees Celsius for the procedure. If you break that threshold you are going to go into a "first level controlled" mode, which basically means that you need to supervise it and watch the SAR, and you become a little bit more responsible for what happens at this level. And this basically means you are keeping the temperature change down to less than 1-degree Celsius during the procedure. If you break that threshold …

well you better have an IRB handy! "How the scanner estimates SAR", and I'm sure different scanners do it differently, and hopefully they all do it, trying to do it as accurately as possible. But the basic algorithm behind it goes through, determines the energy needed for the 90-180 degree flip angles; sums all of the RF pulses in the sequence divides by the pulse repetition time to estimate the power and divides the patient weight for whole body SAR. Peak SAR can sometimes be estimated as about 2.5 times the whole body SAR on a lot of scanners. Now the SAR puts a lot of limits on higher field imaging. Its going to put serious restrictions on your available pulse repetition times (which you can tell by the way the SAR's calculated), the number of RF pulses in a multi echo sequence such as FSE (fast spin-echo, turbo spin-echo, RARE, etc). Your slice efficiency and multi-slice acquisitions it's going to reduce how many slices you can fit into a particular TR period. And its going to limit your ability to use, especially with these multi echo sequences, high SAR pulses like fat saturation pulses, magnetization transfer pulses and inversion pulses. And so you are going to have to play all of these off to stay within the limits … or get an IRB. Ways to work around the SAR limitations? Well you know like I said it's just like a progressive tax, there's tax loopholes. But it always costs you (something). Using RF pulse design using reduced flip angles, like for fast spin echo methods, you can take the 180 degree pulse and bring it down to 120 (degrees). That's going to give you basically a "flip angle squared" reduction in SAR (I think that is near 60% in this case) but your sensitivity is going to go down as well. But the good news is the sensitivity doesn't go down (nearly) as much (because the reduction in sensitivity is approximately linear). It's about 20%, I think, reduced sensitivityfor that particular case. But the caveat is going to be that, when you start playing with the flip angles in a fast spin echo Sequence, you are also going to start messing with the contrast. And so not only are you altering the sensitivity, but you are also going to change the contrast in the resulting images. You are going to be changing the (contributions from) stimulated echoes that arise. You are going to be changing the (contributions from) magnetization transfer contrast. So, while this is probably a great way to reduce SAR, what's going to happen to your contrast (and how you go about optimizing a particular protocol) is going to change somewhat. The use of array coils: there's two ways that we can reduce SAR with the use of array coils. There's transmit receive arrays that can be used to reduce power instead of using the body coil, and, more importantly, probably the workhorse for some of these higher fields, is going to be "parallel imaging" techniques. Which, basically, they don't have to be transmit-receive, they need only to be receive coils, but they must use a multitude of coils. They use an array coil technique a consisting of a multitude of observers. The redundancy in the number of observers is used to drop lines of case base, or to under sample the image (and I'll talk more about this one in a second.) I think it is so important to get a feel for how differing the imaging parameter effect the images when you are trying to optimize your protocols with a higher field. You can also use a rectangular field of view (to help reduce SAR). Odds are you are going to be increasing your resolution anyway, and it comes easier and the frequency encode direction. So you can use a rectangular field of view with a larger field of view. To kind of play off that spatial resolution, but drop lines of k-space. This will give you a reduced number of phase encoding steps. Increasing TR: it may not take you to your happy place, but it will reduce SAR. And dropping slices (being less efficient in your multi-slice acquisitions …probably also not going to take you to your happy place but effective in dropping SAR). Now … Partially parallel imaging. Like I said this is going to be an "enabling technology" at the higher fields. It's pretty much standard software on the new generations of scanners. I think Siemen's calls it "iPat", Phillips calls it "SENSE", GE refers to it as "ASSET" and then the etceteras for

everybody else comes along and gives it a new name. It uses information encoded into the receive array with apriori information on the coil sensitivities. The little caveat here is that any time you use this you are going to have take some kind of calibration scan that lets the reconstruction software know how to process the data. They are acquired very quickly using low resolutions scan to see approximately where the patient data is and what the sensitivity of the coils are. And assumes that there's no bulk motion of the object within the coils after that. This allows the user to speed up the acquisition by collecting less echoes by under sampling k-space. Now, it doesn't always have to be "less echoes" with this technique, but for our purposes, is the enabling part of the technology. Although we're going to be collecting less lines of k-space. It doesn't

compromise the resolution like a reduced resolution technique would, such as a keyhole technique or anything like that. But the SNR is going to be reduced by at least a factor of the square root of 2, okay? Actually, because of the geometry of the situation and because you don't have optimal placement of the receive arrays, which are the observers who you are trying to get a consensus from, that actually causes the SNR drop to be **more** than the square root of 2 … usually. So, you will see a significant amount of work going into designing coils that are at least "as optimal as possible" for some body parts to be compatible with these partially parallel imaging techniques (PPI techniques). The end result: less echoes, less SAR … which helps you out incredibly at higher field. This is basically what PPI looks like in my really quick cartoon. Basically you can collect every

other line of case base and that reduces your field of view. So this (acquisition) has been sped up by a factor of 2 in this particular case, but you alias your object in the phase encode direction. What I didn't draw is usually will have on the order of maybe four arrays. I mean, four receivers in your array. So you would have four separate images … you can take those, together with their sensitivities, and unfold this image because you "know" (from the calibration scan) the sensitivity of the coils, and you therefore know the unfolding matrix. Basically that gets you back your missing data. It does not, for SENSE and ASSET type acquisitions, it **does not actually fill in the lines of k-space**. That (cartoon) is just kind of showing you that your data is back. Techniques such as SMASH (which I forgot to list on there explicitly) work in k-space to fill in the missing

k-space data and reconstruct from that side of the fence with the multiple receivers. Let's move on to gradients. At higher fields, well at any field, high performance gradients are usually wanted to take advantage of the increased SNR for the high resolution and speed up acquisitions. So, at any field you really want high performance gradients for a lot of reasons, but this is the main reason why you want them here (at high field) is to take advantage of the SNR. It basically gives you a way to burn money. It's like having a really slick checking account. Current systems have a max-amplitude any where between 20 and 50 mT/m. The 50 mT/m systems and the higher slew-rate systems are probably more likely to be smaller volume (smaller linear volume) types of systems dedicated to neuro or cardiac applications. The problems you are going to have in designing these

gradients is you're going to have increased reactive coupling to the bore, to the shims or to the RF coils. Its going to be inductive **and** capacitive coupling. It's going to increase the eddy currents, and it's going to increase the non-linear performance of these gradients. The self-inductance of the coils is going to limit the maximal amplitude of slew rates you can achieve. It's really the same old story (as lower fields) but it is slightly exacerbated at higher fields. The easiest fix is to keep on pushing for lower inductance designs (I also didn't mention the actual self-inductance is going to make it a problem for array designs as well). Their array RF coils aside from just gradients. Anyway, so basically, lower inductance designs are our easiest fix … it is going to be a lot harder to address the issues with capacitance in higher fields. Gradient safety at

higher fields: it falls down to pretty much the same thing. At lower fields you are going to have physiological constraints on the dB/dT to prevent peripheral nerve stimulation. That's going to limit your gradient performance. One strategy for overcoming this, is to shorten the linearity volume … and the reason for that is, basically, if you shorten the linearity volume, you can have higher slew rates for the same gradient amplitude, without reaching as high of a dB/dT out at the edges. I guess the one other thing you want to mention with gradient safety is acoustic noise. The force on the coils scales with main field so basically the force is proportional to the current in the coils crossed with the main field. So you are basically going to have increased "bucking" (of the coils). Padding inside the gradients and shielding of the noise from the gradients is also going to

be an issue as we move to higher fields. Field strength and image quality: Well with the increased main field there's that promise of increased signal noise ratio. "How much" depends on the field strength increase. Other things happen though. T1 is increased; T2 decreases slightly (more so for higher fields); T2* (the true transverse relaxation rate) decreases significantly. Spectral resolution is going to be increased. Let's hit each one of those a little bit more. Where's the signal coming from in high fields? … well the sample magnetization is going to be proportional to B0. So if you look at basically the "induced population difference" and here this is the number of spins, Planks constant, gamma for the nucleus. You are looking at Altman's constant and temperature basically the induced magnetization you have available to you is going to scale with the B field

(approximately). Farriday's law, the induced EMF, and the coil that you are receiving It's going to be a proportional time rate of change of the transferred magnetization, which means it's going to be proportional to the Lamor precession frequency and so take both of those together you're basically looking at the multiplication of both these effects. So the signal versus field strength is going to go approximately as B squared. The noise is a function of field strength and it's going to be a combination of noise from the coil and system and noise from the sample or the patient. Which is basically going to be temperature driven … but is also a function of the B field. And the noise from the system goes approximately as the square root of the magnetic field. Well the variance from that. And noise from the sample goes as B squared. So at the low field where the coil noise

and the system noise really dominate, we get an SNR dependence that is about B to the 7/4. So it's approaching B-squared … but not quite. And that is actually seen up into the 1.5T regime. As we move into the 3T and above regime (the midfield and the higher fields) it starts to scale more with B0. Actually we start to get some other effects in high field where the B1 sensitivity, like I said, is no longer easily quantifiable and is not as linear as we would like it to be. But the SNR, because of changes in the noise, is still nearly linear with B0 in this regime. I want to say it's a little "lower than linear" I think in the jump from 4 to7T. T1 relaxation as a function of B0: the spin lattice relaxation both lengthens and, for alot of tissues, it starts to converge together. So you have **less (T1) contrast** as the field strength goes up. Increases (in T1) are seen generally as we go

to 3T at about 30% from 1.5T values. The consequences are going to have contrast and signal noise reduction for T1 weighted imaging. We are going to need longer TR's or preparatory pulses for T1 imaging (in order to achieve similar contrast). We actually need longer TR's as well for your T2 weighted imaging and proton density (because of the longer relaxation times). Longer inversion times are going to be needed for a lot of these sequences as well, which is going to drive up the time. STIR (short tau inversion recovery) for inverting fat; I think the inversion time goes from about 150 ms up to … we use 190 ms … you can go up to 200 ms. The inversion time for FLAIR (fluid attenuated inversion recovery) increases (although not as substantially) as well by the way, (I will show you an image). Double IR pulses, black blood pulses: your inversion time is going

to have to increase as well to invert the blood … but the good news is that with the longer T1's, tissue and blood are going to be more easily saturated into the background (if that's the application you are looking for). Also for this gradient for the gradient echo sequences you are going to have reduced Ernst angles and gradient echo imaging. Pretty much the gradient echo sequences, as far as these T1 changes, they're probably the least effected for all of them. To use a really, really old model (I don't know how appropriate it gets as we get into the 3T and above regime … but it's close and it shows what is going on), I used an old Bottomley paper from 1987 (see slide) and it shows you, basically, the B field dependence of gray matter and white matter. We are talking about going from roughly 800 to 1000 milliseconds up to the possibly 1250-1100 range for gray matter.

White matter will get a little bit farther down the scale … but note fat doesn't change nearly as much. (although you usually are not looking for a lot of contrast between fat and the brain). There are some tissues where the change is not nearly as much. Another thing to bring up, that I didn't put on the graph … and I probably didn't put on a slide … is that the T1 from **contrast agents** actually does not lengthen significantly. So when you inject contrast, the T1 still stays pretty short. So for T1 weighted imaging protocols, what can we do? You can use the SNR boost for higher resolution and keep the similar scan time (which is pretty much what was done right here). Your spin echo T1 imaging is going to be SAR limited but there is not alot you can do about that. So you might have to end up reducing your number of slices. And in MSK type of applications, if that's

what you are after (or body) … if you are going to use fat saturation pulses, its just going to hurt! It's really going to kill you on the SAR. Some solutions in the head: you can use an array head coil, you can reduce the number of slices, rectangular fields of view, longer TR, multiple acquisitions (reduced slice efficiency) and, of course, there is always PPI, which, for some reason, I didn't put on there. So … partially parallel imaging. And here's a real quick MSK of the knee showing a 1.5T versus a 3T. Basically here we only traded in a little is a little bit of the SNR for a little bit of the higher resolution and you are seeing cartilage ligaments better. The structure within the marrow better. You can see some of the venous structure better. I didn't catch that last one slide. T2 and T2* relaxation is a function of B0. The T2s it can decrease slightly at higher fields. At 3T, so

far, no one has really seen a significant decrease in T2s that's really going to effect your selections of imaging parameters significantly. But as you get to higher fields, you have new interactions(that you didn't really see at lower fields) that are going to take over and you actually start to see a reduction in the T2 relaxation. So, T2 will start to decrease you probably won't see it until we start seeing the 7T scanners, 7 tesla scanners, hit the market. T2*, however, is a little bit more dependent on local field in homogeneities, and so it's going to decrease significantly at higher fields. The change is very strong with the tissue environment obviously that it's in. The good news is this gives you increased T2* contrast from contrast agents or background blood. The bad news is it gives you decreased signal in gradient-echo images due to susceptibility effects. So a lot of the

time you are going to be scrambling to use a shorter TE and use those **stronger gradients** that everybody ordered with their high field systems. Also, the other problem that is going to exacerbate this … while the higher signal noise ratio is going to be great for EPI, the "T2*-filtering" of echo trains in EPI (echo-planar imaging) is going to go up, as well. So you will have a **stronger** filtering effect going on there … so more blurring. So although you have more signal to noise ratio to burn on the single shot methods, you might still want to stride to use shorter echo trains and keep that echo spacing short. The other reason for doing that … I'll point out in a second. As far as T2 weighted imaging, the benefits are going to be purely from higher SNR, more than anything (else). You can use longer echo trains with higher bandwidths (SAR permitting). You can perform

higher resolutions scans in a similar amount of time or you can perform similar resolution scans in a somewhat shorter amount of time. Normally you are going to require a longer TR to compensate for the T1 lengthening in order to keep T1 contrast out of your image. Especially for those protocols where the TR was already pretty short, like in the 2000-2500 range. So you expect to see TRs going up from 4 to 7 maybe even 8000 milliseconds. Here is an example of T2 weighted images and FLAIR imaging at 1.5 versus 3T scanner for some white matter. The spatial resolution at higher fields we are going to have larger spectral separation between the different chemical species. MR

Spectroscopy applications are obviously going to benefit form this … and the SNR increase (once again). The chemical shift between fat water increases so instead of being 220 hertz at 1.5T it's going to be approximately 440 hertz at 3T. The bad news is, this is going to give you a faster accrual of phase between the water and fat for a given TE which exacerbates chemical shift artifacts. So you are going to want to use higher bandwidths to kill off that kind of blurring in the artifacts you get from it. The other thing that this means is for those fast imaging techniques that I mentioned, like EPI, the echo spacing is going to be a little bit more critical because its going to determine, basically, if you do have any off resonances aside from fat, how much they are going to play into your image quality. Of course the spectral-spatial pulses associated with these sequences, and how optimally they perform, is going to be a little bit more critical now as well. When you have failures in the spatial-spectral RF or inadequate fat suppression, you're going to get some tremendous artifacts at high field. So, on to some imaging applications. I briefly want to go over some of the major applications that receive the biggest boost from higher field imaging. By no means do I mean this to be exhaustive … like I said, I am trying to cover a lot of ground. Spectroscopy: increased spectral resolution I've already mentioned that and SNR. The higher resolution … this is going to let you do higher resolutions in studies. Also there is the chance now for looking at other nuclei of interest such as calcium, sodium, phosphorus, fluorine, other applications that will open up new avenues for metabolite imaging inside the body and body applications. You now have enough signal noise ratio where it might be worthwhile to investigate doing spectroscopy inside the body. Now, this is just a real quick phantom images of 1.5 versus 3T spectra zoomed in on the relevant metabolites. Here's your choline, your creatine, NAA … and the difference between these two, just running a single voxel technique, was almost a factor of two between our 1.5 and our 3T. If you look down here in the black text (that should have been white) the line widths of the water went from 2 hertz to 4 hertz. It's all pretty predictable in a phantom. Inside real people and real patients, where the shimming may not be as great and as nice as in a spherical phantom at 3T, the reality is … you may want to become very proficient with your higher order shimming techniques (depending where you are in the body). For a general head, you will probably be okay. Bold Imaging: In general the blood oxygen level dependent contrast is going to increase with field strength. There have been CNR increases as you go to 3T reported about 1.8 to 2.2 in the contrast to noise resolution. The overall effects (the reasons for them are pretty complicated, and I don't think we going to hit them today), but for the workhorse of BOLD, the gradient echo bold response, it basically holds true. BOLD, basically is a technique that facilitates looking at brain activation measurements for functional MRI studies orneurosurgeonal planning, without using exogenous contrast agents. During activation the oxygenated blood is going to increase while the deoxygenated blood, which is paramagnetic, decreases. So, you get a signal change, and this contrast is going to change due to the increased T2* contrast we see at higher fields. The SNR of the technique is also going to increase as well (which is a bonus). You can trade that in for higher resolution or higher speed. Here is an example of some FMRI activation studies done at our institution. Remember that in BOLD, the signal change is very slight, so you rely on statistical parameters to verify activation areas. Basically these are not the same patient I should probably qualify that for any body who doesn't notice it from the brain images. But across the board, we are seeing generally an increase in statistical certainty in regions of activation as evidenced by lower P values as you go from the 1.5T studies, which generally you get P values on the order of 10 to the negative 5, 10 to the negative 7 to 3T where you're getting 10 to the negative 10, I think someone reported 10 to the negative 15 on one study (and this was just for a right hand sensory motor type tasks). For diffusion weighted imaging, once again it's the

SNR driving the diffusion protocol, though you probably going to want to think about using thinner slices than the 7 or 8 millimeters that we use at 1.5T now. This can reduce the partial volume at artifacts and give you much more detail because of the higher SNR you have to burn. The other thing that this is going to open up as you move to higher fields is you are going to be able to use higher and higher b- values … because it's the b-values that actually quench all the signal by diffusion, and, aside from gradient performance and eddy currents, is one of the things that limits the use of higher b-values. Diffusion tensor imaging, just like diffusion weighted imaging, is going to benefit from the same things. But you can perform faster acquisitions, you can draw up some of those averages that you use in diffusion tensor imaging and hopefully reduce the amount of

(patient) motion, or (at least) the probability for motion of the patient during the acquisition. But like all EPI based methods, the shortened T2* is going to limit how far you can go with that and just about how much SNR you can pull out of the technique. Perfusion weighted imaging, arterial spin labeling: basically you use an inversion pulse to tag the blood and you acquire images as the tag blood perfuses into the tissue. It benefits, aside from the SNR (which I should just stop saying because it's just kind of obvious at this point), but it benefits from the longer T1 which is going to result in better tagging (of the blood). More persistent tagging will also (I think I will fail to mention this)benefit cardiac imaging as well (for tagged cardiac images). Dynamitic susceptibility contrast: where you basically use a bolus of paramagnetic contrast agent. You are going to have

increased T2* contrast. The T2* effects increase with the field, and so you will have better contrast for your dynamitic susceptibility bolus as it hits the brain (or wherever you chose to do that, as I think its going to considered for body as well now.) Contrast enhanced imaging: there's a lot of images we could have put up here. Basically the increased, the higher SNR, is going to give you the ability to go faster. In cases where you need to go faster it will give you better signal. The longer tissue T1 versus the little bit of change in contrast is going to make it easier to discern the background tissue from the enhanced tissue. It gives you better contrast using less contrast. Probably the big killer for this is going to be (especially with gradient echo methods and I didn't put it on here of course): the T2* effects. You are going to want to be careful because what you might see is basically a reduction in signal if you put in the same amount of contrast and your echo time is too high. You may actually see some darkening of your signal as the bolus goes by. Or, less contrast from that so the T2* effects may limit how much contrast you want to use and what the optimal dose is going to be. (You definitely can get away with using less contrast agent as you go to higher fields). Angiography: time of flight (TOF) in angiography basically relies on saturated normal tissues and bright inflow. The longer T1 time is going to give you better background tissue saturation (even without magnification transfer contrast). But if you look on every web site I think every vendor wants to say the even though it costs SAR, we can implement magnification

transfer contrast in our angiography. So someone must have lit a fire under there … someone over there … to make them make sure you can still do your MTC contrast to further suppress the background tissue. But you must be aware you're going to be more limited by SAR in that case, especially if you are doing some of the 3-D studies. The high field basically results in an increased inflow signal. Here's a nice circle of Willis projection, borrowed (not stolen) from the Phillips web site. Cardiac imaging is the last one we are going to address. Speed is king in most cardiac imaging applications. You can trade in your SNR for speed. Something where speed is not necessarily king, but more efficiency: Black blood imaging. You are going have increased T1 of blood by about 30%. It means you are going to need to use a longer inversion times for your black

blood sequences this could decrease the efficiency. But what you might find for a lot of cases where you are going to be increasing these T1s is will you get enough saturation of the blood signal if you don't increase T1 to the optimal. If you don't increase TI to the optimal TI. I think at least one paper that I've seen out there has gone ahead and said you do not have to increase it as much as you need to and you still have "adequate blood suppression" and good contrast. Larger SNR and slow T1 relaxation gives you basically more chances, once again I'm going to throw in the partially parallel imaging as this works at 1.5 as well, because your chances increase the very limited slice efficiency of this particular method. Which is a problem even at 1.5T to collect more slices per breath hold. CINE imaging: the bad news - things like SSFP and "true fiesta" (that whole

family of sequences) rely on a pretty large flip angle to get SNR. Those flip angles will need to be reduced in order to meet SAR limitations. That's going to take some of the sensitivity away. But so this is going to lead to basically T2-contrast and SNR losses in these types of sequences. I think we're talking about flip angle reduction from about 60 down to maybe 36 degrees. The good news though is that SAR is reduced basically as the flip angle squared. So you don't have to reduce them nearly as much … small reductions in the flip angle will get you into SAR limitations without killing your SNR (nearly as much as you might think you would at 1.5T). As always in the SSFP based imaging, and particularly as we go to high field, the TRs must be short. In fact it is much more critical now that you're at high field that you keep the TR as short as possible,

which again is going to effect that SAR. But otherwise you're going to see the "banding artifacts" that you see at the 1.5T on the low performance gradient systems, where the phase basically wraps around on the edges of the field of view. So when you do CINE

3T, I’m going to go out on a limb and I don’t know, but that 4ms TR is very comfortable at 1.5T. You might want to probably take down at least another millisecond (or as low as you can take it). And the echo time is going to need to be as short as well. I think that’s all I have (time) to talk about today.