Good afternoon.
Today we will finish MRI imaging chapter.
I put the title as Pulse Sequences,
but actually I will also review with you about MRI scanner architecture and a few other things.
I will conclude today's lecture with some brain initiative stuff and some new ideas,
but the emphasis is really your green book chapter.
So I strongly encourage you to read
the chapter very carefully.
So if you understand the lecture, you will do well in the final
examination, but some other information I will provide in the class are still very useful.
After
today's lecture, we will spend two more lectures on ultrasound imaging.
This will be pretty much
your ultrasound chapter.
Certainly I will always add a few more points, some knowledge unit for
your comprehension and for your information.
The optical imaging part used to be two more lectures,
and not in the green textbook.
Now I just cut it into half and waste additional time for machine
learning, which is very hard nowadays.
Then we will have examination three.
For your final grade
I do not know your second examination grade distribution yet, but after we have all three
examinations done, I will do curve fitting.
My target is always the same.
For the past five years,
the grade distribution is more or less the same.
So you have a few students, a few get C.
If you
do really bad, you will fail.
But normally maybe no one fails or one or two students who did really
lousy things.
So this is my idea.
So do not worry about your absolute score.
I will try to see who
will learn better.
So if I just test my class alone, I will always try to get some low mean,
so I see the spreading, get more information.
So anyway, we are talking about MRI imaging.
Last lecture I asked you to read through the book chapter.
I guess by now many of you already
read the green textbook and know a little bit about the hardware part.
So let me just review
with you so you get a better understanding.
So MRI imaging is done with the hardware system.
The
hardware system coupled with software and pulse sequences for inversion and some other advanced
reconstruction algorithms.
Altogether, we call it an imaging system or MRI scanner.
So the key point,
for MRI scanner, you will always have a stationary background field called B0.
So all the
magnetization vector, M vector, within the B0 field, it will point in along the B0 field direction,
which typically we call it G direction.
Okay, this is the result of B0 direction.
Then we have B1.
B1 is a rotating field.
So the rotating field is applied perpendicular to the B0 field and this

is a magnetic field direction.
It's rotating.
So as a result, you have a torque.
So you will
flip this M vector towards X-Y plane.
So you just turn this stable status into an energetic status.
Once you have transverse components and the alternating EM field will be introduced.
So if
you put coils nearby your sample or patient, so the alternating magnetic field will induce signal
called free induction decay.
So you have signal detected.
So this is an energy exchange process.
Gradually, the flipped magnetization vector, the M vector, will gradually return to the lowest
energy status.
This is again aligned with the B0 direction.
So you have B0, B1 coupled together,
really just flip this M vector.
This M vector is not an individual thing.
It's really many,
many small spins or small magnets.
Altogether, you form an overall M vector.
So we learned in
the first lecture, right? And the upper spin, down spin, there are small differences.
So the
collective effect makes this M vector.
So if you just collect the signal with B0 and B1 field,
the signal will come out from the whole sample.
You get the information about the sample,
but you cannot do tomographic imaging.
Then the idea is to have a grating coil that will
generate a grating field, arbitrary grating field, which can be linearly combined with
three components, Gx, Gy, Zz.
So this grating field.
How you play with these three grating
field, Zz, the grating field along Z direction.
Typically used for slice selection.
So we learned
in the previous lecture.
Then Gx, Gy can be used typically for phase encoding and the frequency encoding.
Then we have a very nice case-based theorem and something like Fourier slice theorem.
So hardware is the foundation for us to collect the data.
Then we perform Fourier transform,
inverse Fourier transform to reconstruct the tomographic image.
This is a high-level summary.
So if you have read the green chapter about CT, not CT, MRI scanner architecture, so you know what
I'm talking about.
So let's look a little more detail.
So M vector, this M vector, it's a flip
into a transverse component and ideally 90 degree pulse.
So whole M vector is flipped into XY
plane.
This will give you maximum signal, right? It will rotating and the M vector will be in
precision motion.
So you have the signal induced as a phasor.
Because you have amplitude, also you

have a phase.
So this will keep rotating in XY plane.
If you are in the rotating frame, you think
M vector just stay there happily.
So this is the moment after you apply 90 degree pulse.
So this
signal will introduce, this flipped M vector will introduce signal here and the signal here.
So you
have this X component as XT and as YT.
You have two components.
The two components and you can
compact the two components as real part, imaginary part and you get this very compact, complex value
the expression.
This is just a way to represent the signal.
Another way, if you really hate complex
expression, you can put in real representation.
You just combine sine and cosine components, put
it together, you use identity, you learn in trigonometry and you have just a single sine or
cosine component.
But in that case, you would have a phase angle there.
But if you have sine and
cosine components and you do not need to put a phase factor in either sine or cosine function.
But anyway, this is just a vector stay in XY plane and we stay with this complex value
the representation.
So you remove this fundamental frequency, omega 0, which is a
lambda frequency determined by B0.
So you have the overall signal like this.
Then with the gradient
field, you could introduce phase factors, okay, on top of this fundamental precision of frequency.
Then you can have frequency encoding, you have time varying signals.
So phase encoding,
frequency encoding, inconsistent with this complex domain expression.
So all these effects from phase
and the frequency encoding appears in exponential form.
Then this overall signal amplitude coupled
with phase and the frequency encoding appears to be the same form as for a transformation.
So this
is something we want to underline.
So this is a very cool thing.
The sinusoidal components shown
here is a solution to Maxwell equation.
Maxwell equation electromagnetic field interacts naturally
you have a sinusoidal solution.
So you have sine and cosine.
Then after phase and the frequency
encoding and we can have the signal represented in the case base in the form of Fourier transformation.
Fourier transformation is a mathematical tool and the Maxwell equation is a governing equation
for electromagnetic interaction.
So mathematical physical principle put together you have a case
base theorem.
So this is a very elegant convergence or coincidence.
So that's very cool.
And the MRI
signal on very top level you have this block diagram.
So the big magnetic field offers the

B0 field.
You need to add B1 field.
B1 field is a rotating magnetic field.
So here provided by
RF coil.
RF means radio frequency.
Lama frequency, precisional frequency.
So you offer this B0 field.
Then the induced signal will be detected by the same coil to close by.
So the same frequency
resonant in the coil you read the signal out.
You can just go from house computer.
House computer
you have a program coded here.
Then you send pulse sequence generation instruction.
So you can go
through frequency synthesizer amplifier and then you can you can just go this way to control
reading field.
And the other way to control B0 field you decide when you send 90 degree pulse to flip this M filter.
When you send 180 degree pulse to do the flipping for spin echo.
Then you as I said you receive a signal from same RF coil.
The signal will be what I mentioned the
real part imaginary part of that is signal you collected from patient or a small animal what
is where you put in the MRI scanner.
The signal give you information in the case base or you get
a Fourier component.
So those data will be processed and then you have AD analog digital converter.
Put it back in computer memory you perform inverse Fourier transform.
You got an image
displayed and then something like this.
This is a very high level top picture.
So B0 field,
B1 field, greedy field these are keywords for you to remember.
And the computer control how these
these pulse sequences and the data acquisition steps are performed in coordinated fashion.
And some hardware details I will mention a little bit.
All these you should treat as
description.
So you do not need no too much mathematical detail.
So you see real part
signal imaginary signal and I put in this complex form so that I can I can do Fourier analysis.
So this is for convenience.
Fourier analysis when I told you about Fourier series expansion
I really started with real domain thing.
But later I say if we use complex notation the Fourier
series expression all of a sudden becomes much more compact and only one third of the space you
need.
So that's just a very convenient thing for us to do.
So you have these signals real and
imaginary signal.
If you perform a Fourier analysis and you got something like this I wouldn't show
you why you got this.
You just know real or imaginary signal is sinusoidal signal but subject
to decay.
So this decay is exponential decay.
So the functional form if you perform a Fourier
analysis this is a Fourier analysis you will get a spectrum in this kind of

form.
And we want to
want to convert detected analogical signal which is in very high frequency pre-seasonal frequency into digital signal.
But the frequency is so high the signal
vibrates too rapidly and then no circuit can do digitization immediately.
So you need to do
demodulation a little bit.
That goes through so-called quadrature mixture.
So we bring the
signal from high frequency into a little bit low frequency and still decay following x-peninsular
curve.
So this way you can do digitization.
So you just have this step and it goes to
AD converter analog to digital converter.
So this is the some technical details and we want to
convert high frequency signal into low frequency signal so that we can do digitization.
So we have
half of the conversion done from analog continuous domain to digital domain we put into
digital computer then we can manipulate.
So these are typically electrical engineering stuff.
And for background field there are three ways to generate a background field.
The mainstream way
is to use a superconducting magnet and a very cold environment.
Then the wire will have zero
resistance.
That's a very amazing thing.
And if you do not use a superconducting magnet
you could use a permanent magnet on a very high way but cost effective.
If the total field strength
is less than say 0.35 tesla you can use a permanent magnet.
Indeed for some low-end
or open MR scanner permanent magnetic is indeed in use still in use but mainstream is superconducting
magnet.
The third way you do not use superconducting no permanent magnet and then you use a coil
so like a like some copper coil you inject the current this coil will generate a magnetic field
but this is not very good.
You inject current into a coil you will generate some heat and this
noise is hot is not a very good way and this is at least at this moment superconducting magnet
is the main way.
So in your textbook in grayscale picture you see the
internal internal cross-section and this is not very clear I think so I copied from internet
so we have a color version and you see first you can feel heating into this
this container so this will be very cold this is it will be very cold and that so this ring
is a main winding basically the coils use certain metal alloy and when the heating is cold low enough
the magically the resistance of these main widings all of a sudden will disappear
this is called a superconducting and normally you think whenever you have a circuit the conductor
will have have resistance even small they will have resistance but when the temperature is really
low the resistance totally disappear this is a magic thing and in our physics department many
years ago a professor did some fundamental research explaining super fluid

superconducting
phenomena and he got a Nobel prize okay this is a very cool thing if you click the first link you can see explanation this is nothing different from what I mentioned the
third way you use a coil you inject the current you generate the field this same thing and this
first way superconducting way the only unique thing everything is the same except the resistance
zero then you just have a big current going through no energy consumption so this is just
a good thing and the energy saving and you can generate a very strong magnetic field and the
second link is kind of also very interesting it doesn't make some comments and the second link
is a block and in mixture English Chinese written by my former former postdoctoral fellow
and he developed a certain formalism this is say quantum mechanics quantum mechanics treat matter
as a wave and a particle so as a particle moving around according to probability wave and some
further theoretical extension says the probability wave and the classic theory the current
mainstream theory say the probability wave can only be non-negative okay but in extended quantum
theory says the probability wave can be positive and zero and it can be negative then positive again
then that means the particle in the positive reason could jump to the other reason and the
result appearing in the in the in the middle because in the middle the probability is negative
what what do you mean negative probability this is just not not possible so this phenomena called
teleportation so the object here and all of a sudden appear here so without the continuous
transportation so this is a very cool thing and no one know it is true or not but at least to
certain degree quantum mechanics support such magic and my my former postdoc Dr. Wei believes
this could explain superconducting and superfluid that is his opinion and I'm not expert just some
information for you to know so the big magnetic superconducting magnet offers b0 field and we know
we need a gradient field and how you generate a gradient field gradient field
gradient is constant but the field will change linearly so how you generate that and we need
three gradients okay linear gradients b z b y b x so just to look at the middle portion
it kind of linear how you generate so these are coils just to show you the idea with this kind
of coil you generate a linear gradient here it's not always linear but we only use the middle
portion likewise here why you you wire the coil these ways and then the three gradient field
will be generated so why so we do not need a solve maximum equation to understand and always nice
particularly for undergraduate level medical imaging class you just get a heuristic understanding
why you wire coil this way you could generate this linear change so you may consider have you
when you read the chapter have you ever considered why you generate linear field the idea is very
simple so just to show you here and then we learned in high school so you have a single
10 coil this is a path current this way okay your any single single wire you

pass a current
upward that magnetic field will be formed just the isocircle so you know this okay if you just
put this you just just banded this wire into a circle so the field will be so locally you see
this is a piece of current current moving we say moving this way then the field will go isocircle
but all these small isocircles you banded into a loop they will collectively form a field
towards right hand side so something like this so you make a turn this is somehow like a small
magnet towards right hand side right so the strength is one just one circle if you have
hundred circles then the strength will be increased by hundred folds so this is just
what you learned in high school okay then if you put a symmetric coil pointing the other direction
opposite direction so by symmetric consideration these two things together the middle field will
be zero right if you move towards left hand side and this right component will be stronger
green components will be weaker if you move from the zero position towards right hand side
what i just described still valid but in opposite way so green components will be
stronger if you move this way the right component will be weaker so this idea and in the middle
region can be approximated as a linear curl so this is a linear field formed between that's why
you have the opposite curve opposite magnetic field formed by left and right coil this is z
gradient formed this way that's the idea therefore x and y gradient you cannot just put the circle
the same way because this is a gun try the patient is supposed to go through this tunnel
so you cannot make the same thing for x y z greedy but the idea is the same like for y
gradient you have a top coil and the bottom coil the the top coil plays the same same role the
top coil is the form a loop just in this kind of a saddle curl thing but you still form the the the
current current inside the closed loop so you may have a field go go down and then the bottom one
have a field go up in the middle you have zero you move up then one field will be more dominated
than the other so the same thing so you you you form the y field the whole thing you turn
90 degree then you have the x greeting this same idea so all put together you have a configuration
like this so all these circles lines together you can just excite the way you want you can have
arbitrary g x g y g z greetings formed so the greeting coil just the basic idea i think that's
a good understanding and certainly you can just design the coil how many layers that you can even
add the so-called the shaming coil make sure the field is really linear so a lot of details
the essential idea you have governing equation maximum equation just for four equations and
you do finite element digital computation you add a coil you change the shape add some small things
see if a field get better or not you keep doing try and error you eventually you will have a good
design as simple idea as as this one okay then the b1 field the missing

components the b1 field
is generated by rf coil in this border cage shape the idea again it can be heuristically
understand so if you think these two to cross section so the connecting wire goes this way
the current goes this way you have local field so kind of pointing down okay then here you want
the local field the point up then the current should go the other direction so it does a form
a loop and then this is basic basic configuration so you have a field here going down field here
going down you need adding more cross-section you have a more current going into the page
so you you you just have all these downward field component added together a little weaker
but not not a little weaker than previous current so that this downward component is maintained
so you keep adding things and here the current is even weaker so altogether you form a field
uniformly towards bottom side so just this cross-section so the overall field the b0
field is uniform everywhere pointing towards the bottom and mathematically we can prove
if you make sure the current modulated as a sinusoidal function and as a phi angle so this is
you call this a phi 0, phi 90 degree so you just make the current modulated in this curve
as a function of this see here is a phi angle depends on this the phi angle zero means going
upward so just change the phi angle make sure the current injecting this way moving back
then that way moving back the current intensity depends on this a phi angle so you have a uniform
field and then we say the uniform field b0 need to be a rotating field so that you can flip the
m vector consistently and how you make sure this b0 field right now the field
pointing to bottom how you make sure this just rotate it you just need
modulate the current so at a given moment the maximum is here minimum is here then
next moment you make sure maximum is here then next moment maximum is here accordingly the
minimum will keep moving this direction so this way you just have the this b1 field
keep changing as a function of time so you you can form a rotating b0 okay so you have b0 b1 gx
ggy gg all these basic structures can be understood using high school physics this is
just the basic concept but to be precise you really need to have a sophisticated
optimizer using finite element analysis and so on and the b1 field if you have a surface coil
is not a whole bird's cage covering whole patient you can use the so-called surface coil near the
spinal cord or breast for breast imaging and spinal imaging so you can have the signal generated
near surface coil so you got a small part you can use a mini surface coil to do parallel
MRI imaging this has been very hard for past several years parallel MRI imaging you use
all kinds of coil covering a patient anyway so this is the basic idea of
MRI scanner hardware components and what's going on and why you have
the system configuration looks like what i just showed you and how you can form
field b0 b1 and the gradients xyz and what's the idea and i explained it so just try to stay this
basic level understand what's going on that's good enough so next part really

main part
pulse sequences and then we learned the pulse sequences particularly spin echo so you can measure
t1 weighted t2 weighted proton density and also we will mention grating echo for even faster
imaging speed there are a few variants called MRI angiography and the diffusion weighted imaging
spectroscopy and finally MRI contrast agent and the safety issue so these are basically about
more advanced pulse sequences and then we learned before and the MRI imaging essentially
a Fourier imaging mode and with the Fourier transform we understand what's going on clearly
and this slide is a key so if you understand this slide the rest of the pulse sequences
can be in different forms but you know what's going on so in the stationary frame the overall
signal overall signal the m vector is proportional to proton density okay so that's the proton
density is rho as a function of xy and in selected slides and the base phase encoding and the
and the frequency encoding you have exponential factor so here so gamma g and times the spacial
components times the time upon which the grating field is applied so all these things are added
together is for phase encoding is a phase factor for frequency encoding that's a signal you are
going to measure but overall these are just give you instantaneous phase factor for that
instantaneous phase factor or instantaneous frequency for the particular xy location so the
phase factor the instantaneous resonance frequency all change because of grating field
because of the location specific change you can get tomographic information
otherwise all information in the same precision of frequency then you get a signal from
whole sample whole section you cannot know where signal come from so phase encoding
frequency encoding really decompose the two-dimensional space into just the
specific locations and then you can unravel the system get a tomographic image that's the idea
I mentioned that these time together for these factors times time that get multiplied together
for phase encoding give you phase factor so this is a real thing but to put it in
case-based theorem in Fourier transformation what we do we divided by two pi then we need
a multiply by two pi so this is a real thing is that the physically physically physically
oriented derivation then we do mathematical manipulation we divided by two pi multiplied
by two pi after multiplication with a factor two pi and this is in the form of Fourier transformation
then we know this is a signal after phase and frequency encoding so this overall is your signal
and this signal mathematically is nothing but a Fourier transformation we learned we know
Fourier transformation is a function weighted by by Fourier kernel then you do the two-dimensional
double integral you get that and then we say phase encoding frequency encoding really talk about
you manipulate the m vector in a location specific fashion so m vector usually is an
overall thing for whole section or for whole sample but also we know m vector

really combined
with all of a small m vectors all the small vector each pixel you have a small m vector so all these small m vector added together form your big overall m vector
this phase encoding and the frequency encoding you really manipulate specifically about these
all these pixel specific small m vector all the the pixel associated spins so with phase encoding
you do not do measurement you you just introduce a different phase vectors to some of
or introduce different phase factors to these small spins and with the frequency encoding
you measure the signals at a different frequency of all these small small spins or small m vectors
so phase and the frequency encoding should be interpreted in this way you want to accumulate
phase you use phase encoding you want to measure the signal at a different frequency you use a
frequency encoding so just the two ways so not specific to x or y orientation so that's why I
say you can do nothing about phase encoding you just directly do frequency encoding with both
gx and gy you collect the signal so the frequency domain in the case base will just move along this
line so this is a starting point or you do not do frequency encoding just do phase encoding
accumulate phase vector make sure the phase vector for x and for y for this kx and ky both
you make them negative you move the the current point the system state into this point you do
not do any data acquisition or you just do phase encoding this way then you do frequency encoding
you collect the signal along the the horizontal direction you can do phase encoding move the
current point the current point means the system status what's the phase vector initially nothing
has been done so you got nothing here so you need initial status is at the origin of the case base
okay just here if you do phase encoding more this point current point to this direction
then you do frequency encoding you just collect the signal this way and then you can do phase
encoding the other way more the current point here that means you accumulate a negative phase
vectors with gy phase encoding then you use it with gx phase encoding you move the you introduce
a negative phase vector here then you use gy to do frequency encoding you collect the signal
the collect signal as time goes by so the as time goes by this will keep changing in frequency domain
that's corresponding to a trajectory moving from a current point all the way upward so you have all
the freedom to move the system status initial status is at the origin here and with phase encoding
you have freedom to move this point any any place you want after you have a current location
then you can use gx gy to drive this anyway you want but you this time of frequency encoding
and you start collecting signal you have any signal the red line means you you are recording
the signal so the trajectory moves as you you you drive you direct with the gradients so you
collect the signal this signal a case base signal that gave you four real components one line is

not enough you need to really move one line another line you just need a feeling the whole case base then you can perform inverse for transformation so that's the key idea so you can just do anyway you want as long as you're feeling the whole case base and if the function is a real function you do not need to fill in the whole space it's just a half space you say it doesn't fill in this part the other part by symmetry you can recover but in reality oftentimes the imaging performance is more stable if you're feeling whole for a space so this is slice is a summary if you understand this one so you know the green part is a initial state of the case base and you you can use face encoding put the initial point anywhere then you do frequency encoding you collect the signal along any trajectory so you use a constant here you use a constant gy gradient to collect this way so you use a constant gx and gy you collect along this curve so if you move halfway you change the mind you just make a different gx gy the slope will be changed so this is not necessarily straight line and for each small time incident it goes small straight segment and the next point all depends on how you set gx gy it can go any orientation so this is some arbitrary thing that's why we have many pulse sequences so this is idea hope you follow me otherwise just keep reading thinking and feel free ask ta or myself understand this case space theorem so spin echo we learned so you use it slice selection process so make sure you get your flip the whole body you have all these spins but with slice selection you you utilize the resonance property so you only flip m vector within the slice so you have this positive one then you have this negative one for refacing whenever you use a grading signal all the small spins within the range will be flipped but the field is linearly changing so some field is stronger some field is weaker so stronger field will have a larger phase factor weaker field will have a smaller phase vector so these phase difference will not not be good in terms of overall m vector this is defacing your artificially introduced this is defacing factor can be can be undone with a negative pulse because the negative pulse will just undo the defacing and then you make sure the area for the positive part that's overall defacing that this area for the negative part that's overall
first is defacing and the second part is overall refacing the area refacing
is half of overall area under the curve for defacing why does the half area because when you do defacing everything deface but the middle curve is a standard we want to recover the middle curve is halfway so you do not need to do refocusing all the way back to the original you're just refocusing to the average so they have this half area so for for phase for slice selection you have this process okay for frequency for frequency encoding and then you also need to do the same thing frequency encoding you try to read out the signal you want to get a maximum

signal to know as a result but the frequency frequency encoding is also a defacing process
we use this this part to do refocusing and again the area under the pulse here is just the half
of the area under this so this is just do refacing to in advance refacing in advance to undo defacing
by this frequency encoding path okay but why you see the same
polarity here because of this 180 degree so this looks positive but after 180 degree you have this
pulse and it's just in opposite polarity of the first one so this 180 degree pulse
just make the polarity on both side appears the same direction but actually in opposite direction
and the phase encoding you don't want to undo that because of phase encoding you introduce
different phase factors okay these differences should stay then we can tell difference we know
different phase angle corresponding to different line anyway so this is spin echo sequence
and this is a time for echo time for repetition and this part is not utilized we can fade in
other pulse sequences to utilize the space here and we can use multi-slice imaging so this part
we can use another slice selection say this part we select slice one and this part we still have
time and then we can introduce slice three spin echo then this time we do a slice four slice two
slice four so just in alternating fashion we try to make an efficient use of the spaces why you do
slice selection in this alternating fashion because whenever you do slice selection there are some
blurring spreading effect just in neighborhood so if you just make sure your adjacent
excitation is separate far enough you don't have a crosstalk the image quality will be neater
cleaner okay so this is a multi-slice imaging okay very good so multi-slice imaging spin echo
spin echo is the best to give you a signal to best signal to noise result because the
the echo really used to undo defacing due to t star so you try to recover purely t2 t2 is a
biological effect that is what you want to cover but the downside is spin echo is slow
because you need the tr time for everything returned to the normal so this is a kind of
time consuming for medical imaging spin echo may take say half hour 20 minutes that's too long
so sometimes you want to do imaging within price hold you want to get a sub minute scan
in this case you just do not want to do a spin echo you use the so-called
grading echo imaging so grading echo imaging and there are some discussions in your textbook
and yes in grading echo imaging you do not use 180 degree pulse so you do not flip things
that's the defacing effect due to inhomogeneity in magnetic field you refocus the signal you
get a better signal but you take a longer time so grading echo do not do that so this is idea for
grading echo you make a small angle uh flip then just the just the refocus using using so-called
grading echo imaging so you have a phase imaging you have immediately you have this
frequency frequency encoding then you you have this second phase encoding the signal will be

read out here so the two phase encoding and that gives you two components in the three
dimensional Fourier transform the one frequency encoding gave you a third dimension so this is
for volumetric imaging you really flip you get a signal you do not wait for echo you immediately
read out the signal the signal will decay quickly and the subject to t2 star t2 star is more serious
much more serious than much stronger than t t2 so that's why the signal will be small but you
don't wait for echo so overall 3d acquisition can be done in this way and the 3d acquisition
express a three-dimensional Fourier transform the signal noise result is not as good as
spin echo but the imaging speed is very quick let's just have a rest for seven
minutes come back one clock we finish the rest of the lecture okay
okay
3d grading echo imaging is for faster imaging speed there is a complex complex dynamics involved
this is small spin angle so initially you have m vector you flip a small angle so the larger
angle you get a higher signal for that round so if you make the angle very big like 90 degree
you have very large angle at that part but given small tr time and you recover the m vector
to a small value then next time you flip alpha angle again because you have only small angle
involved at that moment the signal will be small due to that alpha degree flipping so this is a
complicated process really involves tr te alpha and the derivation shows there is an optimal value
alpha angle so there are some discussion in your green textbook but the derivation is not required
just say there are some optimal small angles if you do so without involving 180 degree
pulse without waiting for echo you can still get a signal because the m vector whenever you flip
you will have a horizontal component okay these components will give you a signal certainly this
signal will subject to t2 start decay you need to do everything fast the signal noise result
isn't that good because t2 t2 star is a very strong effect but you can still have a signal
and just for faster imaging oftentimes faster imaging is a paramount important just like
actually ct we say holly grail is a very fast cardiac ct imager so this is 3d
grading echo imaging was designed for the purpose of reducing acquisition time associated with
and we can do even better we use it planar echo planar imaging see this 3d
gradient echo you still need to repeat multiple times and the echo planar imaging in principle
just the one one flipping you're flipping the m vector into the xy plane okay it's 90 degree
flipping and the slice selection is just for one given slice then you do phase encoding in this
way and the frequency encoding in this kind of oscillating way you just get a signal the negative
cycle positive cycle negative cycle so in case space what will happen so the slice selection
specify one one plane say xy plane xy plane on xy plane you have function okay the function
has a Fourier transformation defined in kx ky domain so this phase encoding make this very
negative so the phase encoding more the the system initial status point from the

origin all the way
to negative and the frequency encoding here equal to read because the frequency encoding used
for reading so frequency encoding i think it makes a negative part so the phase encoding here
move this initial phase of a phase vector the state from system state from origin to negative
then you have the negative before you read that you put a phase encoding in in this place you move
this vector towards negative side so this is initial thing then you come to this positive
read greeting then that read greeting will drive this trajectory move from the current
state all the way to this then you have this positive phase vector so you accumulate the phase
move it here then you get a get a phase frequency encoding again but this time is a negative
for negative phase encoding then as time goes by and the trajectory will the right trajectory will
move towards the left hand side then you have a positive phase encoding again move this here so
whenever you have the small phase encoding up up up all these small upward segment no data acquisition
i will happen but the data acquisition will happen when you have the read or frequency encoding
negative or positive when you have a positive greetings here and the trajectory will be driven
this way negative greeting will be driven that way you keep doing the right hand side away
left hand side away then you feed in the k-space so you do so quickly without waiting for echo
and you have you start with initially quite a big signal 90 degree then you try to get the signal
as data acquisition goes on you can understand the signal strength becomes smaller smaller
smaller and this decay subject to t2 or t2 star is t2 star decay so you've got
this echo planar imaging for very fast data acquisition oftentimes the data
decay decreased fast enough and it may be once one echo planar imaging you only cover a quarter
of the forest space you may do it four times but it's still faster than typical 3d greeting echo
pulse sequence so this is echo planar imaging and yet even even better in many cases we use
spiral imaging so spiral imaging no face encoding at all so the initial point when i say initial
point or system face factor or system state start with origin because you have the gx gy
continuously changing the relative amplitude the gx and gy determines instantaneous slope so
initially the instantaneous slope is towards this direction so you move small segment this way then
the relative amplitude the gx gy greeting changed so from this from this initial
direction slope changed to this way this way this way they keep changing you control you you have
all the freedom to control gx gy so this instantaneous direction keep changing this
way so as a result and you you are collecting data following this spiral trajectory and as
spread out the whole case base is covered you start with with the
low frequency then you move to upper frequency and certainly this idea you can modify you can
let a spiral go with the center say this way you do spiral the other way you do spiral you can do
double spiral you spiral from inner location outward or you from some external

some peripheral
location and the spiral inward and the many ways so as i said in the summary slides once you
understand you have full control of the initial phase phase location phase vector and you have
full control of instantaneous frequency encoding direction and you can really cover case base
anyway you want using this zigzag pattern or you use spiral pattern anyway you you want to do
then you can you can collect case base data then you recover underlying image either t1 weighted
or t2 weighted or proton weighted images can be can be done so if you understand the initial
slice this is this slice is very important this slice you understand this one the rest is i would
say piece of cake if you do not understand that one you do not know why the case base data can be
collected through phase and the frequency encoding and the other part will look confusing to you i
hope you either already or just will spend more time to understand the case base data formation
image formation mechanism okay and furthermore and we can design more dedicated pulse
sequence for specific applications so let's say we want to do MRI angiography so first let's recall
what we did for CT angiography we say for CT angiography you try to see vasculature however
vessel blood do not look very much different from soft tissue if you take regular CT image so blood
vessel soft tissue all look similar so you do not see where is your vasculature very clearly
therefore you cannot see if your vessel got blocked you have cardiac disease or your your
blood vessel just look normal so what we did for CT imaging you inject the contrast agent
called iodine iodine is a kind of liquid metal so very high actually linear attenuation coefficient
you inject a bottle of iodine into your bloodstream so you take actually picture your bloodstream
contain iodine it's a more dense and the stronger attenuation so in CT image your blood vessel will
be lightened up so it's a normal diameter is seen all of a sudden get narrowing you say okay your
vasculature in the heart got problem your main vessel got 80 percentage blockage then you need
to put a stenting otherwise you will die from cardiac disease so this is what we do with CT
angiography for MRI angiography we can do something different but the purpose remain the same so you
select one slice okay this one slice you select and what will happen all the spins
all the spins are magnetic magnetic small magnets they flip they use spin you use
eco-planar imaging so all the spins just flip this way and at this very moment if you collect
signal out so all the signal will be collected so the in the vessel and in the blood and outside
the vessel in your soft tissue the signal will be more or less the same because this
soft tissue blood basically water so the signal will be the same however if you wait a little
longer because in the vessel the blood keep moving out of plane so through plane mechanism
can be utilized for MRI angiography so you wait a little longer the the blood in

which
you flip the m vector is a move out so the new blood comes in the new blood no signal
because you didn't flip anything outside the plane you selected so after a little while you
take an image then the the MRI pixel values for the blood and then for the surrounding tissue
will be different so this way you can see blood vasculature clearly so this is what I call
through plane mechanism so this is the idea you need to know but this mechanism only works
when the blood stream is perpendicular the blood motion direction is perpendicular to the slice
you selected but if you have the vessel just move within the slice the MRI slice selection can be
in any orientation the chance is that you have this slice selected the vessel moves within the
plane so in this way this mechanism wouldn't work then we have this face contrast imaging
mode which is a in-plane mechanism actually any direction the blood stream
propagate and circulate it doesn't matter the idea like this look at the imaging sequence like the
echo planar imaging you have alpha pulse this m vector flipped by angle alpha this is the slice
selection and this part is say defacing this is a refocusing effect so you select the slice
make sure all the vectors small m vectors all the spins just have a collective synergistic effect
will give you signal anywhere in the slides then for frequency encoding so you use
frequency encoding you use the face encoding you could collect the Fourier information for that
slice again if you do so if just in the plane you just have a moving blood you have soft tissue
so if you do these regular things you perform Fourier transform not everything will look the
same in terms of t1 t2 row because blood and the soft tissue they are quite the same so signal
pixel values will be quite the same however if in this frequency encoding line and you introduce
this positive pulse and the negative pulse here so these are positive pulse negative pulse
you will have before data acquisition you perform data acquisition here so before data acquisition
you have this positive and negative effect together the positive will increase
and although this is a frequency encoding here you didn't collect the data and the positive
pulse will serve face encoding so this will add the face to everything okay then here you will
reduce the the face so these two things will be combined no effect if nothing in motion however
the blood will move from one place to another place so if no motion then the positive negative
pulses will cancel out their effect but if blood is is in motion so the pulse the positive and
the negative effect will not be cancelled out because the blood blood cell move from one location
to the other location they will be in different local magnetic field so the face factor will be
will be accumulated at a different rate so this way they add together they will not be the same
so you have a absolute face factor introduced here the absolute face factor is not most useful
because the absolute face factor could be due to motion could be due to some

many other things
so what we will do we first introduce this way so we got a face vector then we first put a negative
face a negative pulse here then we put a positive pulse here then we you introduce another total
face these two effect subtracted together then you got a face difference that face difference
is purely due to blood cell motion so that can be imaged to show blood vessel better so they say
face contrast imaging is not like x-ray face contrast imaging that's really talking about
how x-ray is banded due to refractive index here the face contrast imaging talking about
face vector due to blood cell circulate around and it doesn't it doesn't matter
the blood stream goes any direction as long as the blood cell from one place to another place
and they subject to different local field then this face effect positive negative wouldn't be
cancelled out that will show up to give you idea where is your blood vessel if the vessel is narrow
or no problem so this is just for MRI and geography I explained to you through plane
is a positive a passive effect and the face contrast imaging is active effect you really
just make make use of the fact that blood vessel keep moving around then you can have a different
signal contrast okay
and the blood is in circulation and also in human body and we are pretty much a water body
water is also moving around and this is pathologically important if we say you got
some problem your shell got swollen the membrane and the damaged and you have water component
leakage so water diffusion perfusion becomes physiologically pathologically important in this
case and we can do motion imaging pretty much like like angiography imaging but here we're talking
about the diffusion weighted imaging and the idea is is similar I would say and that but if you
look at the pulse sequence and they may look a little different say now we consider spin echo
you have 90 180 degree pulses and it's just that symmetric to this 180 degree pulse and then we
have positive we have left side and the and the right side so we can on both sides symmetrically
we can have a just a grading pulse towards both directions but we know this 180 degree means
upside down so you have a positive side this positive side really a negative side from the
perspective of your left pulse right so if nothing in motion again this pulse side will
accumulate a certain phase and this negative pulse will just undo any phase accumulated
due to this positive pulse and the other things are just a standard spin echo pulse sequence
so these two highlight the same just do nothing for stationary water molecule
in water molecule you have protons that's the source of MRI signal but if the water
keeps moving from one location to another location again same argument the
instant one the water molecule is here and then the instant two water molecule moves to
another location these two locations are in different magnetic field strength so the phase
factor wouldn't be accumulated at both locations wouldn't be the same so you can

have a signal
difference what's the signal difference and you have equation 4.65 so the signal strength due to
the water molecular diffusion depends on the strength of the field and also depends on
the total duration of the field delta and the separation of the paired field this is denoted
by capital delta depends on all these parameters and we can derive and we wouldn't derive and we
do not ask you to know how to derive but the formula shows here is like this so we know
the diffusion efficiency depends on all these and it can be measured so that's important so with
spin echo we can see within one direction how through through plane direction how water
molecular will will diffuse towards that direction if if it's strong that may mean
and then your your shell got some problem and this diffusion rate is not a constant
the diffusion rate is different from place to place and also it's a directionally sensitive
so if you you you measure the diffusion rate along this direction to got certain value along
the other direction the value may be different and again a different value along the other
direction so when you have this directionally dependent vectors putting together and this is
not a simple thing like just a uniform motion can be described by a single vector and the amplitude
is your speed direction is the direction of the motion but here the rate depends on orientation
we call this extended concept of vector called we call it a tensor so for different orientation
you have a different rate so the tensor is here is a matrix just to characterize the
diffusion rate as a function of direction it gave you different value and this is very reasonable
because the diffusion may follow say may follow certain fiber principal axis and the blood
moves along vasculature so vasculature take a certain directions so all these things
putting together and then we can have a colorful images and then encoding x y z direction in rgb
colors and based on the color you know and at a particular point along this direction
the diffusion rate is higher so they you have this basically very colorful
mapping and this is a good for brain imaging as well so you see this functional information
so MRI is often side functional imaging modality and CT is more like anatomical imaging modality
so you see the blood perfusion and the water perfusion through the diffusion weighted pulse
sequence and the last one is a spectral imaging so this is just keep adding layers
on the MRI imaging so you'll get more and more information but the essential idea is still
Fourier imaging mode so what is the spectral imaging so pay attention to this highlighted
sentence and when we say MRI imaging previously we say after phase frequency encoding and you have
different phase different frequency but if you you zoom into a specific pixel or voxel the signal
from that pixel or voxel has a single frequency but here spectral imaging really the single pixel

voxel will give you signals at a different frequency why you have a different frequency
because the water molecules are in different situation or in different combined and the
different signal will come out and these are very important say water molecule in certain protein
we will have a frequency slightly different from pure water background so all these small peaks
show the biomolecules and the protons in different combination composition or in different
micro local environment so you want to measure multiple frequencies from single pixel or voxel
you will have more biological information right so this is idea then it comes out how you can
excite a specific pixel or voxel or specific space get the pixel specific spectral information
and there are two ways this is like privacy we say you have you have
and geography and you have a passive way you have active way here you also have two ways
one way i like this very much it's called positional resolving something the price
and this method one and let me explain this method one and just see how the m vector can be
cleverly manipulated so you get a signal only from one pixel and the other signal i don't care
so i say side without any any manipulation you use a generic spin echo the signal
come out from a whole sample now with this price pulse sequence i can get a signal
from any point or any region how can we do that it still use a spin echo but a modified version
so you use it 90 degree pulse coupled with slice selection the slice selection you select
this right slice thin or thick it doesn't matter you just use it 90 degree so all the spins in this
slab or slice got flipped okay if you measure now all signal will come from this right block
okay okay then you wait for quarter time of te you use this 180 pulse the 180 pulse
and then in this plane you select it just select this green plane so green plane and the right
plane has an intersection denoted by this green line so you do 180 degree
flipping the 180 degree and wait for echo so echo will only happen along this line because
the flipping this one is implemented by gy so gy select this green is a green slab so only spins
flipped initially by 90 degree is in right is in right slice and you use a 180 degree you just
flip 180 degree only within this green slice but in green slice only along this green line
you have an active signal so only spins along this green line got flipped then you wait for
quarter time this is a quarter time of te a quarter time te here quarter time te just put
this quarter time te another quarter time you have a quarter time defacing you need a quarter time
guide the signal back so echo will be formed at this time point the echo signal if you measure
we do not measure but if you measure at this time instant the signal will come from the pixels along
this green line okay then we wait for another quarter time so all the refocus the spins along
green line will be defocused a little bit then here we apply second 180 degree pulse using this

gg here so this is a plane here this is the plane so then when you do this flipping so only because the slice selection effect by gg so only the spins in this blue
slice got 180 degree flipping so effectively the intersection of this this blue blue plane and this green line is the pixel you want to select so only the spins defocus
the defocus the spins within this region of inches that get flipped you wait at the final
quarter te and then you have an echo only from this small pixel so this is the idea and how you
get a signal selected from a single region of interest or a single voxel and then you have a
signal the signal contain multiple components all from the same signal the the signal can be
for analysis that you resolve the spectrum as we hope to get here to get the spectral analysis
this way this is the method of price so just try to understand this idea and the the next method
called a chemical safety imaging this is a little tricky so i put a green button here but the idea
is i think is even better and this is something often used but time consuming so in this case
what you will do i summarize in the right box you have a slice selection you get one slice
then you use two gradients gx gy only for phase encoding so you do phase encoding after phase encoding
and then you collect the signal okay after phase encoding you collect the signal the signal is a
time signal and then you perform forward Fourier transform then that will give you spectrum
of what we want so this explained in this right box but you may not be able to understand
so i just say you read these slides try to understand and just at least superficially but how mathematically all play together this it takes one more layer of complexity
if you are graduate student say if supervisor told you you try to do spectral scoping and just
follow this step and then you you are supposed to fill in out the mathematical detail but for
this undergraduate lecture you just know how this will be performed what outcome will we will get
that's okay okay like a CT imaging and the MRI imaging can be improved with the contrast material
like typically like this one magnet based and this is something shown here you've got some
some electron unpaired unpaired electron locations seven locations and there is a very strong
magnetic
magnetic inhomogeneity that will improve signal to noise ratio so you introduce contrast agent
into human body and the contrast that will accumulate in those area where vasculature
is rich and that is oftentimes a tumor area signal will show strongly the same idea like
x-ray contrast agent just utilize some unpaired electrons so that the local field is altered
and you have a strong signal and usually people argue MRI is a green imaging technology
is very safe it's not like actually CT ionizing radiation is involved so we spend a lot of time
to reduce actually those so MRI has been saying use a magnetic resonance no harm but now we found
this contrast agent is a problem so this is a contrast agent and the recent study indicated

and the the contrast agent is not very safe and oftentimes you put the contrast agent in certain
chemical case but the results the agent could stay in human body for a long time so as a result
the european community prohibit certain kinds of popular MRI contrast agent from being used in
clinical practice so MRI has its problem as well so the contrast agent may stay in brain even go
into bone so contrast agent is a problem so just not every contrast agent so this is something
nice to know and not in your textbook but these are latest development so just for your information
so MRI scanner and the pulse sequences are the main thing the rest the two part I just go through
with you quickly and not required just for your information MRI is very powerful most important
thing for brain imaging and not only for medical imaging also for some basic research we try to
understand the neurological function and try to understand how human brain will work and this
becomes a very hot topic in united states in europe and in china japan and the government
spend a lot of time try to unlock the ultimate mystery of human intelligence how brain
will work and MRI is very helpful so you can find a lot of materials say if you show a subject
just the house subject you show some of human faces or you saw the subject volunteers buildings
the brain reaction look different whenever you think you react so the blood carrying oxygen
oxygen reads the blood and the oxygen oxygen pour blood and it will circulate differently
when you're thinking you need the oxygen reads the blood then you you finish the job and the
energy will be will be taken away so these can be shown in MRI images because oxygen reads blood
I think give you a stronger MRI signal so when you just take an MRI picture during the recognition
tasks so you have different images so you can perform a statistical analysis so when you see
certain type of object the pattern MRI image pattern will be different when you see other
kind of object in this case is the buildings so pretty much you just look at the image you can
reliably infer what you are looking at and this is a very early years experiment later on people
did more and more complicated analysis and the latest result I didn't copy here and based on
image analysis we can reconstruct what you are seeing so not in good resolution so that kind
of tomography based on the signal you reconstruct the image of what you perceived so you look into
your peek into your own private thought so this is a very cool thing and I recommend you
recommend you to watch this video and about 10 minutes video is very much
amazing mind reading and the particular point and the possibility you show criminal the criminal
may say I didn't commit I didn't kill anyone but you just put a criminal in a room you use
a virtual reality show the picture one room the other room and oftentimes when the picture is the
location where he or she committed the crime and then the brain signal will be will be different
so you can just use MRI imaging to read a read a mind and then in the future you

can do other
testaments so many fascinating opportunities this is the I wouldn't play the YouTube here but you
really should your homework okay you really should watch it the last one again not required
this is a few minutes and minds and some no idea so far we learned the CT we learned the
nuclear imaging now we cover the MRI in terms of imaging modality fusion CT spec that so
the CT spec the CT already made for cancer imaging and also
pattern and the MRI put it together in so-called MRI pattern scanner by Siemens so this is just the
for synergy between pattern and MRI and we argue CT and MRI should be put together as well like a
cardiac imaging and the CT show vasculature calcification MRI shows soft tissue function
so this will be the last dual modality combination so eventually we hope
all the imaging modalities can be put together so our group has been promoting this direction
we call it omni tomography we say all in one all imaging modality CT nuclear MRI put it together
and you acquire data not you not do separately you just do CT then you do nuclear then you do MRI
you really want to do one scan CT nuclear MRI all data together is called all at once so we
are working along this direction this is a vision paper or perspective paper arguing why we want to
do this how we want to do this in the paper we build a toy system with all the scanner together
and then more specifically we build the MRI scanner as we build the we finish the design of
MRI scanner okay that's the first step how you put a CT MRI scanner together so those you are
interested that you can check our paper and then we also considered make a low end version
and not a CT MRI high performance low performance we use permanent magnetic field so for one view
you get an MRI projection and the x-ray projection together and then you rotate
and you can get a CT MRI together so all these are possibilities and use the MRI scanner to guide
releasing therapy so when you have cancer releasing therapy will send a highly energetic beam to kill
the cancer this should be guided by image like this interior MRI only show MRI image within a
small region of interest so we are collaborating with UT Southwestern professors so we're working
along this direction a latest one we reported the last year based on polarized radio tracer
previously we learned gamma ray imaging the radio tracer the
I made a gamma ray photons randomly any direction but a polarized radio tracer has
directional preference the gamma ray only emitted along horizontal direction okay the
vertical direction no gamma ray at all and this polarization direction can be manipulated by
MRI mechanism pretty much like the m vector we use a pulse sequence you use the
the RF signal we can be one field we can flip the m vector here use b1 field you can flip the
orientation like in this configuration you don't have gamma ray photons along the z direction
but you flip the m vector not m vector we may call it n vector we flip it this way
then you can you can collect the gamma ray photons along z direction so this way you can

collect the signals for nuclear imaging the result reported in a nature paper they say
emission can be emission tomography can be done to map radio tracer spatial distribution
and our paper say you cannot only measure the emission tracer concentration this way we can
derive attenuation background as well just like a nuclear imaging you need to do attenuation
background imaging so with this polarized tracer we can actually measure both tracer
concentration and attenuation coefficient attenuation coefficient is a CT job so with
this polarized radio tracer we can do both emission and the transmission tomography
together idealized polarized tracer should be something within 30 minutes or
minutes but the available product either too long a half life too long or too short so we are working
collaborating with some chemists that try to find good tracer and we want to find a cost effective
way to polarize the radio tracer that we can use this is the MRI imaging mode we just learned
you can selectively turn any pixel on using this system design so I mentioned each polarized
tracer like a donut you can flip any way you want certainly you wouldn't get any signal
so along this line so you have detected you have no signal but if you turn on one signal
so you got a measurement this is one way the measurement the other way so each pixel you
have two unknown the mu is a local linear attenuation coefficient lambda is a local
concentration so you have two unknown you have two measurement left and the right you can turn
individual pixel on so you get both the mu and the lambda resolved so this is a rough idea and
how you use a polarized tracer to do emission and the transmission tomography this is in
MRI framework so it's not surprising you can collect the MRI signal as well so this will be
a good way to do CT in terms of attenuation MRI in terms of radio tracer concentration
and nuclear imaging in terms of radio tracer concentration you can also do MRI whole body
imaging because now the radio tracer is flipped the gamma ray will be detected
either this location or the other location so the collimation is done magnetically you do not need
a mechanical collimator mechanical collimator only get a signal from one direction so a lot of
gamma ray photon is wasted and here you do not waste any gamma ray photon so i think this is a
kind of future possibility so last slide and you watch the youtube video and also you draw
diagram for all power sequences covered in this lecture try to understand the
imaging principle and read the textbook from next lecture on and we learn
ultrasound okay so much for today