Optimizing MRI Protocols
(SNR, CNR, Spatial Accuracy)

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Overview

- Parameters Affecting Image Quality
- Manipulating Image Contrast (Standard)
- Classifications of Pulse Sequences
- Relationships Between Resolution & SNR
- MR Image Speed
- Manipulating Image Contrast (Advanced)

Image Quality

- Image Contrast
- Image Resolution
- Signal-to-Noise Ratio
- Imaging Speed

Image Contrast

- Basic image contrast is effected by the amplitude and timing of the RF pulses used to excite the spin system.
- More advanced methods may use gradient pulses (to modulate motion) and alter tissue properties with exogenous contrast agents

Intrinsic (Tissue) Parameters

- Tissue Water Density (Proton Density)
- Longitudinal Relaxation Time (T1)
  - Magnetization transfer rate coefficients
- Transverse Relaxation Time (T2)
- Chemical Shift (water vs. fat)
- Tissue Motion
  - Macroscopic (flowing blood)
  - Microscopic (apparent diffusion coefficient)
- Tissue Susceptibility (air, fat, bone, blood)

Extrinsic (Selectable) Parameters

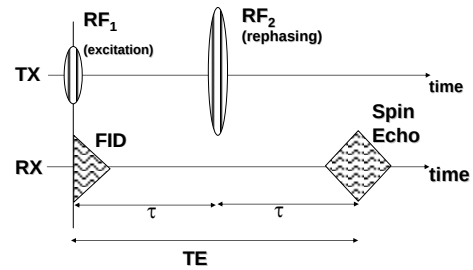
- Magnetic Field Strength
- RF Pulse timing
  - Excitation pulse repetition time (TR)
  - Time to echo (TE) & inter-echo spacing (T_{ie})
  - Inversion time (TI)
- RF pulse amplitude (flip angles)
- Gradient Amplitude & Timing
  - b-value
- RF pulse excitation frequency & bandwidth
- Receiver bandwidth

Spin (Proton) Density

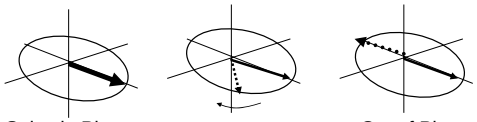
Tissue	% Water	Tissue	% Water
Liver	70 %	Spleen	78%
Kidney	75%	Brain (GM)	85%
Muscle	73%	Brain (WM)	75%
Heart	78%	Tendon	60%

From Akber SF, Physiol Chem Phys & Med 1996; 28: 205-238.

Spin Echo Pulse Sequence



Out of Phase Spins
(Transverse Magnetization)

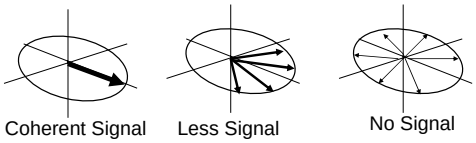


Spins in Phase — Precessing Off-resonance by 17,040 Hz — Out of Phase

17, 040 Hz = 17, 040 cycles per second = 360 × 17, 040 degrees/sec

$180^o \div (360^o \times$ 17, 040 degrees/sec) = 3×10^{-5} s = **30μs**

Dephasing of MR Signal
(Transverse Magnetization)



Coherent Signal — Less Signal — No Signal

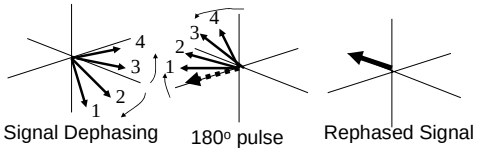
Signal decays exponentially:

(after 90° rf pulse) $M_{xy} = M_o \exp[-\ TE / T_2^*]$

where

$1/T_2^* = 1/T_2 + (\gamma/2\pi) * \Delta B_o$ ← (Magnetic field inhomogeneity)

Rephasing of the MR Signal
(Spin Echoes)

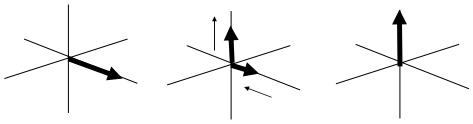


Signal Dephasing — 180° pulse — Rephased Signal

A rephasing 180° radio frequency pulse, changes the phase of the net magnetization vectors by 180°. Thus spins precessing in the same direction come together of moving apart. This forms a SPIN ECHO.

Longitudinal (T_1) Relaxation

Longitudinal relaxation is a ***recovery*** process:



After 90° pulse - all spin energy is kinetic

Spins lose energy to their environment, signal decreases

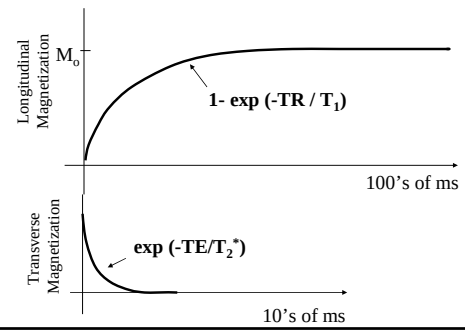
After $5*T_1$, full potential of net magnetization is reestablished

Comparison of T_1, T_2 and for Various Tissues

Tissue	T_1(ms)	T_2(ms)
Liver	675±142	54±8
Kidney	559±10	84±8
Muscle	1123±119	43±4
Gray Matter	1136±91	87±15
White Matter	889±30	86±1.5

Akber, 1996 (at 63 MHz)

Time Scale of MR Relaxation Processes



Manipulating Contrast

- The "weighting" of image contrast
- Gradient Echo – manipulating image contrast by varying the flip angle
- Spin Echo – manipulating image contrast with 180° refocusing pulses
- Inversion Recovery – manipulating image contrast with 180° inversion pulses

Rules of Thumb

- TE controls T2 dependence
- TR controls T1 dependence
- T1 competes with T2 and proton density

"PD Weighted" = long TR, short TE

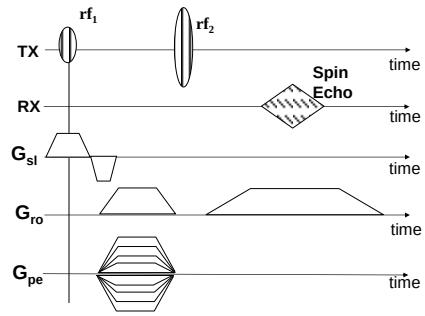
"T1 Weighted" = short TR, short TE

"T2 Weighted" = long TR, long TE

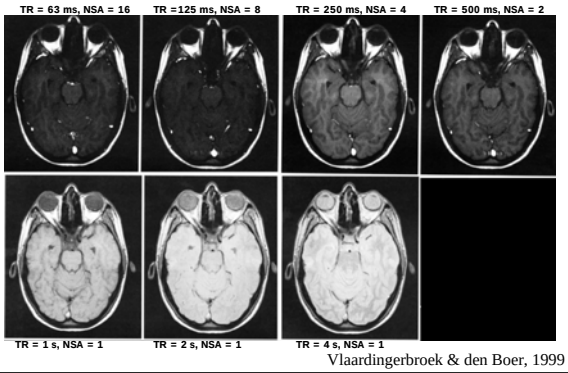
Pulse Sequence Classifications

Name	*RF Pulses*	*Contrast Weighting*	*Application*
Gradient Echo	One	T1 or T2*	Fast imaging (3DFT)
Spin Echo	Two or more	T1, PD or T2	conventional
Inversion Recovery	Three	T1 and T2	Excludes certain tissues

Spin-Echo *Imaging* Sequence

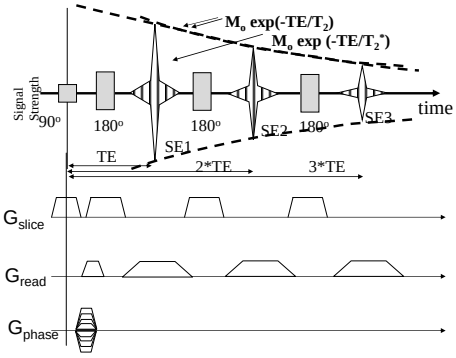


Spin Echo Imaging – Effect of TR



Vlaardingerbroek & den Boer, 1999

Multi-Echo Acquisitions

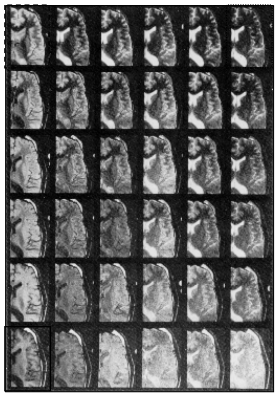


Multiecho Image Matrix

— Most T_1 Weighted

- - - Most Proton Density Weighted

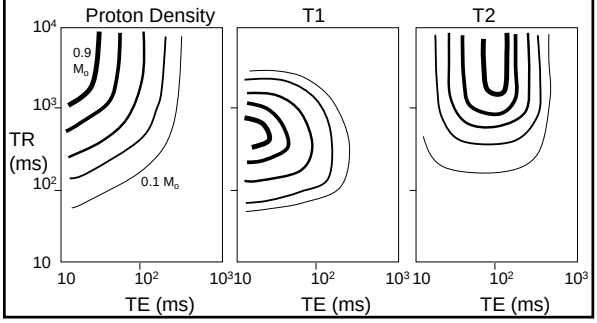
..... Most T_2 Weighted



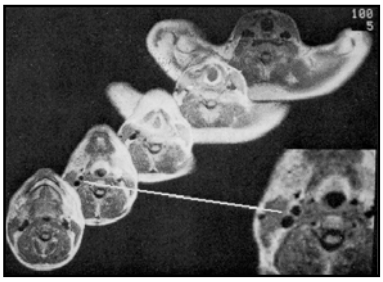
TR (s): 4, 2, 1.5, 1.2, 0.9, 0.6

TE 30 60 90 120 150 180 ms

Sensitivity Plots
(pulse sequence optimization)



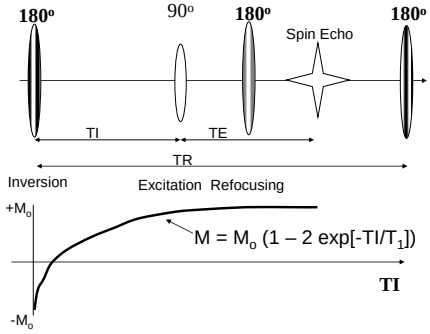
Multi-Slice Imaging



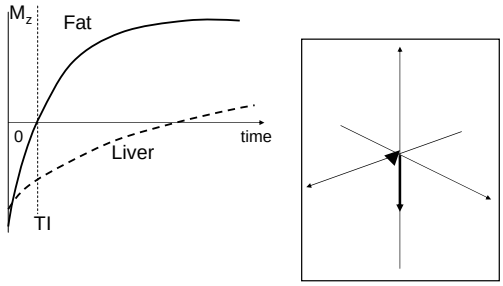
- Increased efficiency by scanning multiple planes during TR interval

(Crooks L, Arakawa M, Hoenninger J et al. Radiology 1982; 143: 169-174.)

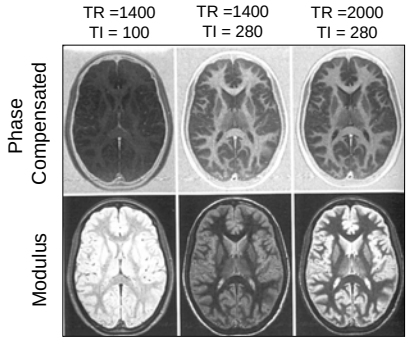
Inversion Recovery



STIR
(**S**hort **T**I **I**nversion **R**ecovery)

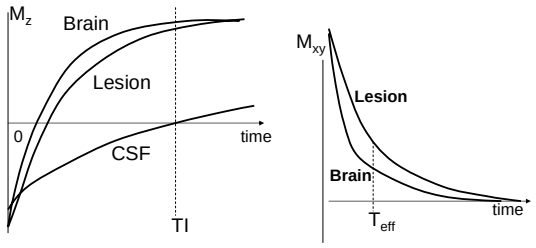


Inversion Recovery FSE

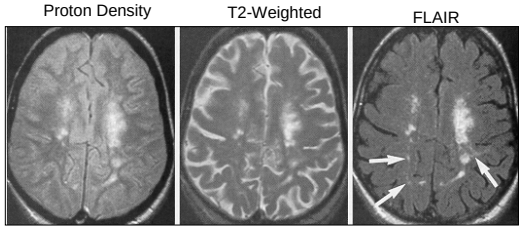


Vlaardingerbroek & den Boer, 1999

FLAIR
(**FL**uid **A**ttenuated **I**nversion **R**ecovery)



Multiple Sclerosis



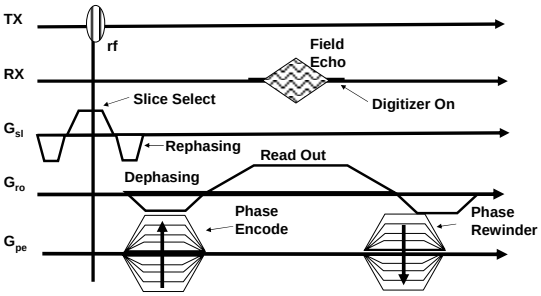
TR = 2350
TE = 30

TR=2350
TE= 80

TR=2600
TE=145
TI= 11,000

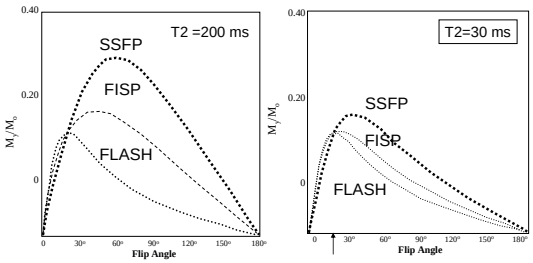
Rydberg JN et al. Radiology 1994; 193:173-180

Steady-State Free Precession
(SSFP or True FISP)

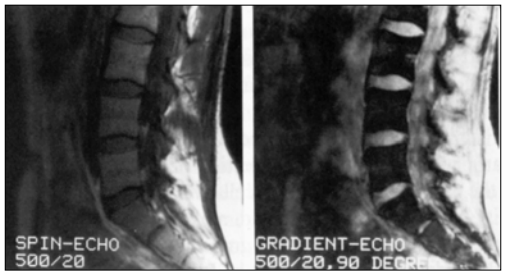


Also called FAST, ROAST

Relative Sensitivity of Gradient Echo Sequences



Gradient-Echo Imaging

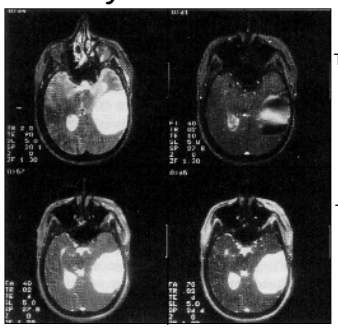


Reference: Wehrli, Fast-Scan Magnetic Resonance. Principles and Applications

Cystic Mass

Spin Echo
TR/TE
= 2500/90
NSA =1
5 mm

FISP
TR/TE = 22/10
NSA =8
8 mm



True FISP
TR/TE = 16/6
flip = 40º
NSA =8
5 mm

True FISP
TR/TE = 16/6
flip = 70º
NSA =8
5 mm

Signal-to-Noise Ratio

- Signal-to-noise in an RF coil:

$$S/N \propto \frac{\omega_o M_o \int B_1(\vec{r})\, dV}{\sqrt{4kT\, \mathcal{BW}\, R_t}}$$

S = signal
N = noise
ω_o = resonant frequency
M_o = net magnetization
$B_1(r)$ = RF field distribution
dV = elemental volume of tissue
k = Boltzman's constant
T = patient temperature
$\mathcal{BW}$ = receiver bandwidth
R_t = total resistance (coil + patient)

SNR and Imaging Parameters

$$SNR \propto \frac{FOV_{ro}}{\sqrt{M_{ro}}} \frac{FOV_{ph}}{\sqrt{M_{ph}}} \cdot \Delta z \cdot \frac{\sqrt{NSA}}{\sqrt{BW_{rx}}}$$

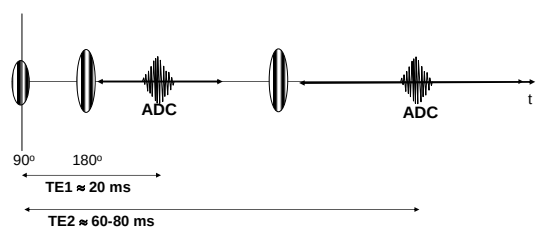
FOV = field of view
M = matrix size
n = number of signals averaged
BW_{rx} = receiver bandwidth
ro = read out (frequency encoding) direction
Δz = slice thickness
ph = phase encoding direction

Matched Bandwidth

- Bandwidth on ADC_1 is limited by finite T_{max} & desire to minimize TE_1.
- T_1 weighting and SNR is sacrificed more by T_2 decay than by BW
- T_2-weighted image - lots of time for ADC_2, poorer SNR. It would be nice to decrease BW (increase T_{max})

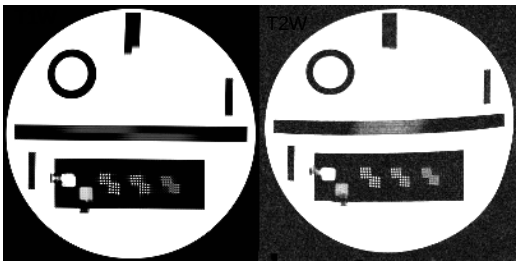
Mugler & Brookeman, Magn Reson Imag 1989; 7:487-493.

Matched Bandwidth



Mugler & Brookeman, Magn Reson Imag 1989; 7:487-493.

Matched Bandwidth = Unmatched Distortion



- Smaller BW on T2W image leads to increased image distortion

Chemical Shift

- Chemical shift (fat-water) ~3.5 ppm
  - At 1.5T:

$$\Delta f_{fat-water} = 3.5\times10^{-6}\cdot\frac{42.6MHz}{T}\cdot 1.5T \cong 220\ Hz$$

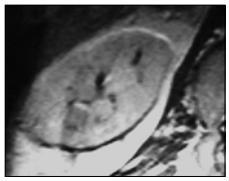
  - At 0.5T:

$$\Delta f_{fat-water} = 3.5\times10^{-6}\cdot\frac{42.6MHz}{T}\cdot 0.5T \cong 73\ Hz$$

- ↓ field strength …. ↓ chemical shift

Chemical Shift Artifact

- Occurs in
  - Readout direction
    - Conventional SE
  - Phase encode direction
    - Echo-Planar
- Controlled by
  - Fat Pre Saturation
  - STIR sequence



Chemical shift artifact seen in axial image of kidney

Contrast-to-Noise Ratio

$$CNR = \sqrt{n}\,\frac{(I_a - I_b)}{\sigma}$$

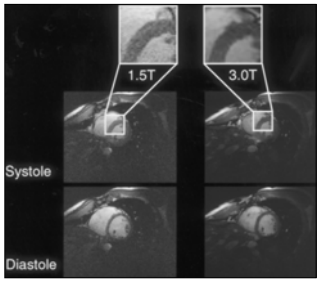
σ = standard deviation of the background signal (the noise)

n = number of signals acquired

I_a,I_b = signal intensities from tissues “a” and “b”

Steady state free precession (SSFP)

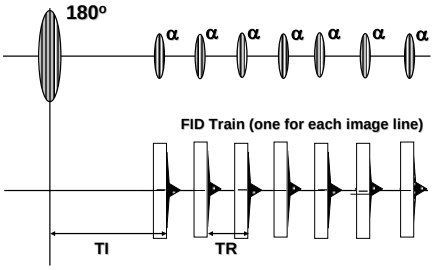
Signal is produced by rapidly applying balanced gradients and RF pulses. Use to maximize the overall signal.



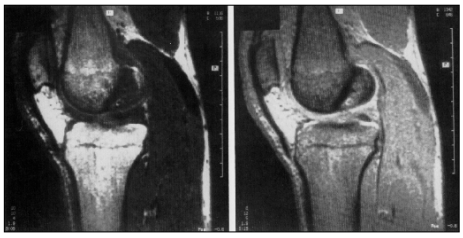
- FIESTA (fast imaging employing steady state acquisition)
- Balanced FFE (fast field echo)
- True FISP (fast imaging with steady precession)

Hinton et al. *Invest Radiol* 2003; 38:436

IR Turbo-FLASH



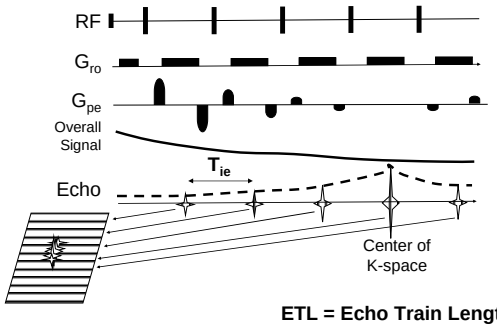
3D FLASH vs. 3D Turbo FLASH



IR Turbo FLASH
TI = 500 ms, TR/TE = 10/4.5
NSA =1, flip = 10º

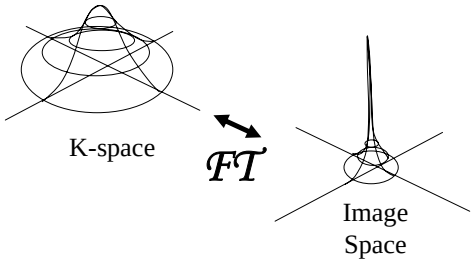
FLASH
TR/TE = 12/4.5
NSA = 1, flip = 8º

FSE Pulse Sequence

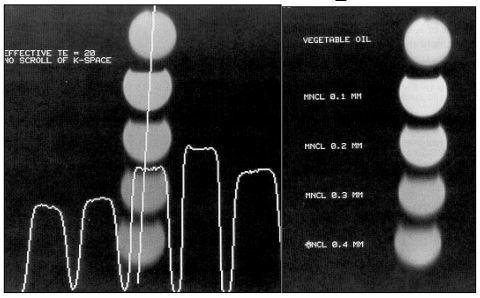


ETL = Echo Train Length

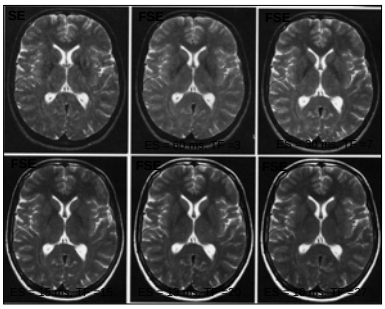
Things That have "Blurry" point spread functions are "Sharp" in the Image



FSE Point Spread Function Depends on T_2



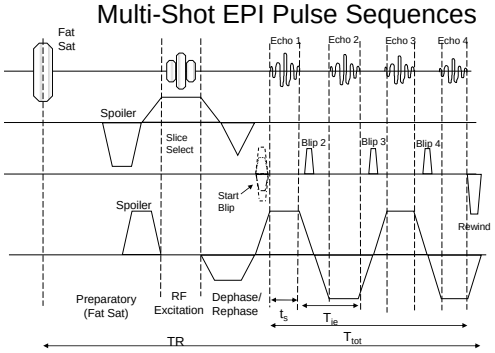
Effect of Echo Spacing



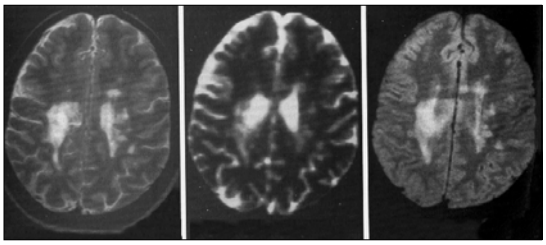
Signal-to-noise decreases for short T2 tissues (gray & white matter) leading to a decrease in spatial resolution

Vlardengerbrook & den Boer, 1999

Multi-Shot EPI Pulse Sequences

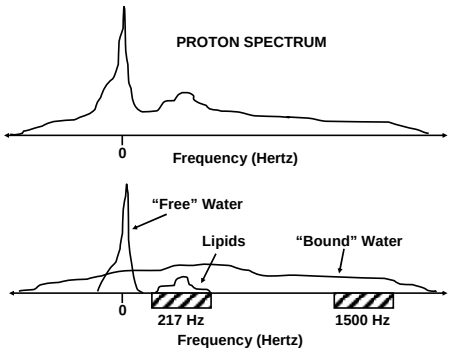


Comparison of EPI and SE

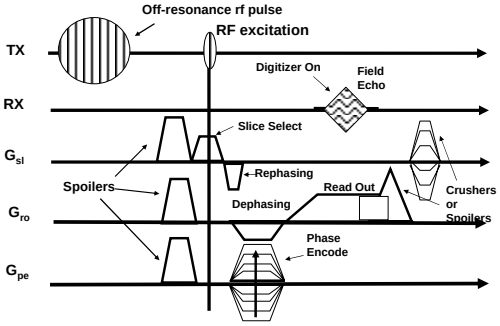


T2-weighted SE TR 2400, TE 80 192x256; 7:44	Single shot EPI TE =80 128x128; 120 ms	Nine-shot EPI TR 3000, TE 21 252x256; 1:06

Magnetization Transfer



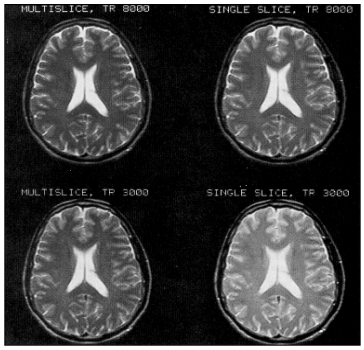
Gradient Echo with MTC Pulse



Magnetization Transfer Contrast

Multislice FSE:

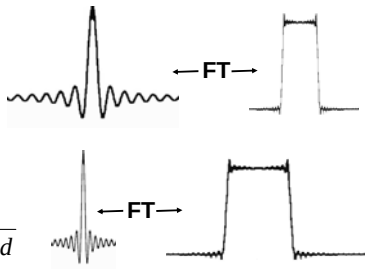
Magnetization Transfer Contrast Enhances T_2 Weighted Appearance



Slice thickness - RF bandwidth

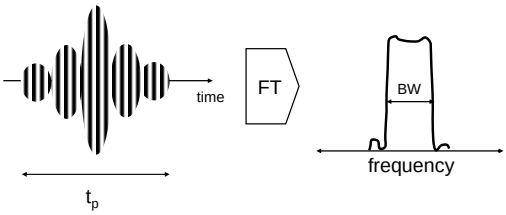
- thinner slices require longer RF pulses
- $\downarrow \Delta z \downarrow \Delta\omega$

$$Bandwidth = \frac{1}{period}$$



Crafted RF Pulses

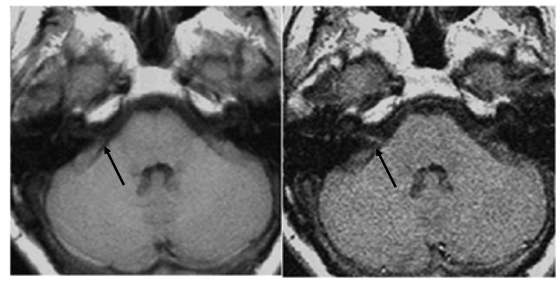
A *sinc function* ($\frac{\sin x}{x}$) envelope on the r.f. pulse produces a nearly square excitation profile of the phantom…..



MRI Slice Thickness

- Signal ramps have a slope of 10:1
- Signal from ramp is 10 x slice thickness
- Two ramps are used to compensate for in-plane rotation of the phantom
- Phantom <u>does not compensate</u> for tilting backwards or swaying left-right

Cranial Nerves



10 mm slice 3 mm slice

Frequency Encoding & FOV

– The field of view (FOV_x) is determined by the range of frequencies in the x axis which are sampled

$$FOV_x = \frac{Bandwidth}{\gamma \cdot G_x}$$

– The receiver bandwidth is <u>not</u> the same as the RF bandwidth

- ↑ BW ↑ FOV_x
- ↓ G_x ↑ FOV_x

– FOV must be sufficient to cover all tissue in the slice to avoid aliasing

Phase Encode Gradient

The maximum phase-encoding gradient is :

$$G_{ph-\max} = \frac{2\pi}{\gamma} \cdot \frac{BW}{FOV} = \frac{\pi}{\gamma} \cdot \frac{N}{FOV \cdot T_y}$$

where FOV is the desired field of view

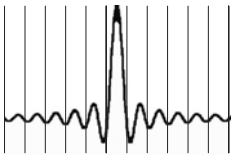
The phase-encoding gradient increment is :

$$\Delta G_{ph} = \frac{\pi}{\gamma} \cdot \frac{1}{FOV \cdot T_y}$$

- Note that a factor of two is gone from $G_{ph\text{-}max}$ because G_{ph} runs from- $G_{ph=max}$ to $G_{ph=max}$

Sampling the Signal

– Each signal is digitally sampled to produce one line in the k- space matrix



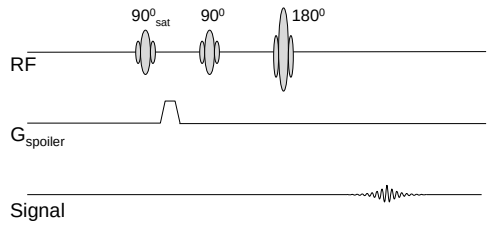
$$\Delta k_x = \gamma \cdot G_x \Delta t_x$$

$$\Delta k_x = \frac{MHz}{T} \cdot \frac{mT}{m} \cdot \text{msec}$$

$$= \frac{cycles}{m}$$

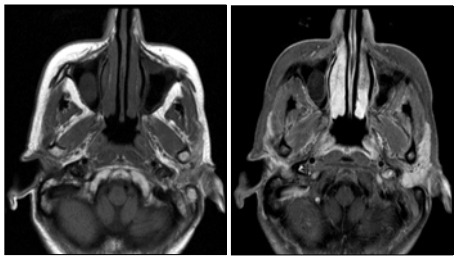
$$\Delta k_x = \frac{1}{FOV_x}$$

CHESS



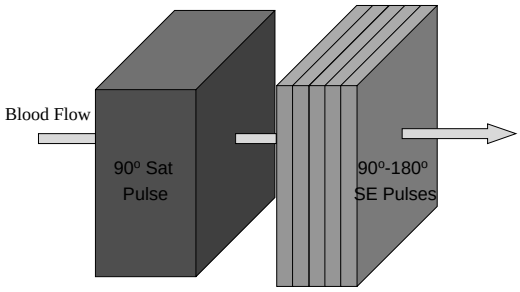
- This is typically accomplished by preceding a SE or FSE sequence with a 90° pulse that is frequency, not spatially, selective.

Fat Suppression

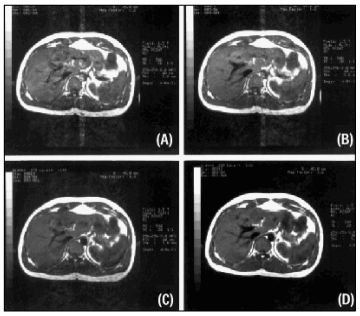


T1W images without (left) and with (right) fat suppression.

Spatial Saturation



Spatial Saturation



a. No Sat Pulse
b. Inferior Sat Pulse
c. Superior Sat Pulse
d. Inferior and Superior Sat Pulses

GE Signa Applications Guide, Vol 1

Gadolinium Contrast Agents

- *GD-DTPA, Gd-DOTA, Gd-HP-DO3A:*

the old standards, generally diffusable but not in brain due to Blood Brain Barrier

- In low doses decrease T1
- In higher doses decrease T1 and T_2^*

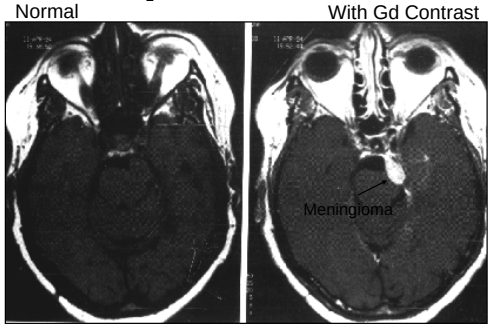
NEW INTRAVASCULAR AGENTS -

- Blood pool agents
  - Magnetic iron oxide particles
  - Bind serum albumin, have higher relaxivity

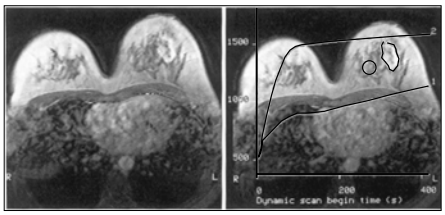
Gadolinium Contrast Agents

T_1 weighted Images

Normal With Gd Contrast



Dynamic Contrast Studies



- Dynamic study of breast tumor
- Curves denote difference between uptake of normal glandular tissue & lesion

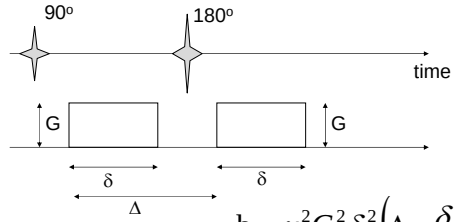
Vlaardingerbroek & den Boer, 1999

Attenuation Due to Diffusion

$$A(TE) = A(0)\exp[-\gamma^2 G^2 D_{app}\delta^2\alpha^2(\Delta - \frac{\delta}{4})]$$

Where: $\alpha=\pi/2$;
G is amplitude of diffusion sensitive gradient pulse;
δ is duration of diffusion sensitive gradient;
Δ is time between diffusion sensitive gradient pulses;
D_{app} is the apparent diffusion coefficient

Diffusion Weighted Imaging: Prototype Pulse Sequence



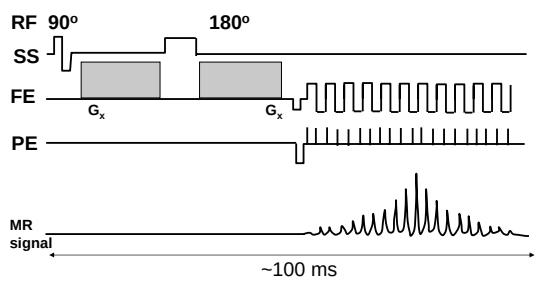
$$b = \gamma^2 G^2 \delta^2 \left(\Delta - \delta/3\right)$$

Stejskal EO & Tanner JE, 1965. 42: 288-292

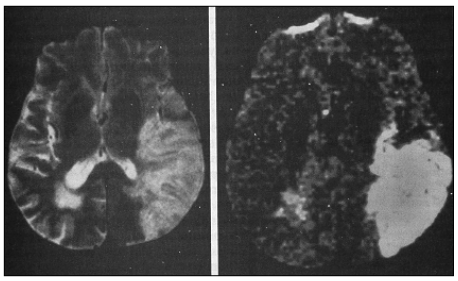
The b-value

- Controls amount of diffusion weighting in image
- The greater the b-value the greater the area under the diffusion-weighted gradient pulses
  - longer TE
  - stronger and faster ramping the gradients

Diffusion EPI Pulse Sequence



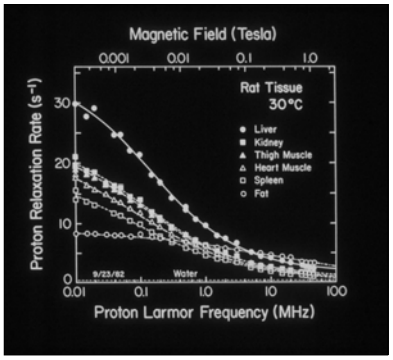
Diffusion Imaging of Infarcts



SE Echo Planar
TE = 80 ms

SE Echo Planar
b = 1205 s mm^{-1}

Biorelaxometry



Koenig, et. al, 1983

Specific Absorption Rate (SAR)

- The patient is in an RF magnetic field that causes spin excitation (the B1 field)
- The RF field can induce small currents in the electrically conductive patient which result in energy being absorbed.
- The RF power absorbed by the body is called the **specific absorption rate (SAR)**
- SAR has units of watts absorbed per kg of patient
- If the SAR exceeds the thermal regulation capacity the patient's body temperature will rise.

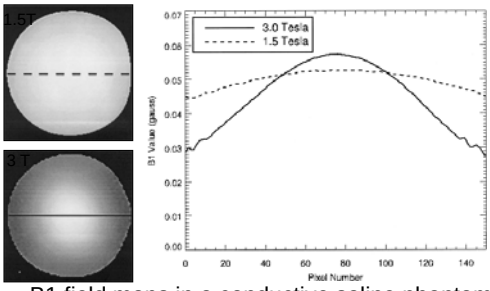
Scan Parameters Effecting SAR

- Patient size: SAR increases as the patient size increases – directly related to patient radius
- Resonant frequency: SAR increases with the square of the Larmor frequency (ω_o)
- RF pulse flip angle: SAR increases as the square of the flip angle (α
- Number of RF pulses: SAR increases with the number of RF pulses in a given time

SAR Effects on Pulse Sequences

- Decrease number of slices per study
- Requires decreased flip angles, even in gradient echo sequences
- Forces increases in TR
- Limits use of Fast Spin Echo imaging

Uniformity at 3 Tesla



- B1 field maps in a conductive saline phantom (18 cm diameter)

RL Greenman et al. JMRI 2003, 17(6): 648-655

Summary

- RF pulses can be crafted to select slices
- RF pulse timing (TE, TR & TI) is used to manipulate soft tissue contrast in MR images
- Gradient echo imaging with partial flip angles is faster than spin echo imaging
- Spin Echoes correct for poor magnetic fields
- Inversion recovery can be used to get rid of fat or CSF from images
- Contrast agents are used to manipulate tissue T_1

Summary

- Presaturation schemes can effect flow, chemical shift and T1-weighted contrast
- Fast imaging methods are often applied to imaging physiology as well as anatomy
- Typically, SNR is reduced with increases in resolution, contrast and imaging speed
- Various image parameters will have to be adjusted for each magnetic field strength