Optimizing MR Imaging Procedures:
The Physicist as a Consultant

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Substantial number of slides courtesy of Geoff Clarke, UTHSCSA

Overview

- Image contrast in standard clinical sequences (pulse timing parameters)
- Interactions between spatial resolution, imaging speed and signal-to-noise ratio
- Adapting MR protocols to physiology and system configuration

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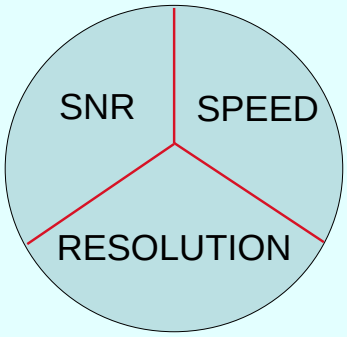
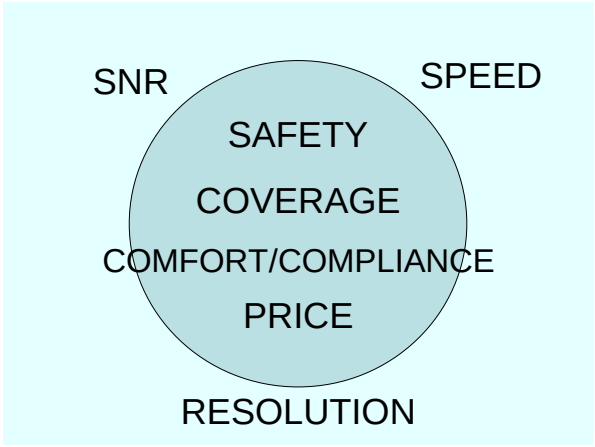
Morphology & Physiology

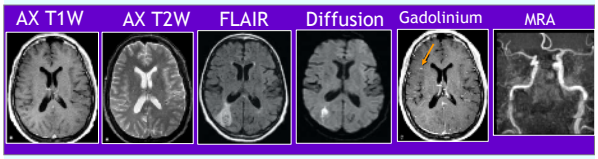
- Tissue parameters (T1, T2, PD, mag transfer)
- Chemical shift (water vs. fat)
- Blood motion (macroscopic & microscopic)
- Gross motion (peristalsis, respiration)
- Tissue susceptibility
- Diffusion of water
- Patient (clinical status, body habitus, prep)

adapted, G. Clarke





MR Brain Imaging



Brain MR Imaging requires:

- Good gray-white matter contrast
- High spatial resolution
- Excellent timing and gradient control

- See inside bony structures
- Depict white matter lesions
- Evaluate cerebral blood flow (angiogram or perfusion)

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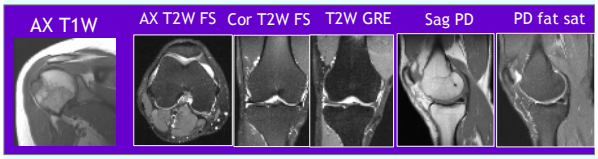
MR Knee Imaging

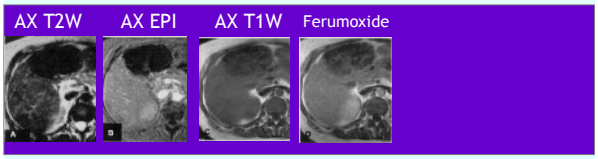


Skeletal MR Imaging requires:

- small FOV, high spatial resolution
- off-center imaging
- avoidance of wrap-around
- elimination of fat signals

- Soft tissue contrast
- See tendons, ligaments, bone marrow, cartilage
- arthroscopy or kinematic evaluation

MR Liver Imaging



Body MR Imaging requires:

- Control of respiratory and other motion artifacts
- Identification and/or elimination of fat signals
- Avoidance of wrap-around (aliasing) artifact

Advantages:

- Soft tissue contrast
- High degree of contrast manipulation
- Lesion characterization
- High sensitivity to iron

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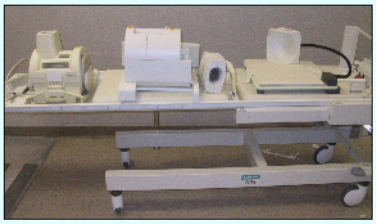
User Selectable Parameters

- Magnetic Field Strength (B_o)
- Coil selection



adapted, G. Clarke

User Selectable Parameters

- Magnetic Field Strength (B_o)
- Coil selection
- RF pulse timing (TR, TE, TI)
- RF pulse amplitude - flip angles (α)
- Receiver bandwidth (BW)
- Gradient amplitude & timing (b-value)
- RF pulse excitation frequency & bandwidth

adapted, G. Clarke

Image Contrast

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

adapted, G. Clarke

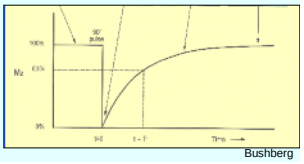
T1W Images

Spin Echo Sequence

22 axial slices
20 sagittal slices

CSF has weak/no signal

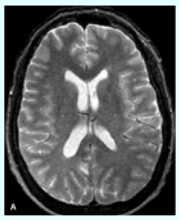
fat emits a strong signal

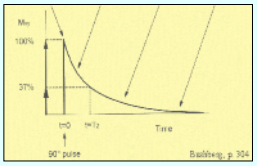


Bushberg

T2W Images

Spin Echo Sequence



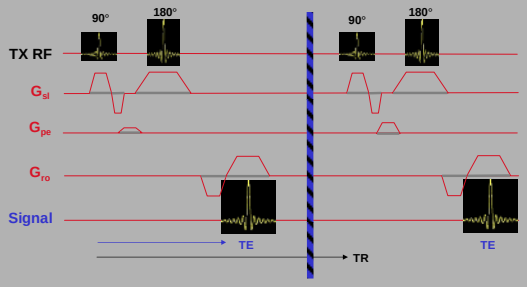


CSF emits a strong signal.

fat emits a weak signal.

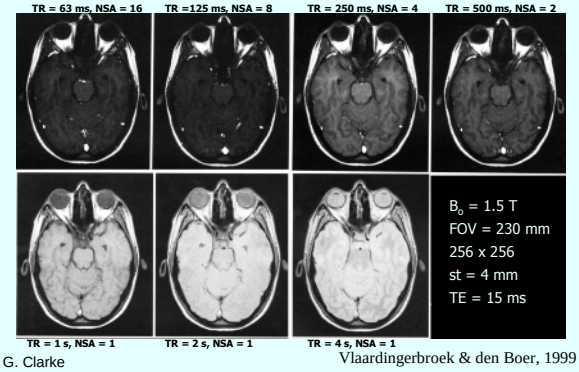
22 axial slices

Spin Echo Pulse Sequence



C. Keener

SE – Effect of TR



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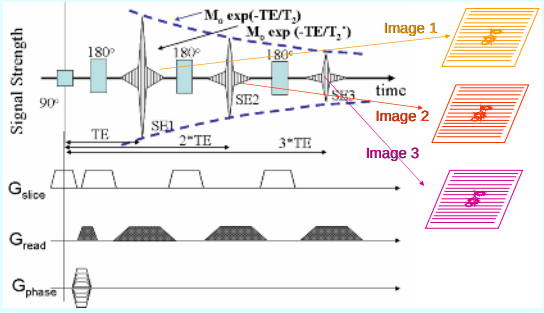
Vlaardingerbroek & den Boer, 1999

Multi-Echo Acquisitions



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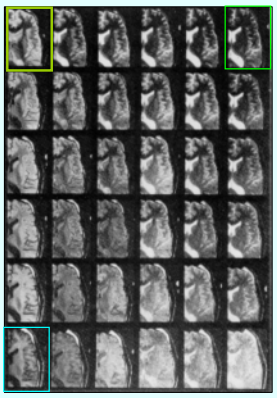
Multiecho Image Matrix



Most T_1 Weighted

Most Proton Density Weighted

Most T_2 Weighted

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Spin Echo - Rules of Thumb

I is proportional to $M_0[1-e^{-TR/T1}]e^{-TE/T2}$

- TR controls T1 dependence
  - ↑↑ Scan time
  - ↑↑ SNR
  - ↑↑ #slices possible in multi-echo
- TE controls T2 dependence
  - ↑↓ SNR
  - ↑↓ #slices possible in given TR

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

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Akber, 1996 (at 63 MHz)

~ T_1 for Various B_o

Tissue	0.5T	1.5T
Fat	215	250
Liver	323	675
Kidney		559
Muscle	600	1123
Gray Matter	656	1136
White Matter	539	889

(example values from multiple sources)

Manipulating Contrast

- The "weighting" of image contrast is related to delay times, TR (repetition time) & TE (echo time)
- Spin Echo – manipulates image contrast with 180º refocusing pulses (insensitive to B_o inhomogeneities)
- Gradient Echo – manipulates image contrast by varying the excitation flip angle (fast scans)
- Inversion Recovery – manipulates image contrast with 180º inversion pulses

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Pulse Sequence Classifications

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

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MR Sequences

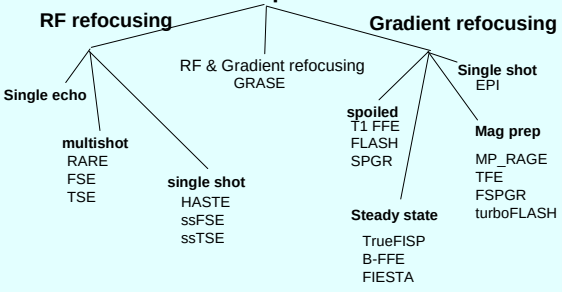
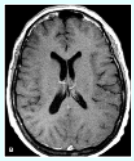
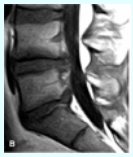


Fig 4.23 Leyendecker

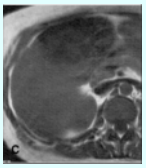
T1W Images

Brain or Spine:
Spin Echo or FSE





Liver:
Gradient echo or EPI



Manage effect of respiratory motion.

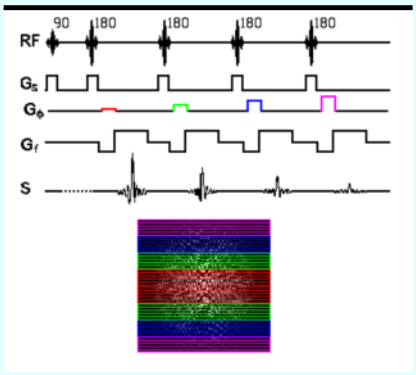
images from G. Clarke

Fast Spin Echo

Scan time depends on # TR

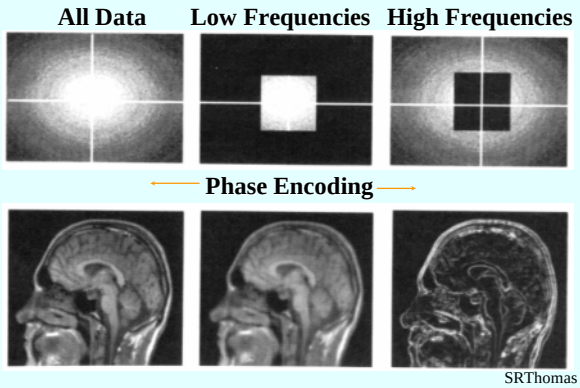
Conventional SE: one k-space line per echo per TR

FSE: multiple k-space lines per TR
multiple echoes per TR - echo train length (ETL)
one k-space line per echo



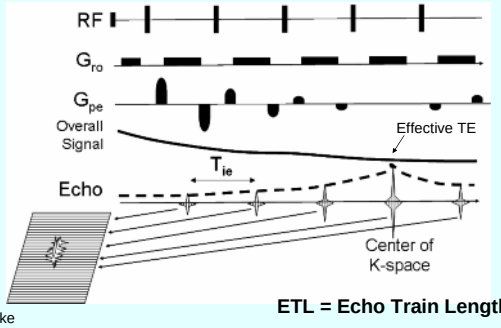
web lecture

K-Space Region vs. Contrast & Resolution



SRThomas

FSE Pulse Sequence



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ETL = Echo Train Length

FSE

Contrast is a mixture

effective TE (ETE): echo placed in center of k-space

echo train spacing (ETS): T2 contribution, #slices

Example: bright fat on T2-weight FSE

Consider time of first and last echoes

as well as echo spacing

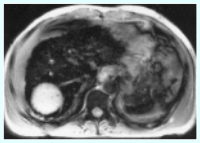
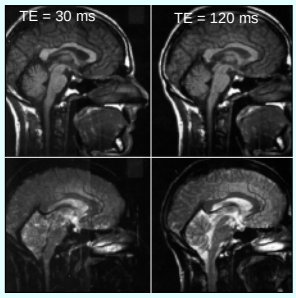


image from G. Clarke

Spin Echo vs. Fast Spin Echo

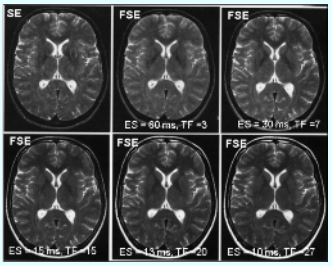


T_1-weighted (TR = 500)

T_2-weighted (TR= 2000)

G. Clarke **Spin Echo** **Fast Spin Echo** **(Echo Train Length = 4)**

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

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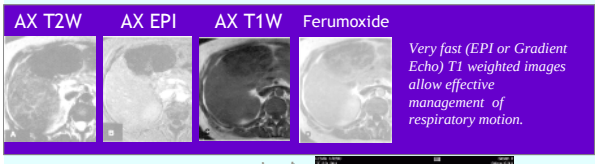
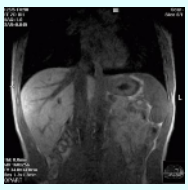
Liver Imaging

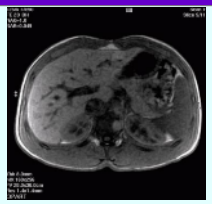


Very fast (EPI or Gradient Echo) T1 weighted images allow effective management of respiratory motion.

PDW /T1W SGE



PD/T1W



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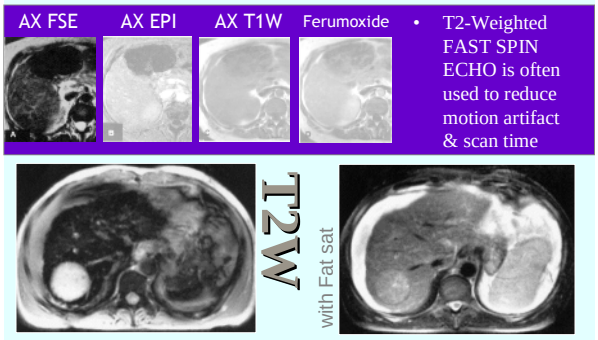
Liver Imaging



What is 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.

G. Clarke

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) – therefore ↑ with B_o^2
- RF pulse flip angle: SAR increases as the square of the flip angle (α^2)
- Number of RF pulses: SAR increases with the number of RF pulses in a given time

G. Clarke

Fast Spin Echo - Rules of Thumb

- ETL controls scan time
  - ↑↓ Scan time --- fit with TR
  - ↑↑ image blurring
  - ↑↑ SAR
- ETE controls contrast

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 NSA = number of signals averaged
BW_{rx} = receiver bandwidth ro = read out (frequency encoding) direction
Δz = slice thickness ph = phase encoding direction

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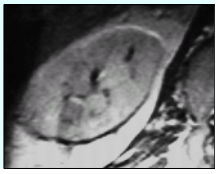
Bandwidth Conversions

Values are field dependent

- Version A: quoted in kHz, is ± kHz
- Version B: quoted in Hz/pixel

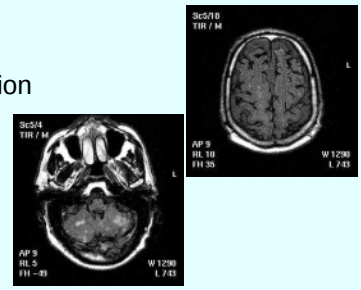
- Conversion at 1.5T:
  12.8 kHz for a 256 matrix = 25.6 kHz for 512 matrix
  = 100 Hz/pixel

  220 Hz chemical shift of fat
  => 2.2 pixel fat-water shift

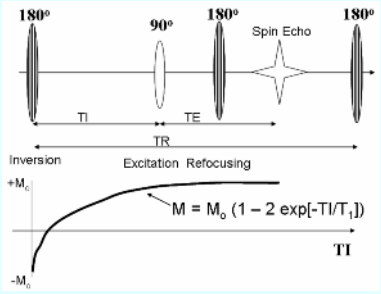


FLAIR Images

- Spin Echo Sequence, with Inversion Recovery



Inversion Recovery



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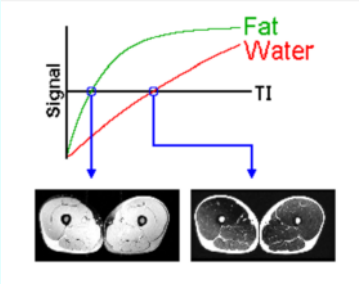


web lecture

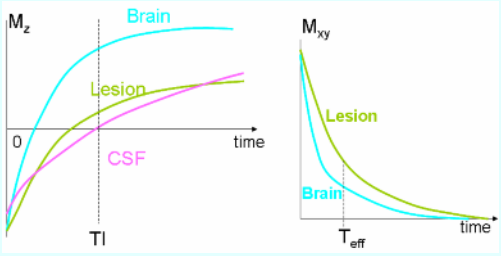
Fluid Attenuated Inversion Recovery (FLAIR)

- Uses magnitude display.
- Initial 180º pulse applied.
- $M_Z = 0$ is the "bounce point."
- At TI, 90º pulse applied: longer TI 1800 -2500ms.
- If $M_Z = 0$ at TI, maximum possible echo = 0.
- Allows selective suppression of contrast limiting signals, e.g., CSF in ventricles.

CSF SUPPRESSION: NEUROLOGICAL

FLAIR

(FLuid Attenuated Inversion Recovery)



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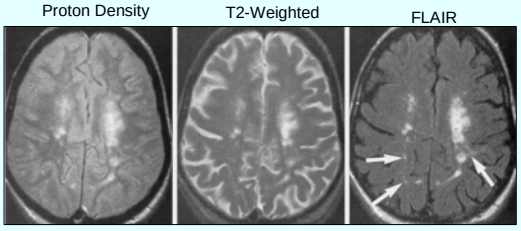
Multiple Sclerosis



TR = 2350
TE = 30

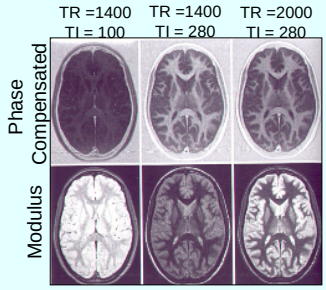
TR=2350
TE= 80

TR=2600
TE=145
TI= 1000

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

G. Clarke

Inversion Recovery FSE



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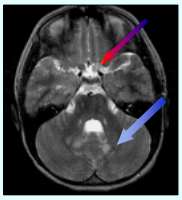
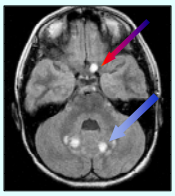
Vlaardingerbroek & den Boer, 1999

FLAIR Imaging



T2W-FSE

TE/TR = 98/3500ms,
Slice 5/1.5mm, ET:8 (split)
256x224, 1 NEX,
20x20 cm FOV, 3:23



FLAIR-FSE

TI/TE/TR = 2200/147/10000ms,
Slice 5/1.5mm,
256x160, 1 NEX,
20x20cm FOV, 3:40

G. Clarke

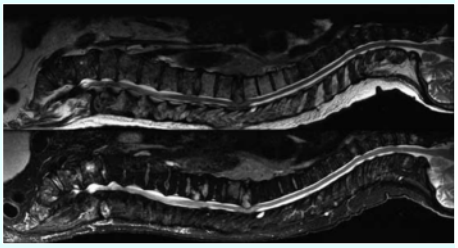
Short Tau Inversion Recovery (STIR)

- Uses magnitude display.
- Initial 180^{o} pulse applied.
- M_Z = 0 is the "bounce point."
- At TI, 90^{o} pulse applied (TI-110-150ms).
- If M_Z = 0 at TI, maximum possible echo = 0.
- Allows selective suppression of contrast limiting signals, e.g., fat around orbitals.

FAT SUPPRESSION: MUSCULOSKELETAL

Spine Imaging

Bottom: STIR
- Short
- TI
- Inversion
- Recovery

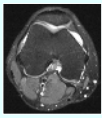


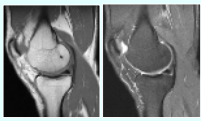
adapted, G. Clarke

Fat saturation in MSK MRI

Fat is not your friend!

– Chemical shift saturation
- Precession of fat and water are different
- Fat peak can be selected for saturation
- Higher field strength required





– Inversion recovery
- high and low field strength systems
- requires more time

adapted, Wissman

Chemical Shift

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

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

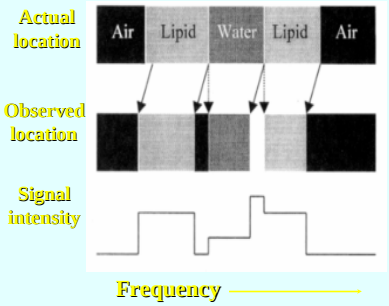
  – At 0.5T:

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

- ↓ field strength …. ↓ chemical shift

G. Clarke

Chemical Shift in the Frequency Encoding Direction

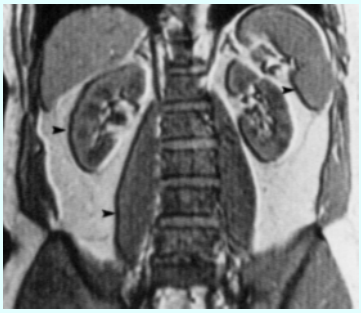


Lipid signal is shifted to a lower frequency.

Produces a signal void (dark band) on the high-frequency side of the lipid and an increase in signal (bright band) on the low-frequency side

SR Thomas

Chemical Shift – Clinical Presentation



Coronal T1W fast multiplanar spoiled gradient-echo image (FMPSPGR)

TR(ms)/TE(ms)/α: 103/5.6/80^0

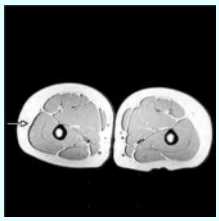
Frequency encode: right-to-left

Chemical shift artifacts at the lipid-water interfaces.

SRThomas

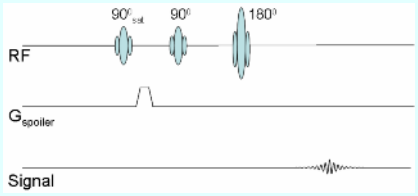
Chemical Shift Artifact

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



adapted, G. Clarke

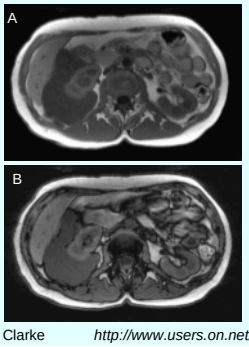
CHESS

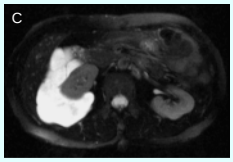


- This is typically accomplished by preceding a SE or FSE sequence with a 90º pulse that is frequency, not spatially, selective.

G. Clarke

Liver Imaging
Chemical Shift





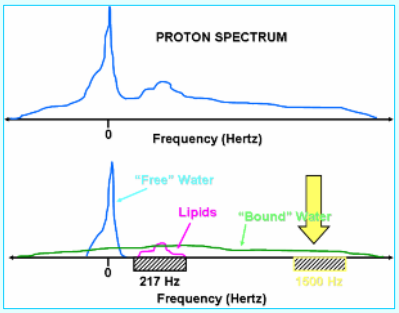
A. In phase-spoiled FFE image w/ TE= 4 ms

B. Out of phase spoiled FFE images w/ TE = 2 ms

C. T2 breath-hold FSE with fatsat pulse

G. Clarke *http://www.users.on.net/~vision/papers/abdomen/abdominal-mri.htm*

Magnetization Transfer

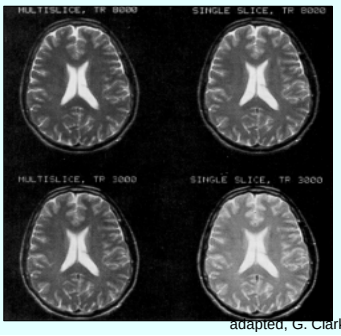


adapted, G. Clarke

Magnetization Transfer Contrast

Multislice FSE:

Magnetization Transfer Contrast Enhances T_2-Weighted Appearance

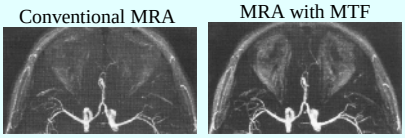


adapted, G. Clarke

3D Imaging - MTF

- MTF background suppression
  - –Saturate restricted protons (macromolecules)
  - –Spin-exchange with more mobile water protons
- Good: reduces background
  - – doesn't saturate ***moving*** blood, CSF
- Bad:
  - –Orbital fat is more obvious as parenchyma is less

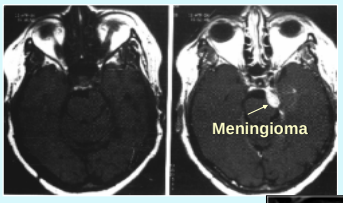
Conventional MRA MRA with MTF

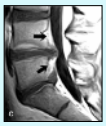


Ross Case 5

Post-Contrast T1 Images

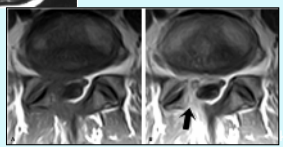
Images from G. Clarke



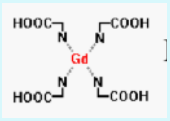


Left – Axial T1W image of S1 (note nerve root)

Right – Gd-enhanced image confirms abnormal soft tissue is scar

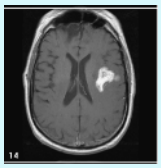


Contrast Agents - Gd



Gadolinium chelate - paramagnetic

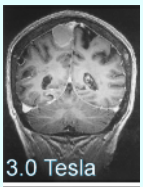
- Seven unpaired electrons
- unpaired electrons react with protons in adjacent water molecules shortening their relaxation time

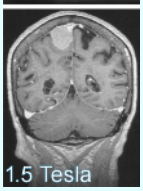


- reduces T1 relaxation times
- enhances T1 signal intensity in low concentrations

adapted, G. Clarke

Contrast Agents & B_o Strength





- Due to increases in tissue T1's, Gd-based contrast agents are more effective at 3T compared to 1.5T
- Use less contrast agent to get same tissue contrast

or

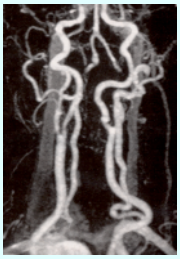
- Achieve much higher tissue contrast for the same dose

Nobauer-Huhmann IM, *Invest Radiol* 2002; 37:114-119

G. Clarke

Contrast-Enhanced MRA

- T1-weighted sequence for bright blood
- bolus injection of high dose (40-60ml)
- acquire central k-space when contrast is in arteries in desired region
  - may require test bolus or automatic detection

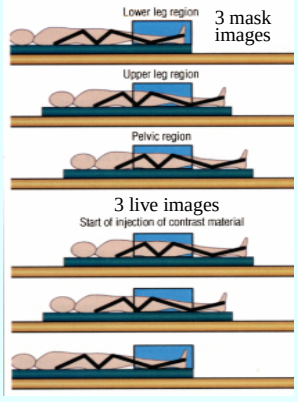


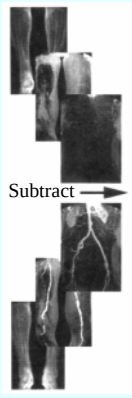
3D CE MRA: First pass carotid, elliptical-centric (60 sec acquisition)

image from SR Thomas

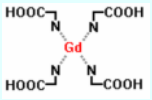
MoBI-track MR Angiography

SRThomas





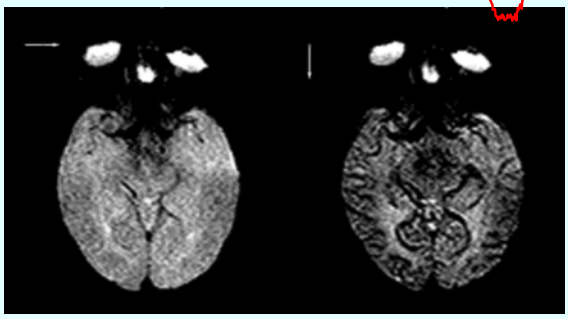
Gadolinium



- shortens T2 relaxation of water
  - lowers SI on T1 weighted images in high concentrations
- Nonuniform distribution of Gd-DTPA increases magnetic susceptibility differences
  - Decreases MR signal on $T2^*$-weighted images

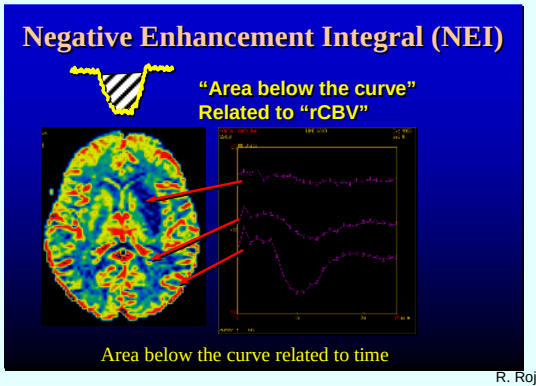
adapted, G. Clarke

Perfusion



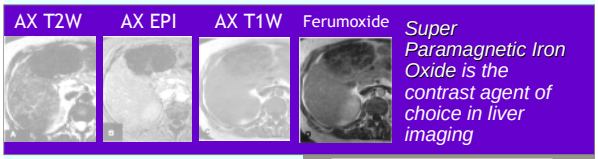
adapted, R. Rojas

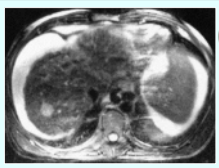
Perfusion



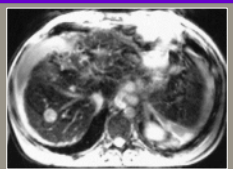
R. Rojas

Liver Imaging





Contrast agents



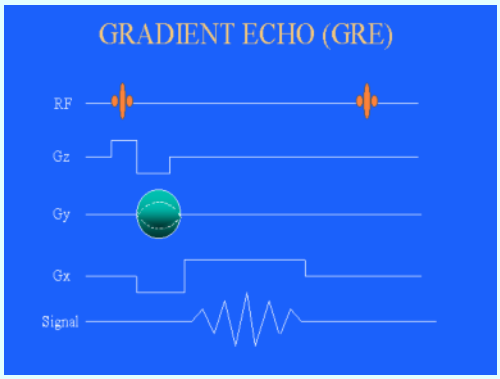
T2W Fast Spin Echo

T2*W Gradient Echo

G. Clarke

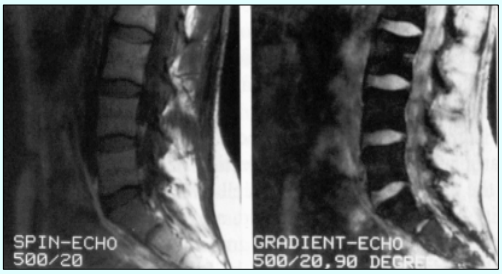
Fast Scanning

- Short - TR Sequences
- Segmented k-space
- Echo Planar Imaging (EPI)
- Parallel Imaging



web lecture

Gradient-Echo Imaging



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

G. Clarke

GRE Sequence Advantages

- Fast
  - Short TR values allow for fast scanning (~ 1 sec/image)
- No 180^0 pulse
  - Decreases by >5X RF power deposition
  - Lower minimum TE --> better T1W
- Low flip angle
  - Partial (<90^o) flip angle keeps all longitudinal magnetization from being used up
  - Higher signal intensity for short TR

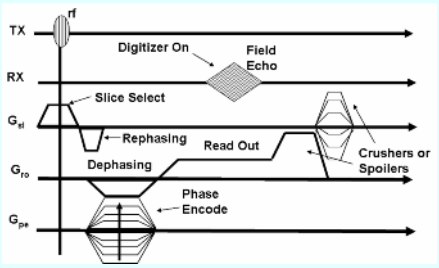
Spoiled GRE

- Destroying any residual transverse magnetization (M_{xy})
- Used in steady-state imaging, with very short TRs
- Short TR, short TE, large flip angle

SPGR and FLASH

G. Clarke

Spoiled Gradient Echo



Also called **spoiled GRASS, fast field echo, FLASH, etc.**

G. Clarke

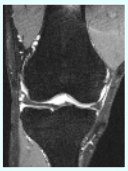
GRE contrast

Flip Angle
- <30°, minimizes T1, thus proton density or T2*
- >30°-60°, T1

TR
- Long (200ms), allows full M_{xy} decay
- Short (<50ms), steady-state precession condition

TE
- Short TE values preserve SNR
- Long TE => T2* contrast, not T2
- Short TE for T1

Sensitive to susceptibility



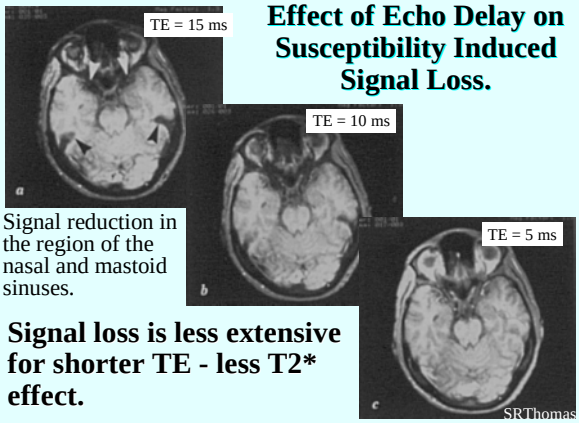
TR=9.5ms, TE=3.5ms
Flip=28°; 3D we

Magnetic Susceptibility Effects

Material	Signal	ρ (g/cm^3)	χ (ppm/cm^3)
Air	No		0.0
H_2O	Yes	1.0	-9.05
Bone (Cortical)	No	1.7-2.0	-8.86
$Cu(SO)_4 + H_2O$ (0.12 g/ml)	Yes		3.52
Pyrex	No	2.25	-13.91

G. Clarke

Effect of Echo Delay on Susceptibility Induced Signal Loss.



Signal reduction in the region of the nasal and mastoid sinuses.

Signal loss is less extensive for shorter TE - less T2* effect.

Gradient-Echo Imaging

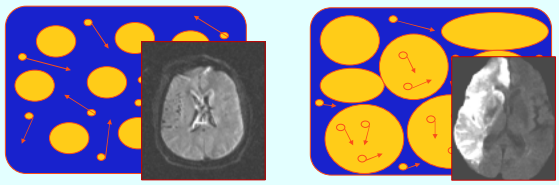
The susceptibility-induced artifacts in GRE images:

- Increase with TE - limiting the utility of GRE T_2*-weighted images in many cases.
- Are worst for tissue/air interfaces, but noticeable at tissue/bone interfaces.
- Are usually a detriment, but are useful in some circumstances (*e.g.,* blood-sensitive imaging, BOLD contrast functional imaging, etc.).

G. Clarke

Diffusion Imaging : Principles

- **Diffusion gradients sensitize MR Image to motion of extracellular water**
- **More motion = Darker image**



Freely Diffusing Water = Dark Restricted Diffusion = Bright

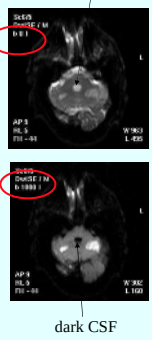
DWI Images

$$S(b) = S(0)\exp(-bD)$$

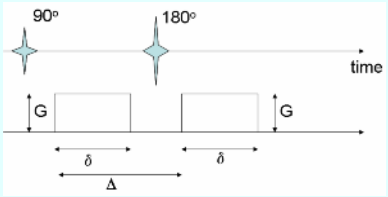
Large D: mobile water --> low signal
Small D: restricted motion --> high signal

b: larger --> more diffusion weighting

DWI contrast is like an inverse T2 weighting
Watery tissue - mobile molecules - low signal
Solid tissue - stronger signal



DWI Pulse Sequence



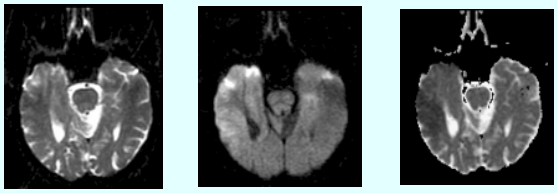
$$b = \gamma^2 G^2 \delta^2 \left(\Delta - \delta/3\right)$$

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

adapted, G. Clarke

Hyper acute CVA 4Hrs. Evol.

- MRI Diffusion



T2 Echo planar **b-value 1000** **ADC**

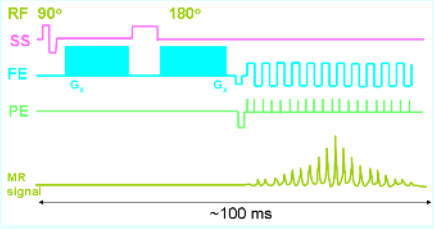
adapted, R. Rojas

Echo Planar Imaging (EPI)

ultrafast data acquisition
fill k-space by rapid gradient reversals and echoes
after a SINGLE set of RF pulses

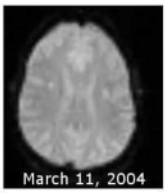
Peter Mansfield, 1980s

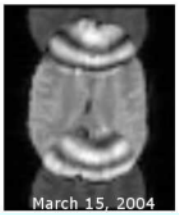
Diffusion Echo-Planar Imaging



- Signal has to be acquired in time ~T2
- Images in less than 100 ms but poor spatial resolution (~ 3mm x 3mm pixel)
- Requires very good B_0 homogeneity → big susceptibility artifacts

G. Clarke





EPI limits

Hardware requirements
- gradients - bigger, faster
- rapid A/D
- memory

Artifacts
- chemical shift
- eddy currents

Acoustic noise

Sequence flexibility

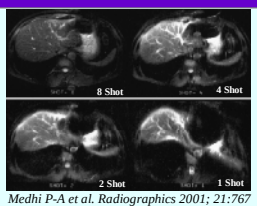
Induced currents in patient

G. Clarke

Liver Imaging

Echo Planar

- Echo planar is the fastest imaging sequence and can be used to minimize motion artifacts
- Long TE Gradient Echoes produce T2* contrast to identify tumors



Medhi P-A et al. Radiographics 2001; 21:767

Parallel Imaging

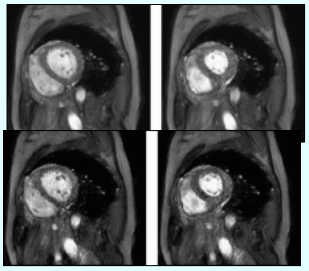
- Uses spatial information obtained from arrays of RF coils
- Information is used to perform some portion of spatial encoding usually done by gradient fields and RF pulses
- ***Multiplies imaging speed***
  - without needing faster-switching gradients
  - without additional RF power deposited

adapted, G. Clarke

Image Acceleration

Conventional breath-hold cardiac MRI Requires 14 heartbeats.

SENSE breath-hold cardiac MRI Requires 3 heartbeats.



http://www.mr.ethz.ch/sense/sense_application.html

G. Clarke

Summary

Resolution	Signal-to-Noise	Contrast
FOV & matrix size	FOV & matrix size	Relaxation times
Slice thickness	RF Pulse flip angles & timing	RF Pulse flip angles & timing
FSE inter-echo spacing	B_o field strength	Preparation pulses
Motion artifact	Receiver bandwidth	Gradient timing (b-value)
Chemical shift artifact	RF coil sensitivity	Magnetization transfer

G. Clarke

Pulse Sequence Factors

- Pulse sequence factors have varying effects
  - ↑ TR ↑ SNR by allowing more M_z regrowth
  - ↑ TE ↓ SNR by allowing more M_{xy} dephasing
  - 180° refocusing pulses ↑ SNR
    - SE or FSE
  - ↑ TI ↓ or ↑ SNR
  - ↑ α ↓ or ↑ SNR depending on Ernst angle

C. Keener, MARP

Suggested Reading

(In order of increasing complexity)

- MRI: From Picture to Proton McRobbie DW, Moore EA, Graves MJ & Prince MR. Cambridge Univ. Press, 2003; ISBN: 0521523192
- Magnetic Resonance Imaging 3rd ed. Vlaardingerbroek MT, den Boer JA, Luiten A. Springer 2002; ISBN: 3540436812
- Handbook of MRI Pulse Sequences Bernstein MA, King KF, Zhou XJ. Elsevier, 2004; ISBN: 0120928612

G. Clarke

Suggested Reading

(practical and specialty references)

- MRI Optimization: A hands-on approach Woodward P, Orrison Jr WW. McGraw Hill, 1997; ISBN: 0070718016.
- Practical Guide to Abdominal & Pelvic MRI Leyendecker JR, Brown JJ. Lippincott 2004; ISBN: 0781742951 (sections 1,4)
- *T1, T2 relaxation and magnetic transfer at 3T*. Stanisz et al., MRM 2005 54(3): 507-12.
- *MR imaging of the spine at 3T*. Shapiro MD, MRI Clin N Am 2006 14(1): 97-108.
- *Abdominal MR imaging at 3T*. Merkle et al., MRI Clin N Am 2006 14(1): 17-26.