Magnetic resonance imaging
Part 3

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[1] http://www.cis.rit.edu/htbooks/mri/

Fast imaging

Contrast

Spatial resolution

Medical applications

Chemical shift

Angiography

Tagged MRI

In-vivo spectroscopy

MRI hardware

Safety

Why Should We Go Faster ?

Patient acceptance

- claustrophobia
- pain

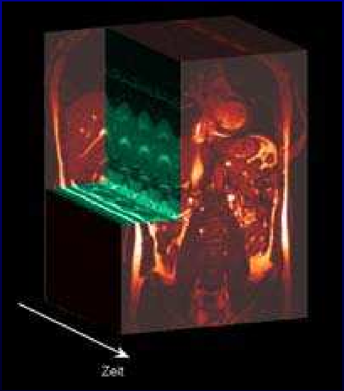
Patient Throughput

Reduction of Artefacts

- breathing
- beating heart
- patient movements

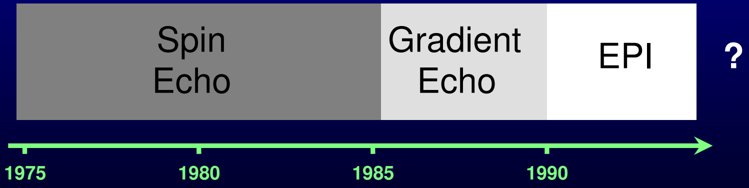
Dynamic Studies

- swallowing and speaking
- contrast agent dynamics
- movement of joints
- tracking of biopsy needles or catheters

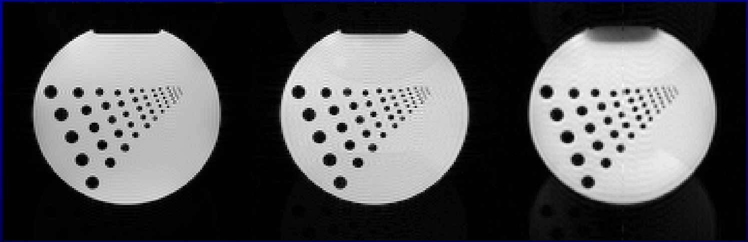


MR History

TA: min s 0.1 s



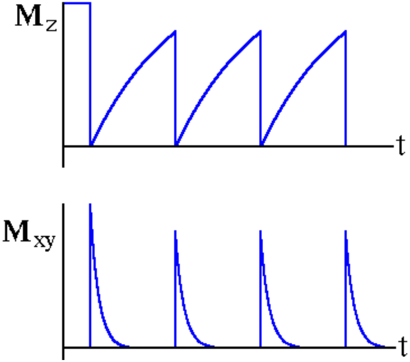
MR Acquisition Times



	Spin Echo	FLASH	EPI
TE	15 ms	5 ms	29 ms
TR	600 ms	15 ms	0.8 ms
TA	1 min 17 s	1.9 s	70 ms

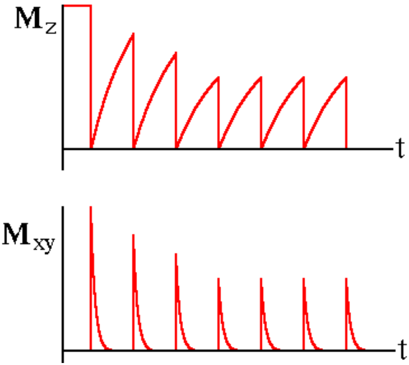
Partial relaxation

- For maximum signal we need to wait ($T_R \gg T_1 \approx 1\,\text{s}$) — long



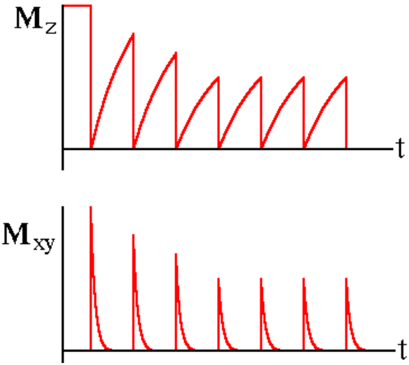
Partial relaxation

- For maximum signal we need to wait ($T_R \gg T_1 \approx 1\,\mathrm{s}$) — long
- Smaller *flip* angle $\longrightarrow$ weaker signal & shorter T_R



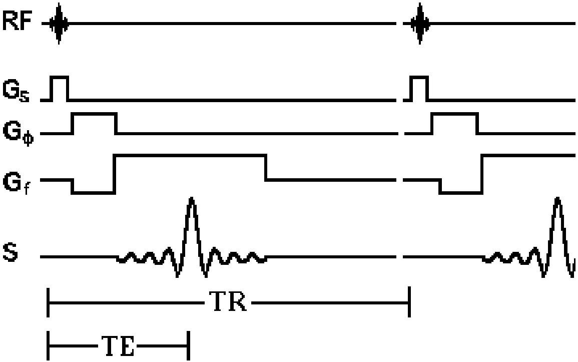
Partial relaxation

- For maximum signal we need to wait ($T_R \gg T_1 \approx 1\,\mathrm{s}$) — long
- Smaller *flip* angle $\longrightarrow$ weaker signal & shorter T_R
- First few 'calibration' cycles discarded



Gradient echo

Time diagram:



Gradient echo (2)

- Flip angle $10^\circ \sim 90^\circ$
- Desynchronization G_f (together with G_ϕ)
- $\ldots \longrightarrow$ resynchronization (maximum echo) in time T_E
- G_f changes sign (unlike in spin-echo, 180° pulse missing)
- Short T_R, tens of ms

Gradient echo $\times$ spin echo

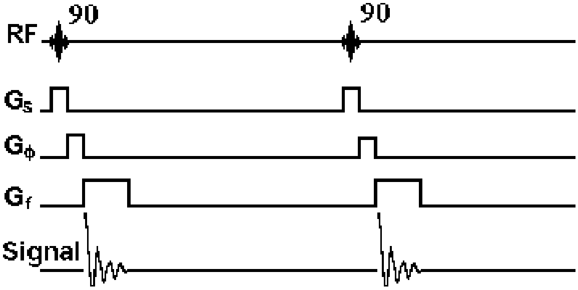
GE $\times$ SE

- Spin synchronisation:
  - RF puls in SE
  - gradient in GE
- Sensitivity to magnetic field inhomogeneity:
  - Small for SE, inhomogeneities compensated
  - Large for GE
- Speed
  - SE is slow
  - GE much faster, especially for small flip angles

$\longrightarrow$ GE is used for speed, e.g. fast 3D acquisition for fMRI
$\longrightarrow$ SE yields better images (more signal, less noise, less geometric distortion, magnetic field inhomogeneities compensated)

Multislice imaging

Time diagram of the 90° FID sequence



- Most time is unused.
- Acqusition time:

$$T_R \approx T_1 \approx 1\,\text{s} \times 256 \text{ excitations per slice } \times 20 \text{ slices} = \mathbf{1\,h\,25\,min}$$

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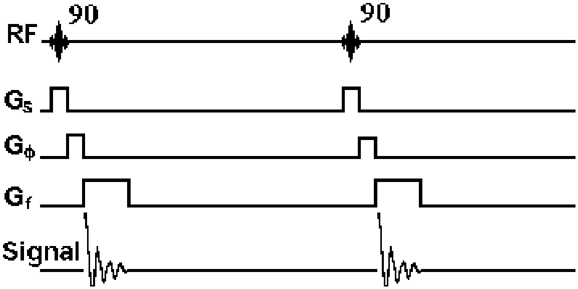

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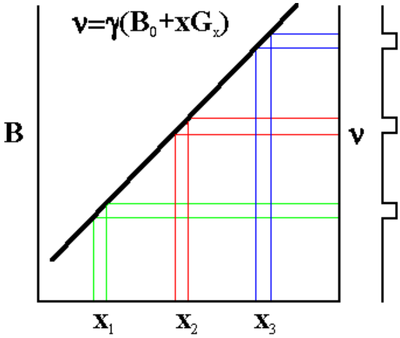
$$T_R \approx T_1 \approx 1\,\text{s} \times 256 \text{ excitations per slice} \times 20 \text{ slices} = \mathbf{1\,h\,25\,min}$$

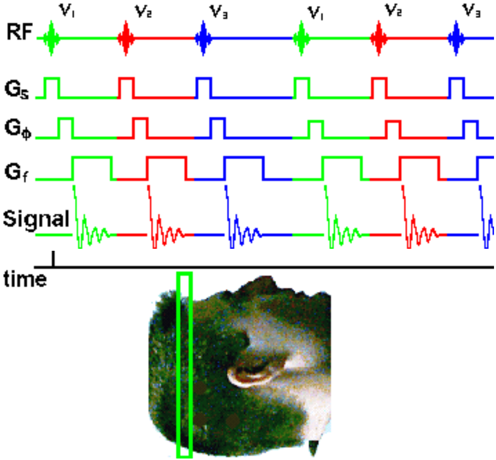
- $\longrightarrow$ While waiting, other slices can be excited.

Multislice imaging — excitation

- Slices should not influence other slices
- $\longrightarrow$ Constant $G_x = G_s$
- $\longrightarrow$ Different RF pulse and resonance frequencies
- Frequencies must be sufficiently distant



Multislice imaging — time diagram



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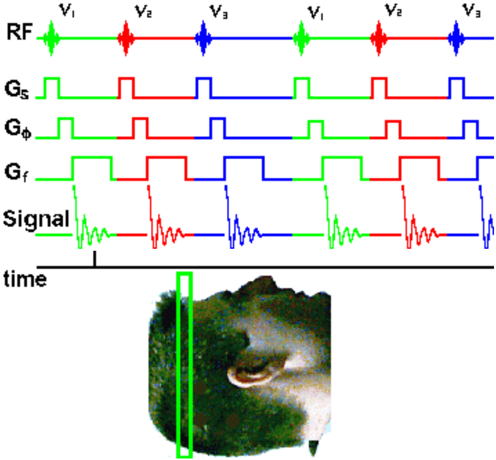

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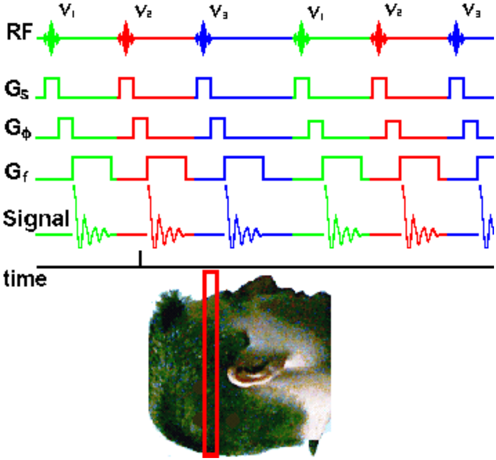

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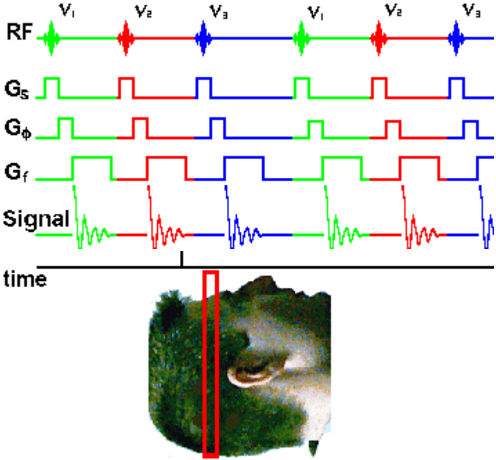

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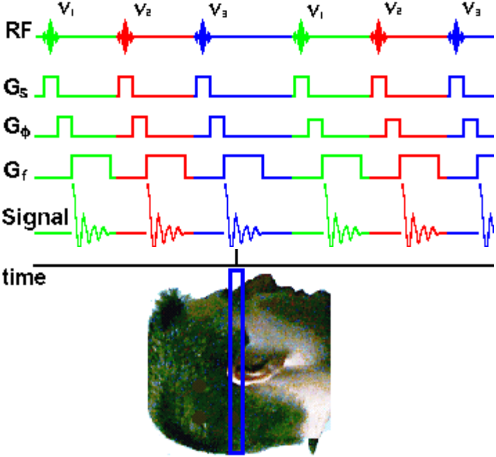

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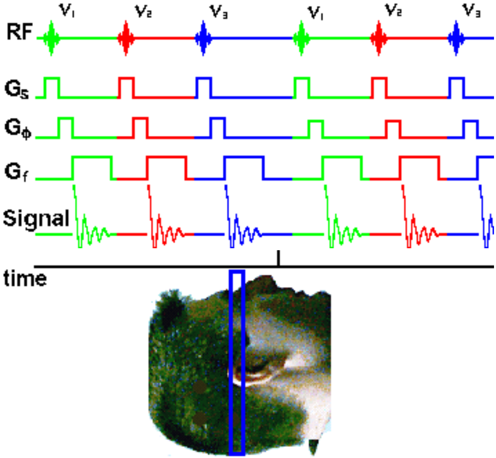

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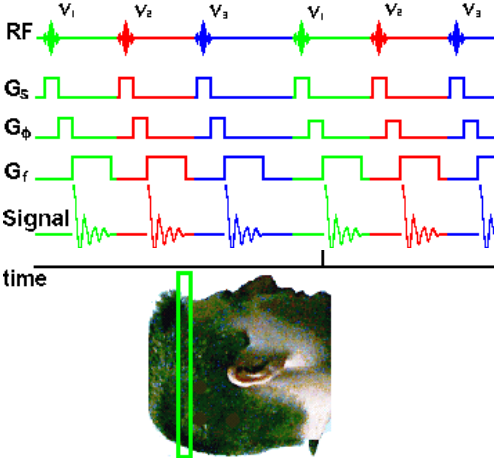

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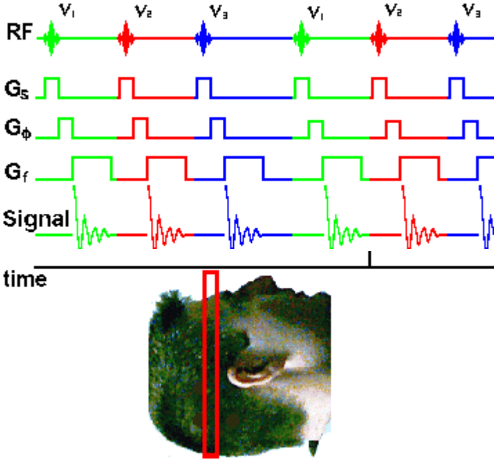

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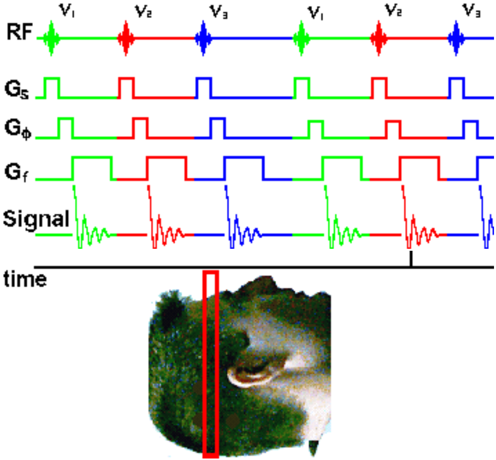

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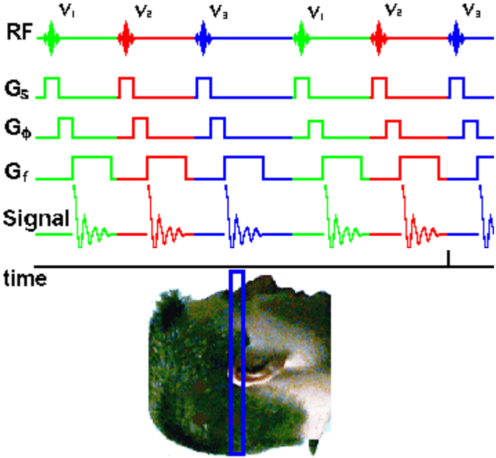

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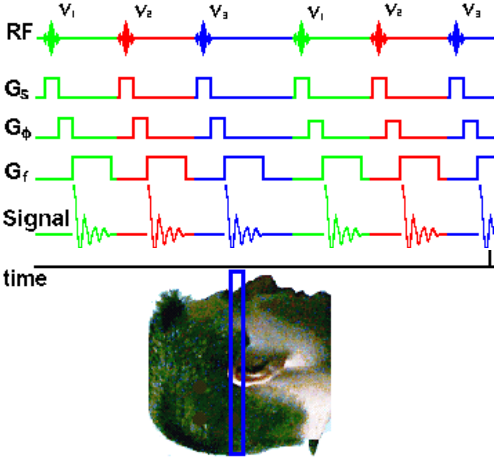

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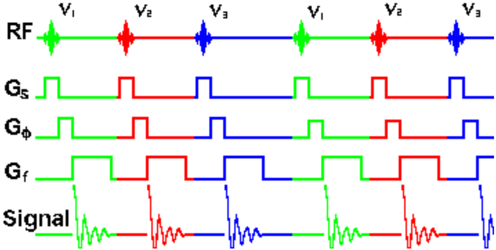


Significant acceleration $\sim 10\,\text{min}$

Fractional imaging

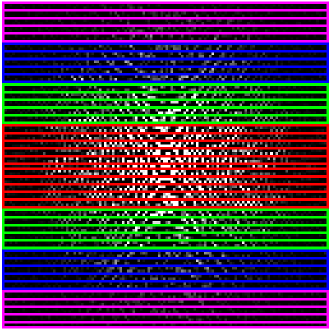
Partial coverage of the k-space

- k-space image is a Fourier transform of ρ
- ρ is real $\longrightarrow$ k-space is symmetric, $F^*(\mathrm{k}) = F(-\mathrm{k})$
- **Half Fourier:** $N_{\mathrm{ex}}N$ phase encoding steps, $0.5 < N_{\mathrm{ex}} \leq 1$
- Low frequencies important for the global shape tvar
- or **Partial echo:** Acquire half of the signal samples in time.
- Advantage $\longrightarrow$ shorter acquisition (up to $1/2$)
- Disadvantage $\longrightarrow$ lower SNR

Fast Spin-Echo

(Multiple echo)

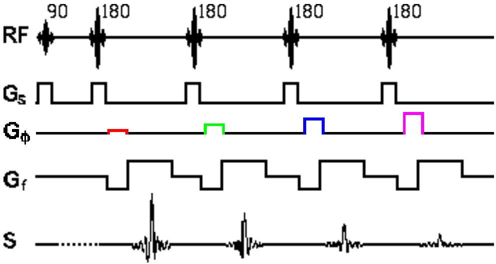
- One 90° excitation several refocusing 180° pulses



Fast Spin-Echo

(Multiple echo)

- One 90° excitation several refocusing 180° pulses
- Acquisition acceleration
- Later echo signals are weaker



Echo planar imaging (EPI)

- Very fast method ($20 \sim 100\,\text{ms/slice}$)
- Complete k-space in one excitation
- Mostly used for *fMRI* (functional MRI)

k-space (reminder)

Signal from the whole slice:

$$s(t) \propto \int_{(x,y)\in\text{slice}} \rho(x,y) \mathrm{e}^{-2\pi j (k_x(t)x + k_y(t)y)} \, \mathrm{d}x\mathrm{d}y$$

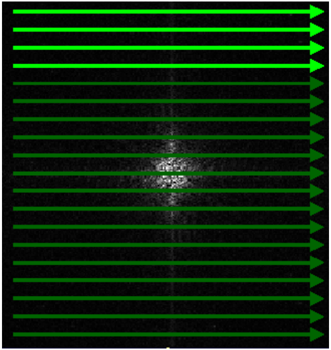
$$k_x(t) = \gamma \int G_x(t)\mathrm{d}x \qquad k_y(t) = \gamma \int G_y(t)\mathrm{d}x$$

$$s(t) = S\big(k_x(t), k_y(t)\big)$$

- $S(k_x, k_y)$ is a 2D Fourier transform of $\rho(x, y)$.
- We sample $S(k_x, k_y)$ at points $\big(k_x(t), k_y(t)\big)$.
- Trajectory $\big(k_x(t), k_y(t)\big)$ controlled by gradients

k-space sampling line by line

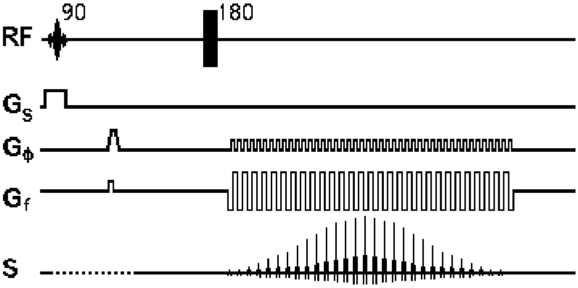
One line — one excitation



Echo Planar Imaging

sequence

- Initial G_f, $G_\phi \longrightarrow$ initial point in the k-space
- Subsequent G_f, $G_\phi \longrightarrow$ traversing the k-prostoru



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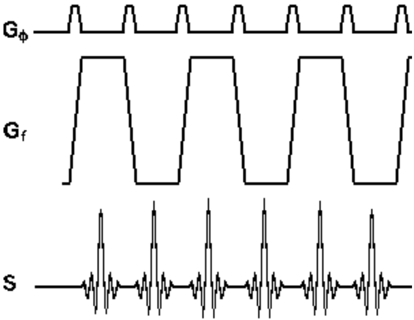
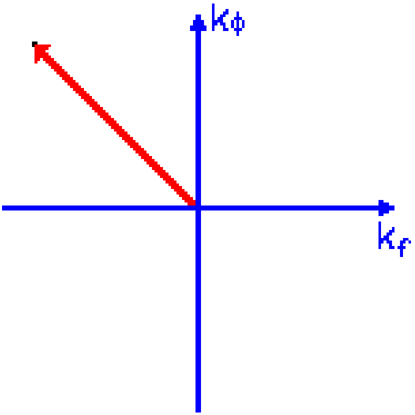


detail

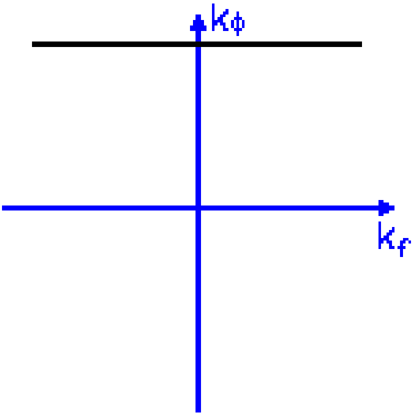
Echo Planar Imaging

Trajectory in k-space



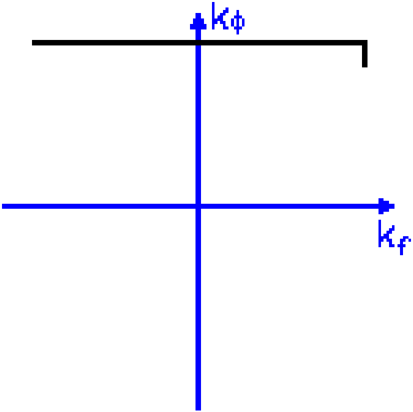
Echo Planar Imaging

Trajectory in k-space



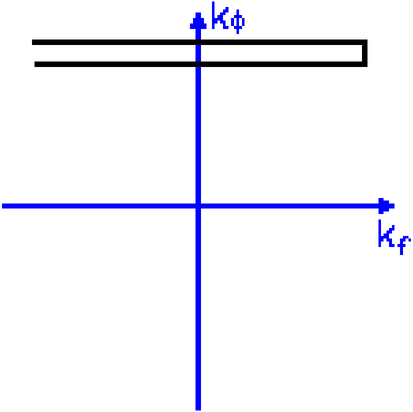
Echo Planar Imaging

Trajectory in *k*-space



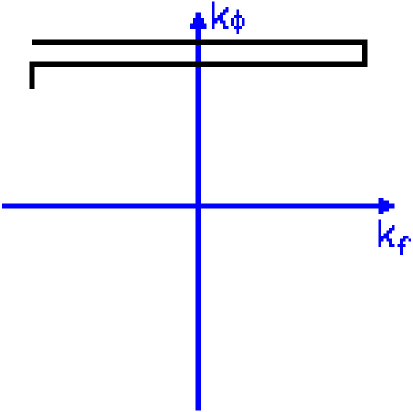
Echo Planar Imaging

Trajectory in *k*-space



Echo Planar Imaging

Trajectory in k-space



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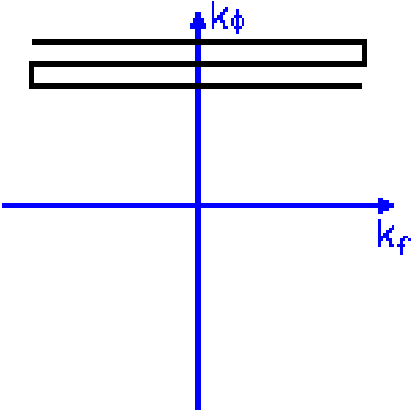

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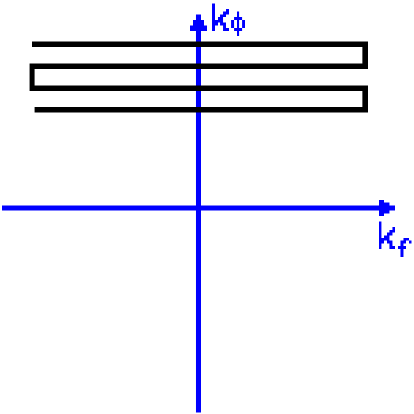

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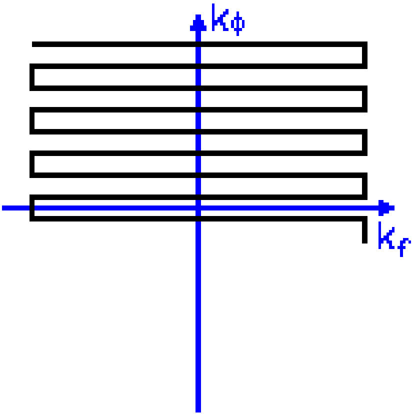

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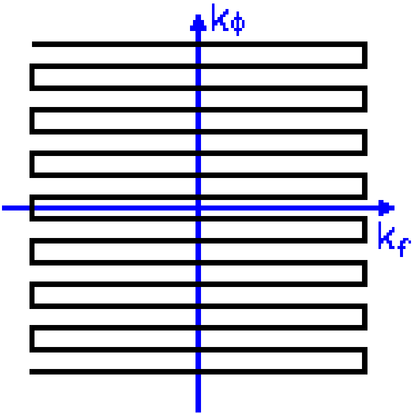

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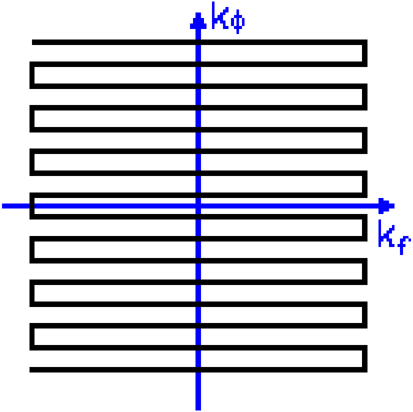
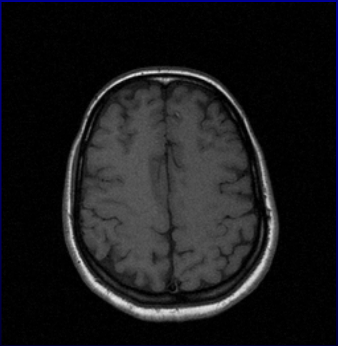
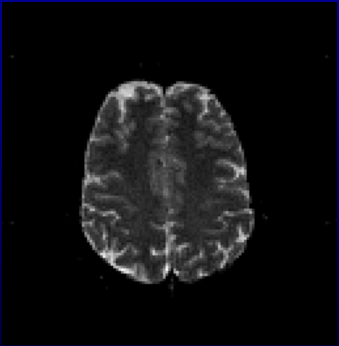


Other trajectories possible (spiral)

Comparison: Spin Echo vs. EPI

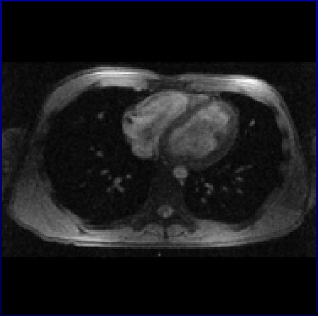


2D SE
TR / TE = 600 / 15 ms
TA = 1 min 55 s



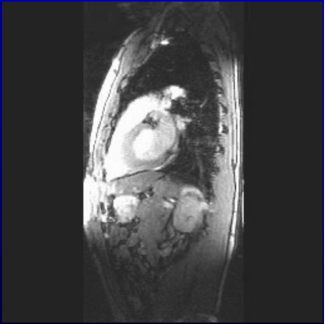
2D EPI
TR / TE = - / 66 ms
TA = 220 ms

Application: Real-Time MRI of the Heart



Segmented EPI

Application: Real-Time MRI of the Heart



TrueFISP 2D

Contrast

How to set the parameters

- Tissue parameters (what we want to visualize, from most to least important)
  - Spin-lattice relaxation constant T_1
  - Spin-spin relaxation constant T_2
  - Spin/proton density ϱ
  - Combined spin-spin relaxation constant T_2^* (including B_0 inhomogeneity)
- Imaging parameters (what we can influence)
  - Repetition time T_R
  - Echo time T_E
  - Inversion time T_I
  - Flip angle ϕ
  - T_2^*

Signal intensity

Summary

Spin echo

$$S \propto \varrho\left(1 - \mathrm{e}^{-\frac{T_R}{T_1}}\right)\mathrm{e}^{-\frac{T_E}{T_2}}$$

Inversion recovery 180°–90°

$$S \propto \varrho\left(1 - 2\mathrm{e}^{-\frac{T_I}{T_1}} + \mathrm{e}^{-\frac{T_R}{T_1}}\right)\mathrm{e}^{-\frac{T_E}{T_2}}$$

Gradient echo

$$S \propto \varrho\frac{\left(1 - \mathrm{e}^{-\frac{T_R}{T_1}}\right)\sin\phi\,\mathrm{e}^{-\frac{T_E}{T_2^*}}}{1 - \cos\phi\,\mathrm{e}^{-\frac{T_R}{T_1}}}$$

Optimal *(Ernst)* angle: $\cos\phi_{\mathsf{Ernst}} = \mathrm{e}^{-\frac{T_R}{T_1}}$

Typical tissue MRI parameters

Head tissue

Tissue	T_1 [s]	T_2 [ms]	ϱ [pu]
CSF	$0.8 \sim 20$	$110 \sim 2000$	$70 \sim 230$
White matter	$0.76 \sim 1.08$	$61 \sim 100$	$70 \sim 90$
Gray matter	$1.09 \sim 2.15$	$61 \sim 109$	$85 \sim 125$
Meninges	$0.5 \sim 2.2$	$50 \sim 165$	$5 \sim 44$
Muscle	$0.95 \sim 1.82$	$20 \sim 67$	$45 \sim 90$
Adipose (fat)	$0.2 \sim 0.75$	$53 \sim 94$	$50 \sim 100$

[pu] = percentage units relative to water. Calibration: $\varrho = 111$ for a 12 mM aqueous $NiCl_2$.

Contrast (2)

For tissues A, B

- Define $C = S_A - S_B$, for signal amplitudes S_A, S_B

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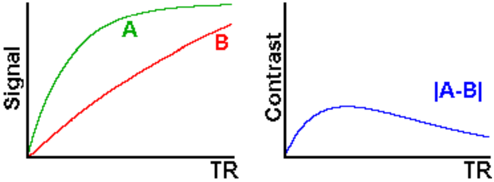

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For tissues A, B

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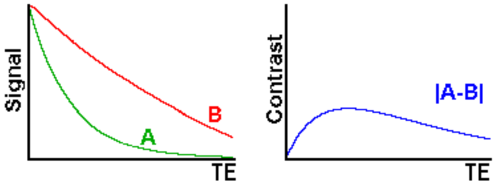
- Dependence on T_E



Weighted sequences

- T_1 weighted
- T_2 weighted
- Spin/proton density weighted (PD)

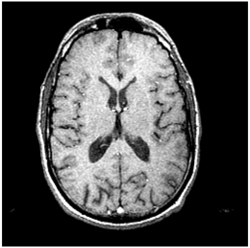
Parameter choice

Weighting	T_R	T_E
T_1	$\sim T_1$	$\ll T_2$
T_2	$\gg T_1$	$\sim T_2$
ϱ (PD)	$\gg T_1$	$\ll T_2$

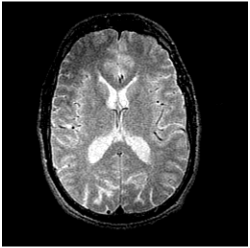
- $T_E \ll T_2 \longrightarrow T_2$ relaxation has no effect (not enough time to decay)
- $T_R \gg T_1 \longrightarrow T_1$ relaxation has no effect (full relaxation)

Typical settings

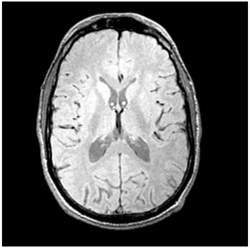
Spin echo



T_1 contrast
$T_R = 500\,\mathrm{ms}$
$T_E = 20\,\mathrm{ms}$
bone yes, water no
contrast tissue/non-tissue

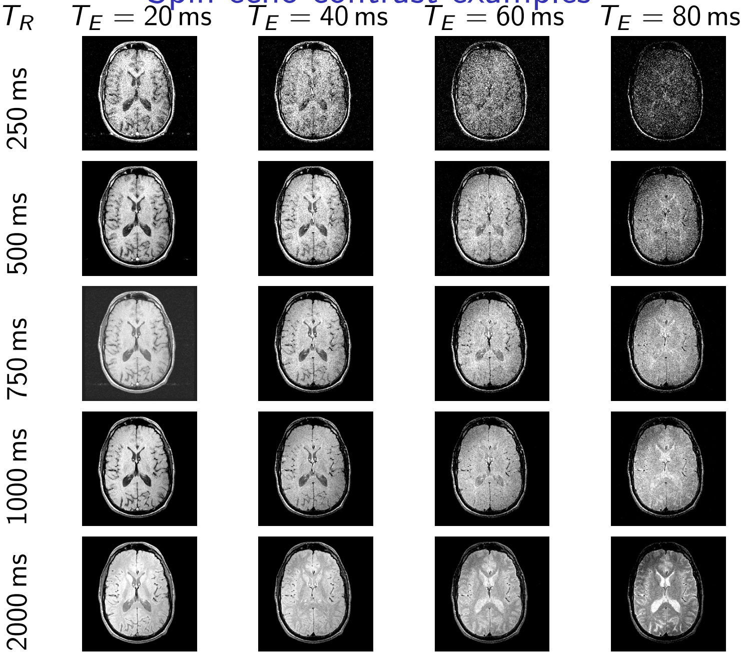


T_2 contrast
$T_R = 2000\,\mathrm{ms}$
$T_E = 80\,\mathrm{ms}$
bone no, water yes
soft tissue contrast

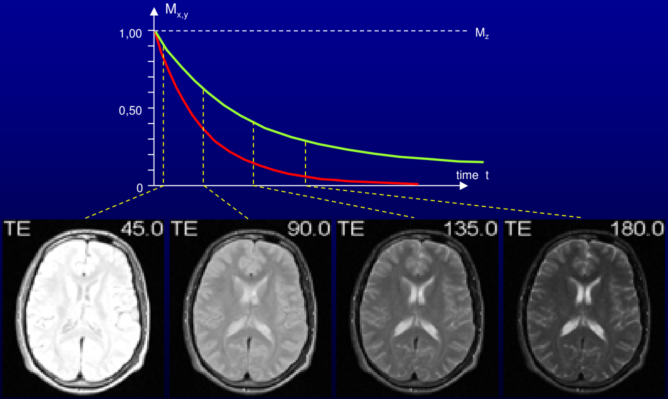


PD contrast
$T_R = 2000\,\mathrm{ms}$
$T_E = 20\,\mathrm{ms}$
bone yes, water yes
density

Spin echo contrast examples



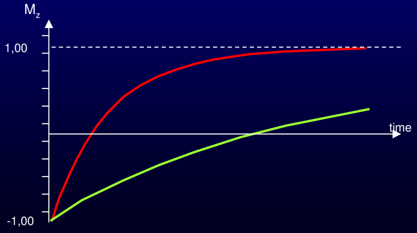
T2 Weighting

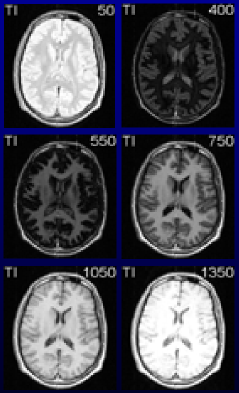


Inversion Recovery

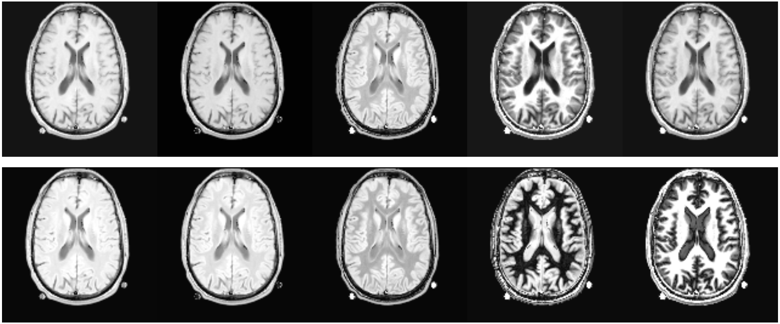
Measurement Timing

- 180° rf pulse
- Signal readout at inversion delay TI





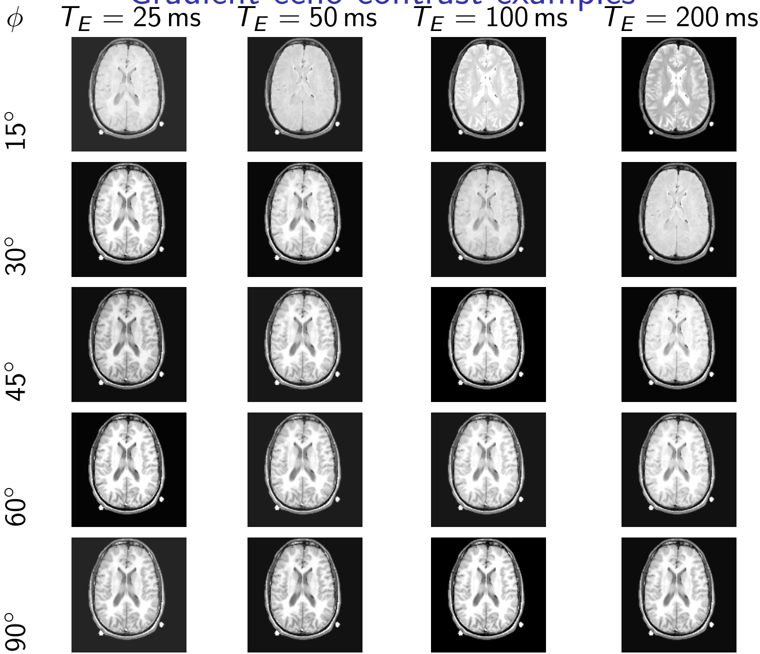
Inversion recovery contrast examples



Dots = calibration standard

T_I — specific tissue suppression, T_R — intensity, interaction

Gradient echo contrast examples

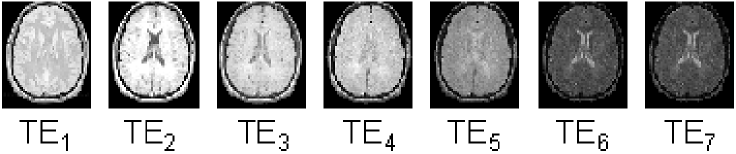


Exact imaging of T_1, T_2, ρ

- To find T_1, T_2, ρ exactly

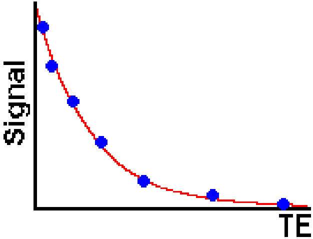
Exact imaging of T_1, T_2, ρ

- To find T_1, T_2, ρ exactly
- Sequence of acquisitions for different T_E



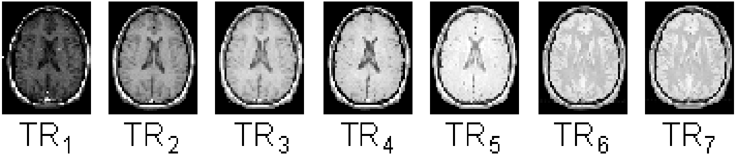
Exact imaging of T_1, T_2, ρ

- To find T_1, T_2, ρ exactly
- Sequence of acquisitions for different T_E
- Dependence of s on $T_E \longrightarrow T_2$



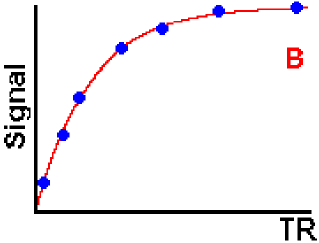
Exact imaging of T_1, T_2, ρ

- To find T_1, T_2, ρ exactly
- Dependence of s on $T_E \longrightarrow T_2$
- Sequence of aquisitions for different T_R



Exact imaging of T_1, T_2, ρ

- To find T_1, T_2, ρ exactly
- Dependence of s on $T_E \longrightarrow T_2$
- Sequence of aquisitions for different T_R
- Dependence of s on $T_R \longrightarrow T_1$



Exact imaging of T_1, T_2, ρ

- To find T_1, T_2, ρ exactly
- Dependence of s on $T_E \longrightarrow T_2$
- Sequence of aquisitions for different T_R
- Dependence of s on $T_R \longrightarrow T_1$
- Knowing T_1, T_2, $s \longrightarrow \rho$

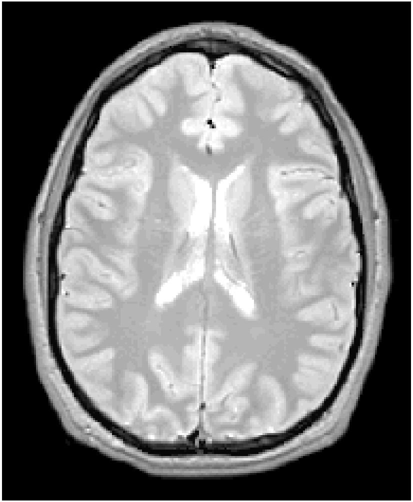
Exact imaging of T_1, T_2, ρ (2)

T_1

Exact imaging of T_1, T_2, ρ (2)

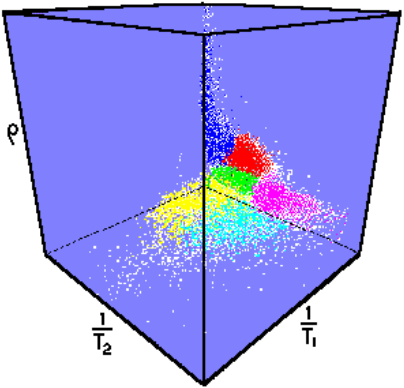
T_2

Exact imaging of T_1, T_2, ρ (2)



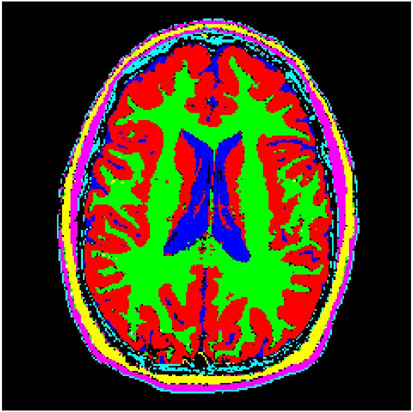
ρ

Exact imaging of T_1, T_2, ρ (2)



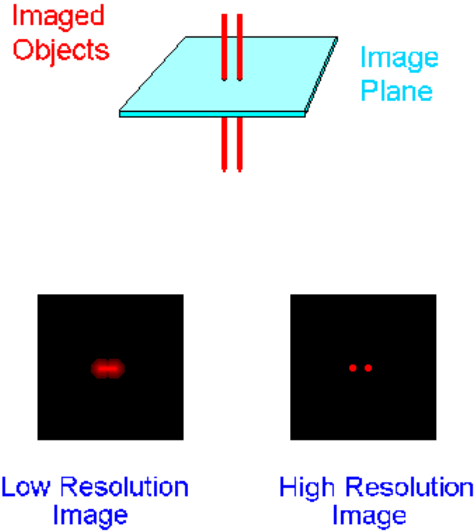
3D histogram

Exact imaging of T_1, T_2, ρ (2)



Segmentace

Spatial resolution



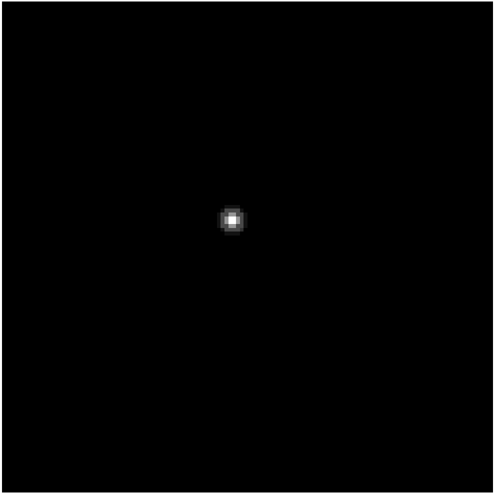
resolution = minimum distance of distinguishable objects

Spatial resolution (2)

- In the signal equations $s(t)$ we neglected relaxation
- $s(t)$ decays exponentially as $h(t) = \mathrm{e}^{-\frac{t}{T_2^*}}$
- Image $\mathscr{F}^{-1}\{s\}$ is a convolution of ρ and the impulse response $\mathscr{F}^{-1}\{h\}$
- Spatial resolution $w = (\pi G \gamma T_2^*)^{-1}$

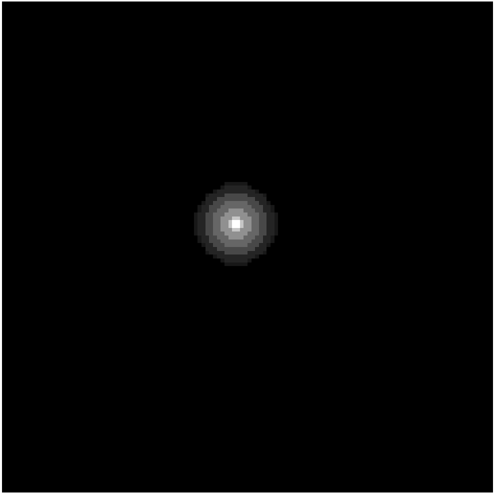
Spatial resolution (3)

Long T_2^*

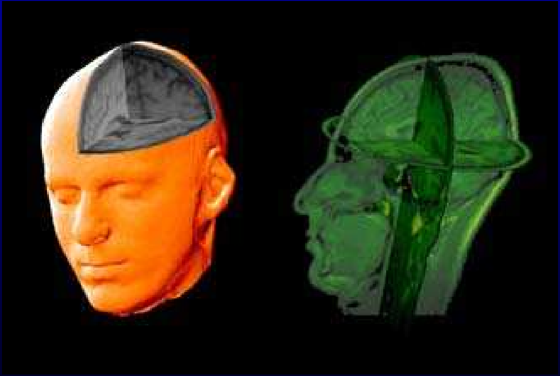


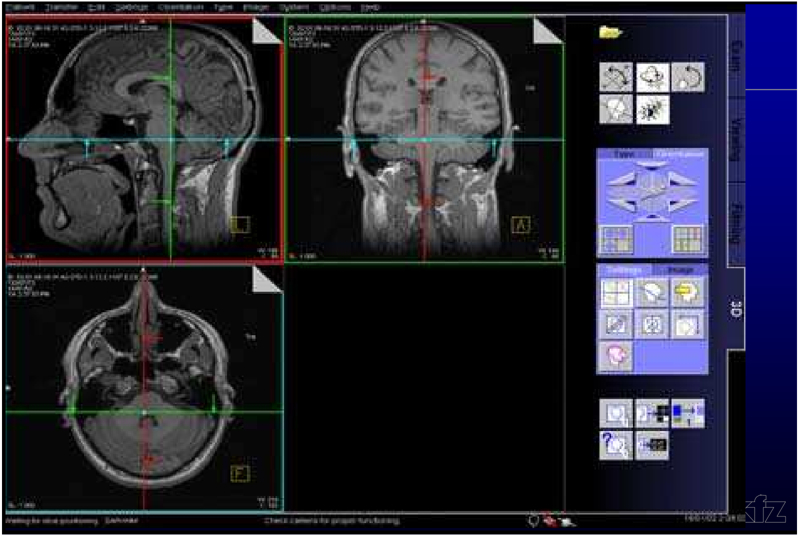
Spatial resolution (3)

Short T_2^*



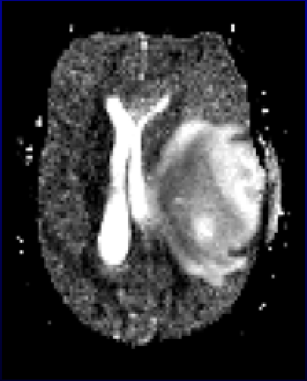
Applications: Brain Imaging




3D

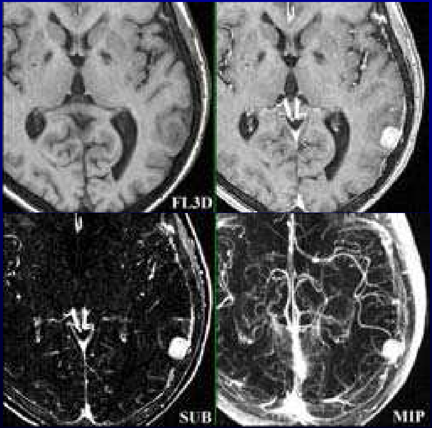
Application: Tumor Diagnostics

SE T1, post CA



Diffusion Map

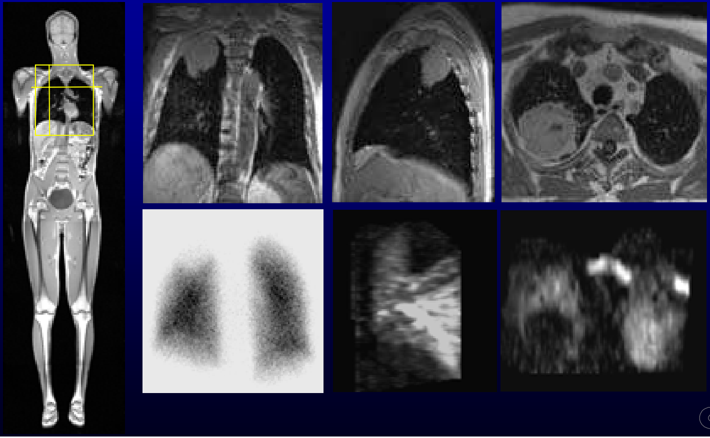
Application: Brain Metastasis



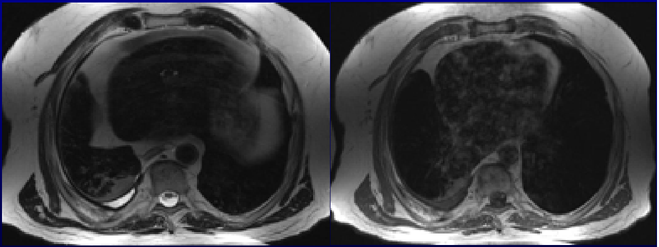
Schad L et al., DKFZ

dkfz

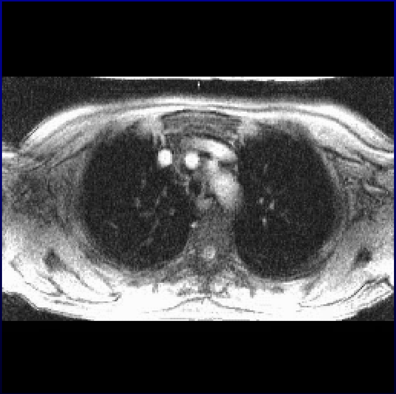
Application: Lung Cancer Diagnostics



Application: Asbestosis



Application: Relapsing Perichondritis



Sequence

- 2D FLASH
- TR = 4.4 ms
- RecFOV = 6/8
- Matrix = 128x256
- TA/Image = 550 ms

Application: Liver Tumor Diagnostics

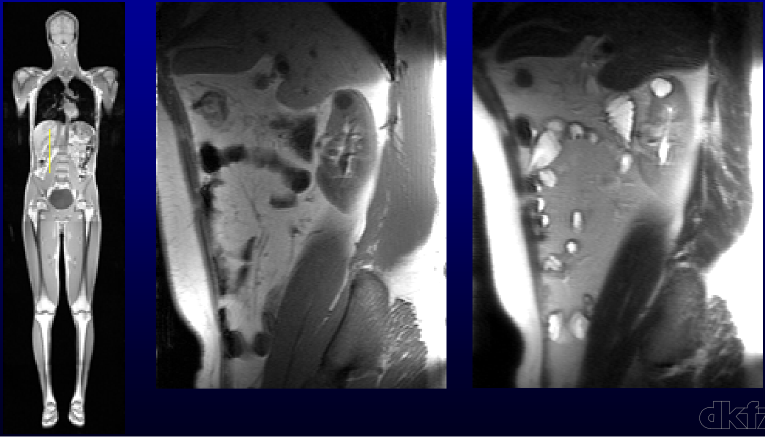
FLASH T1 (in phase) | FLASH T1, fat sat | FLASH T1, fat sat, Gd (phase2)

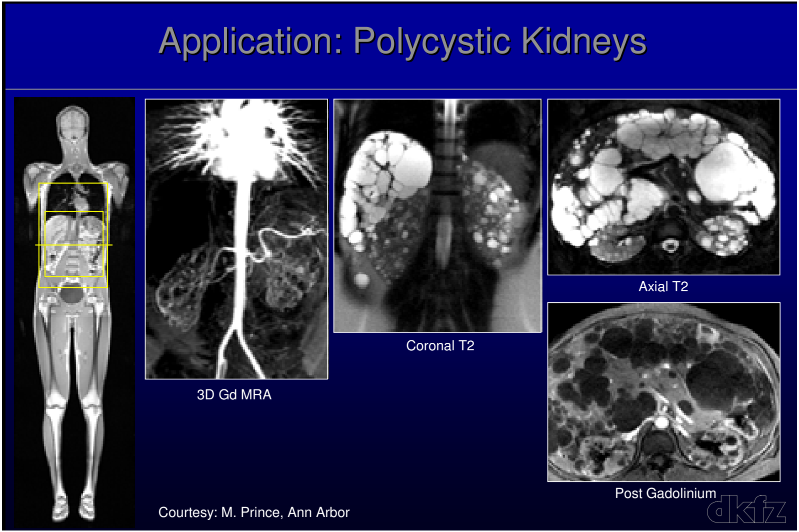
FLASH T1 (opposed phase) | FLASH T1, fat sat, Gd (phase1) | FLASH T1, fat sat, Gd (phase3)

Multiple Hepatocellular Adenomas

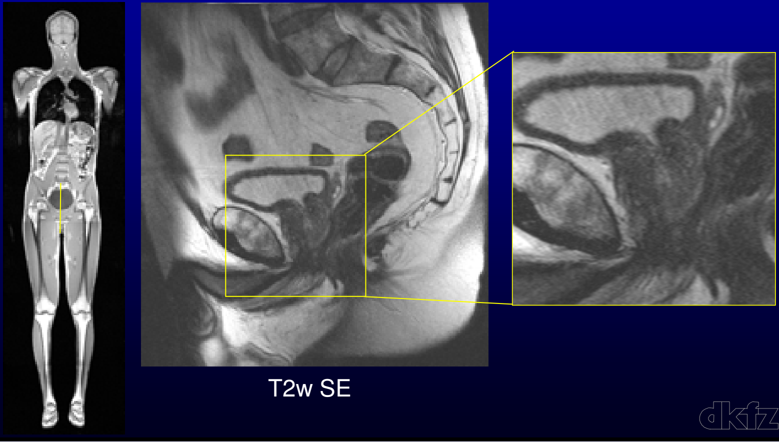
Courtesy: Op de Beeck, Antwerp

Application: Renal Cyst



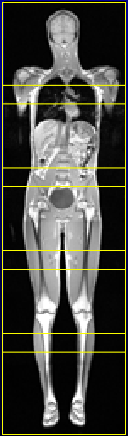

Application: Polycystic Kidneys
3D Gd MRA
Coronal T2
Axial T2
Post Gadolinium
Courtesy: M. Prince, Ann Arbor
dkfz

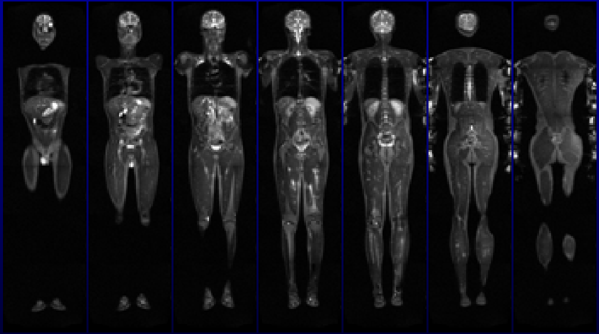
Application: Prostate MRI



T2w SE

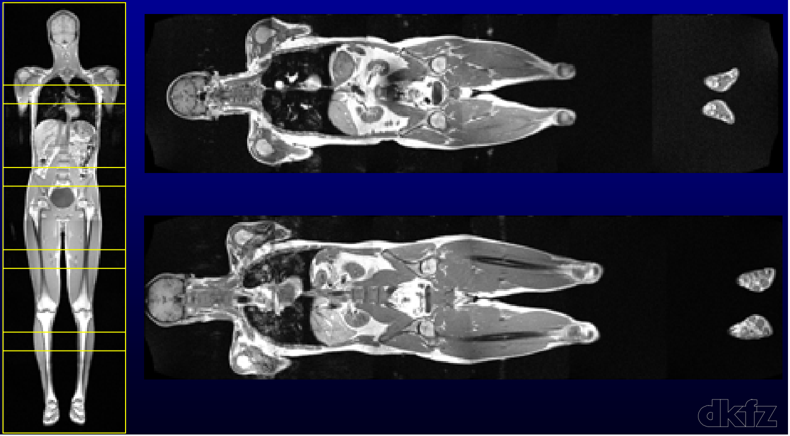
Application: Whole Body MRI





2D HASTE

Application: Whole Body MRI

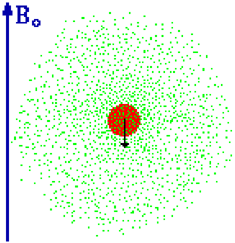


Atom in a magnetic field

- Atom in a magnetic field B_0
- Electrons rotate around the magnetic field axis
- $\rightarrow$ magnetic field oriented against B_0
- Effective magnetic field decreases

$$B = B_0(1 - s)$$

factor $0 < s \ll 1$



Chemical shift

- $=$ decrease of intensity of B due to chemical bonds
- Decrease of the resonance frequency
- Difference in [ppm] (parts per million):

$$d = \frac{f_{\text{ref}} - f}{f_{\text{ref}}} 10^6$$

- Depends on B_0
- For H in fat and water Δf is $\sim 3.5 \cdot 10^{-6} = 3.5\,\text{ppm}$

Chemical shift imaging

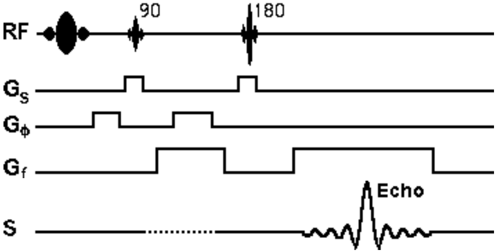
(Fat Suppression)

- **Inversion recovery**

Chemical shift imaging

(Fat Suppression)

- **Inversion recovery**
- **Saturation** by a frequency selective pulse $\longrightarrow M_z$ of fat 0
- Dephasing gradient ($M_{xy} \to 0$)
- Spin-echo sequence, B_0 must be homogeneous, T_1 must be long



Fast imaging

Contrast

Spatial resolution

Medical applications

Chemical shift

Angiography

Tagged MRI

In-vivo spectroscopy

MRI hardware

Safety

MRI angiography
(Flow Imaging)

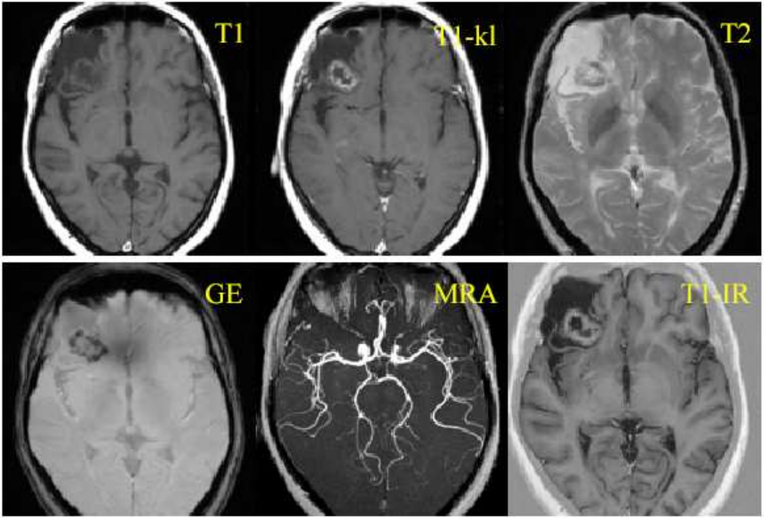
Imaging of blood vessels and flow.

- Contrast enhanced angiography
- Time-of-flight angiography
- Phase contrast angiography

Contrast enhanced angiography

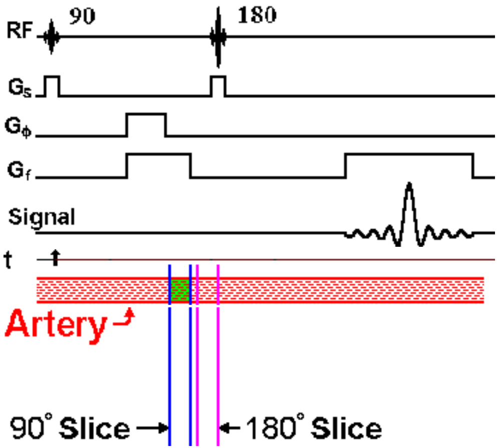
- Shortening of T_1. Short T_R sequences.
- Typically paramagnetic metal (Gd,Fe,Cu,Cr,Mn,...). Bound to decrease toxicity (EDTA, DTPA,...)
- $\longrightarrow$ very short T_1 of the blood
- Short T_R (fast 3D sequences)
- $\longrightarrow$ tissue signal suppressed
- Best contrast of angiography methods
- Other uses of contrast agents in MRI
  - Tumors
  - pH
  - Ca^{2+} contrast

Kontrast



Time-of-flight angiography

- 90° a 180° pulses with different *f*
- Signal only from volume influenced by both pulses



Time-of-flight angiography

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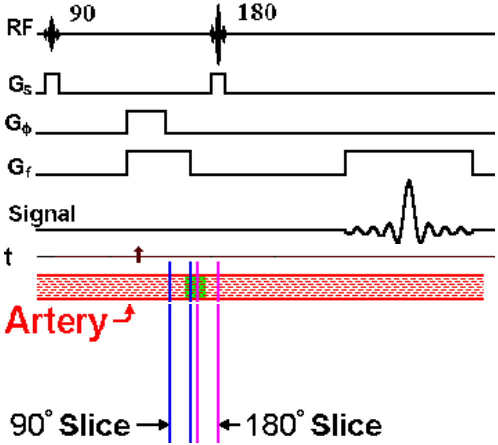

Time-of-flight angiography

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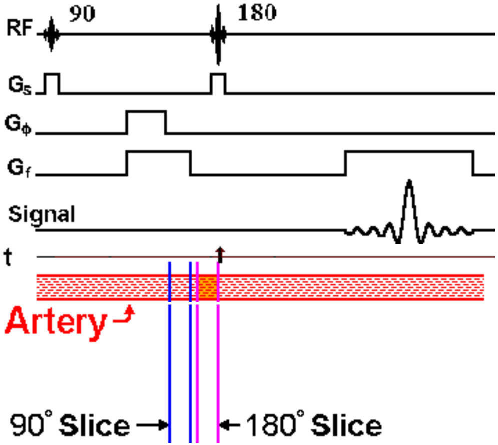

Time-of-flight angiography

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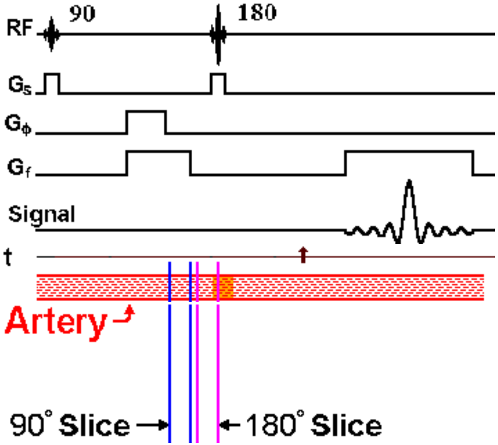

Time-of-flight angiography

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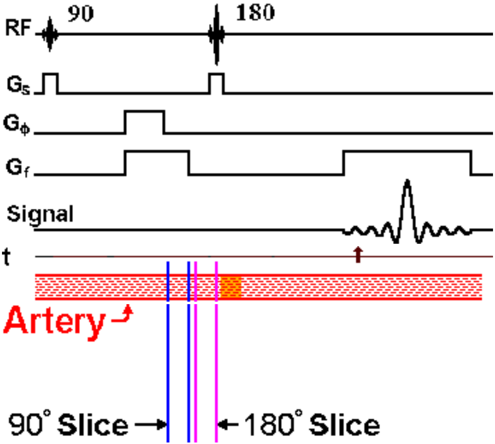
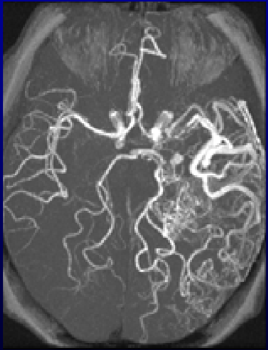
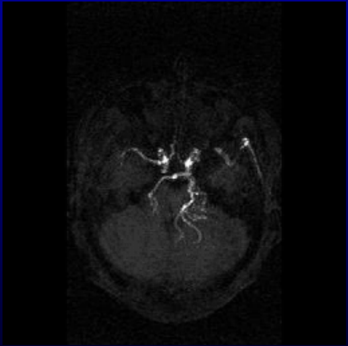


Application: Temporal AVM



TOF MRA



STAR

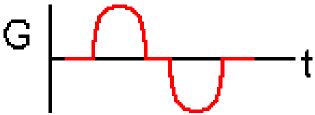
TI = 100-1000 ms

Application: Black Blood Coronary MRA

Courtesy: Philips, Best, NL

Phase contrast angiography

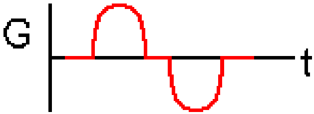
- Bipolar gradient



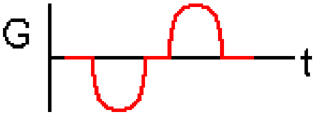
positive negative

Phase contrast angiography

- Bipolar gradient
- Total integral zero $\longrightarrow$ no effect for stationary spins



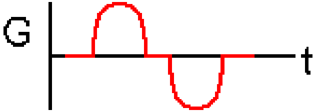
positive



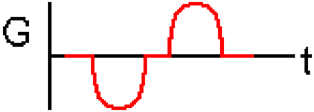
negative

Phase contrast angiography

- Bipolar gradient
- Total integral zero $\longrightarrow$ no effect for stationary spins
- $\longrightarrow$ influences spin moving in the gradient direction



positive

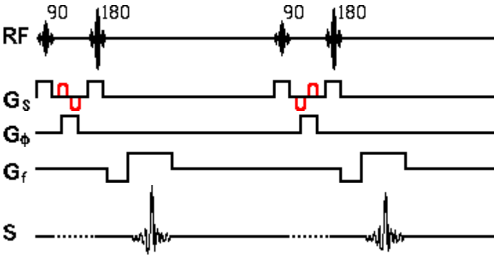


negative

Phase contrast angiography (2)

Time diagram

- Subtract images with positive and negative bipolar gradient (BPG)
- $\longrightarrow$ only moving spins visible
- $\longrightarrow$ signal increases with speed (for phase $< \pi$)



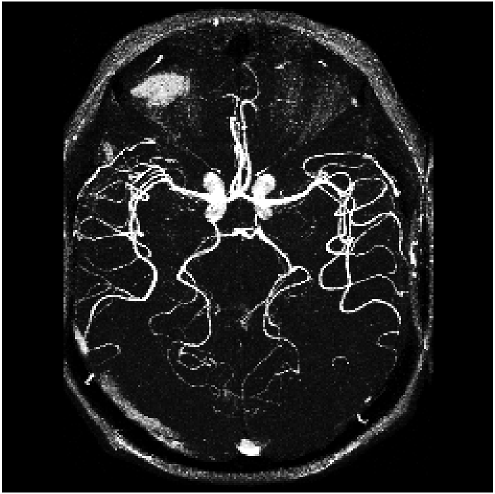
Phase contrast angiography (3)

Examples

Head coronary projection

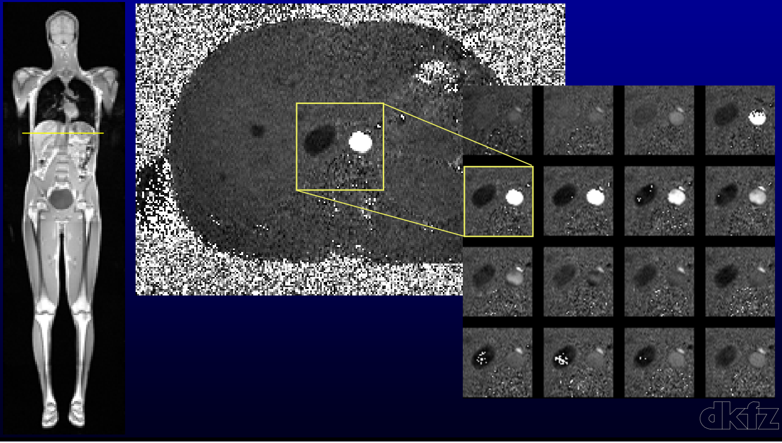
Phase contrast angiography (3)

Examples

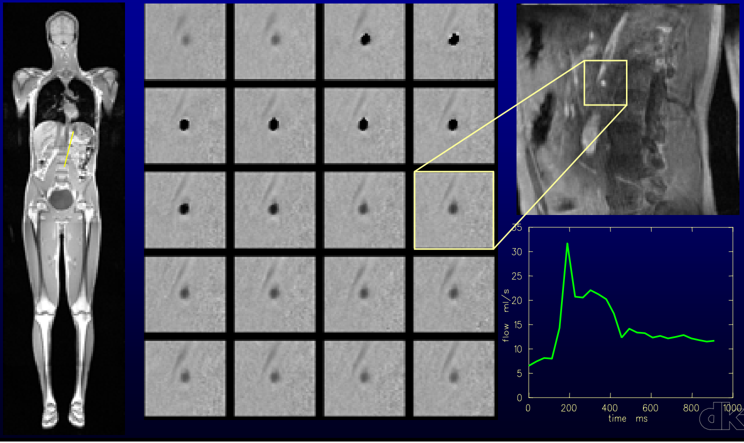


Head axial projection

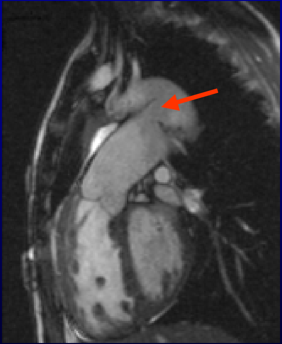
Application: Aortic Flow Measurements



Application: Renal Flow Measurements



Application: MR Angiography of the Aorta



TrueFisp
Patent Ductus Arteriosus

Subsecond 3D MRA

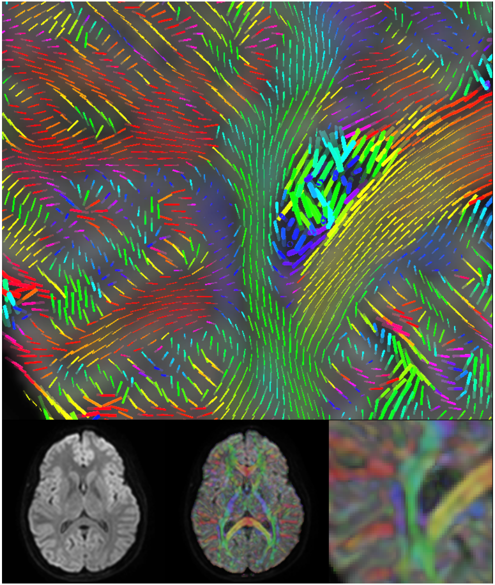
Courtesy: NWU Chicago

Diffusion MRI

(Diffusion tensor imaging)

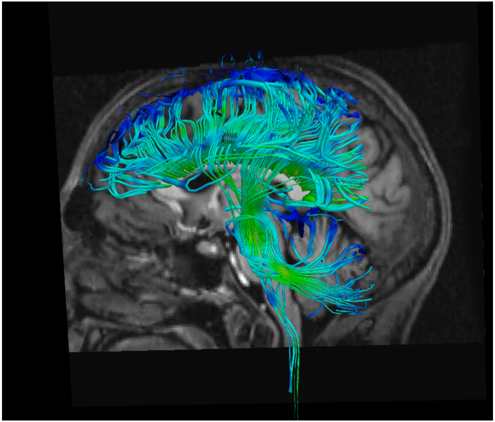
- Measure spatial diffusivity of water (tensor of diffusivity)
- Like phase contrast angiography but much slower speeds
- Connectivity of neural fibers in the brain

Diffusion MRI — examples

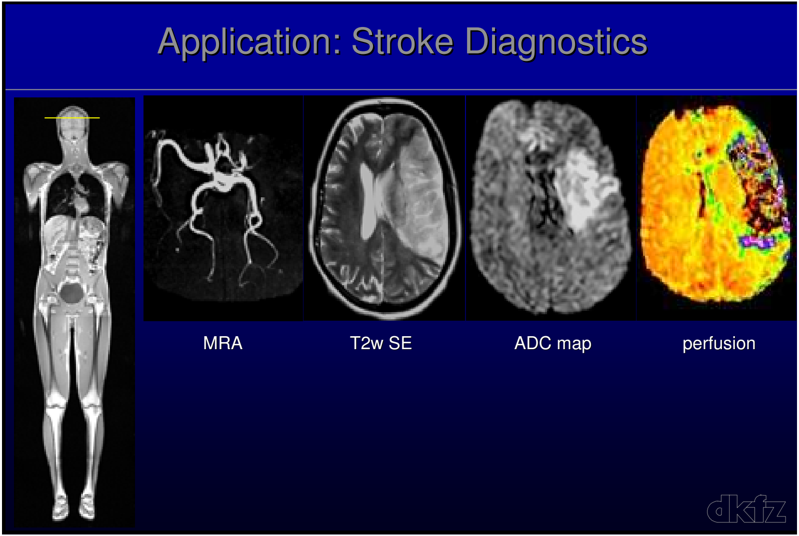


http://people.csail.mit.edu/lauren/dtmri.html

Diffusion MRI — examples

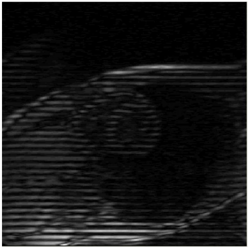
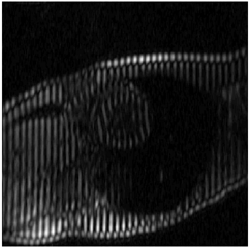


http://people.csail.mit.edu/lauren/dtmri.html


Application: Stroke Diagnostics
MRA
T2w SE
ADC map
perfusion

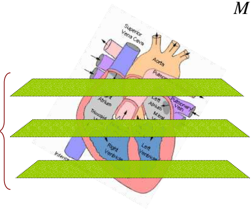
Tagged MRI

- Create virtual markers deforming with the tissue, last about $\sim 700\,\mathrm{ms}$
- Simple spatial modulation of magnetisation (SPAMM):
  - 90° RF impuls $\longrightarrow$ transversal magnetizace
  - Gradient $\longrightarrow$ spatial modulation of phase
  - Second RF pulse $\longrightarrow$ longitudinal magnetisation
- $\longrightarrow$Periodic spatial modulace of the magnetization, last about $\sim 700\,\mathrm{ms}$, can be done in 2D

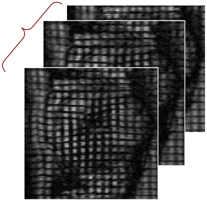



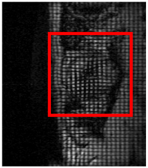
2-D Cardiac MRI Images

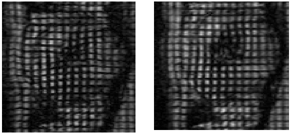
N slices

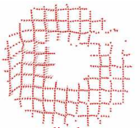


M frames per slice

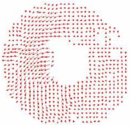








sparse displacements



dense displacements

Electrical & Computer ENGINEERING

Y. Sun, Y.L. Wu, K. Sato, C. Ho, and J.M.F. Moura,
Proc. Annual Meeting ISMRM 2003

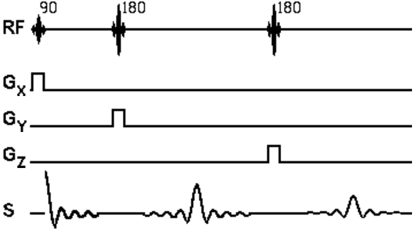
National Center for Research Resources

Spektroskopic imaging

Slice Selective Techniques

$$f = \gamma B$$

- RF selective pulsees in all 3 axes

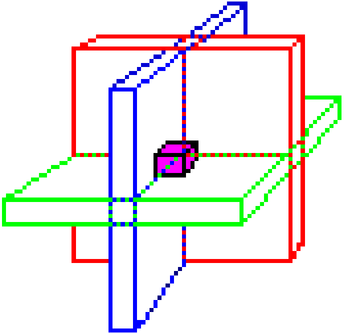


Spektroskopic imaging

Slice Selective Techniques

$$f = \gamma B$$

- RF selective pulsees in all 3 axes
- Only the intersection is excited

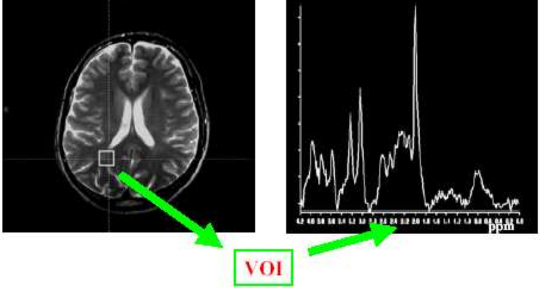


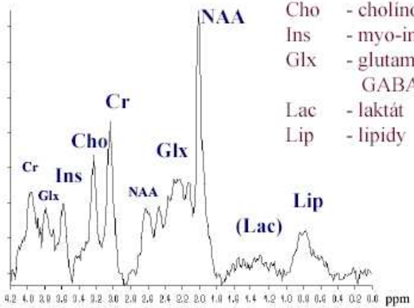
Spektroskopic imaging

Slice Selective Techniques

$$f = \gamma B$$

- RF selective pulsees in all 3 axes
- Only the intersection is excited
- Point resolved spectroscopy (PRESS)
- Stimulated echo acquisition mode (STEAM)
- Elected volume excitation using stimulated echoes (VEST)
- Image-selected in vivo spectroscopy (ISIS)
- Depth-resolved surface spectroscopy (DRESS)





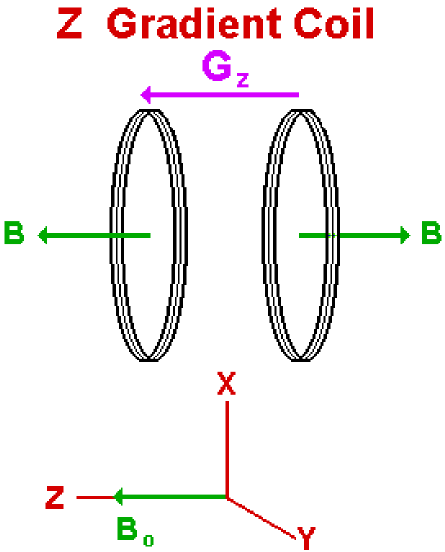
NAA - N-acetylaspartát
Cr - (fosfo)kreatin
Cho - cholínové sloučeniny
Ins - myo-inositol
Glx - glutamát, glutamin, GABA
Lac - laktát
Lip - lipidy

[1]H spektrum z lidského mozku, 1.5 T, sekvence STEAM,

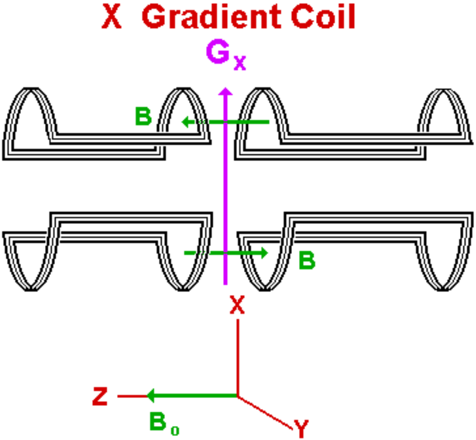
Gradient Tube

Gradient in z

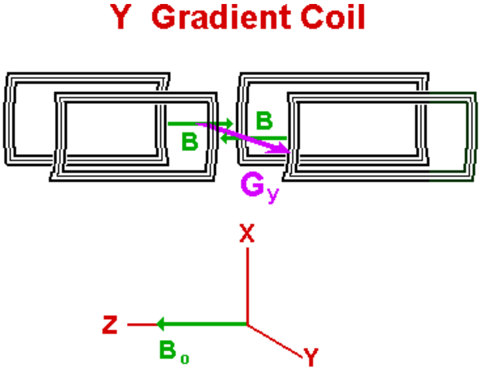
Antiparallel Helmholtz coils



Gradient in x



Gradient in y



Radio Frequency Coils: Volume Resonators

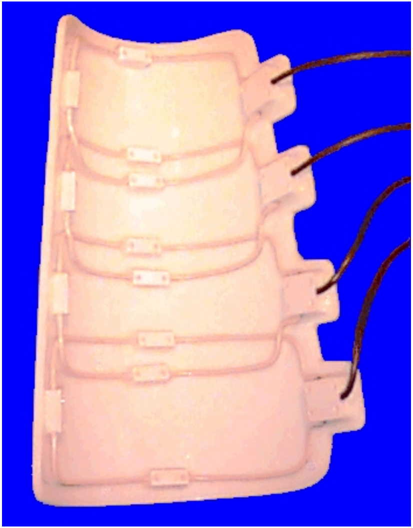





Bird cage

Most often used volume coil, for head images

Phased array coils



Phased array

Only for reception

Phased array coils

Phased array pro pMRI

Only for reception

Surface coil

- Only for reception
- Good SNR
- Short range

universal

Surface coil

- Only for reception
- Good SNR
- Short range

knee

Surface coil image example

spine

Note the intensity decrease

Fast imaging

Contrast

Spatial resolution

Medical applications

Chemical shift

Angiography

Tagged MRI

In-vivo spectroscopy

MRI hardware

Safety

MRI Safety

Advantages

- Not invasive
- No ionising radiation

Risks

- Strong magnetic fields
- Magnetic fields variable in time
- Magnetic fields variable in space
- High frequence (RF) electromagnetic field
- Cryogenic liquids (liquid nitrogen and helium)

Safe limits

FDA, 2003

		limit
B_0	newborns	4 T
	$>$ 1 měsíc, adults	8 T
$\mathrm{d}B/\mathrm{d}t$	no painful sensation	
$\mathrm{d}B/\mathrm{d}z$		
energy	full body, $\geq$ 15 min	4 W/kg
	head, $\geq$ 5 min	4 W/kg
	head, torso, $\geq$ 5 min	8 W/kg
	extremities, $\geq$ 5 min	12 W/kg
noise	peak value	140 dB
	mean value (RMS)	99 dBA

Extremely strong magnetic fields

- Can pull ferromagnetic objects from meters away

Extremely strong magnetic fields

- Can pull ferromagnetic objects from meters away
- No ferromagnetic objects allowed in the room

Extremely strong magnetic fields

- Can pull ferromagnetic objects from meters away
- No ferromagnetic objects allowed in the room
- Magnetic field may move metal implants.
- Magnetic field can make eletronic implants fail.
- Magnetic field can damage magnetic discs, credit cards etc.

Other risks

RF coils

- Can heat up on failure

Lack of oxygen

- Increased evaporation of He or N may reduce the concentration of O_2
- Monitoring of the O_2 concentration is necessary