Physics of Imaging Systems

Basic Principles of Magnetic Resonance Imaging V

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Spin-Echo Sequence

k-space: after 1. TR

k-space: after 2. TR

k-space: after 256. TR

Spin-Echo Images

\[ S_{SE} = \rho \cdot \left[ 1 - e^{-\frac{TR}{T1}} \right] \cdot e^{-\frac{TE}{T2}} \]

Pw
TR = 2775 ms
TE = 17 ms

T2w
TR = 2775 ms
TE = 102 ms

T1w
TR = 575 ms
TE = 14 ms

- SE gold standard technique for T1 and T2 morphology
Spin-Echo Contrast: TR, TE

- TR: 300 - 800 ms
- TE: 1500 - 3000 ms
- T1-weighted
- T2-weighted
- no contrast
- SNR low

Spin-Echo: T1 Dependency

T1-factor: $[1 - \exp(-TR/T1)]$

- GM: T1 = 970 ms
- WM: T1 = 600 ms

T1-contrast

$C = \left| \frac{S_A - S_B}{S_A + S_B} \right|$
Spin-Echo: T2 Dependency

\[
T2 - factor = \exp(-TE/T2)
\]

GM: \(T2 = 110\, \text{ms}\)

WM: \(T2 = 90\, \text{ms}\)

source: Reiser and Semmler. "Magnetresonanztomographie" 2002

Spin-Echo: TR, TE

**Spin-Echo: TR, TE**

- TR = 600 ms, TE = 10 ms
- SE contrast between grey and white matter

**Spin-Echo: Multi-Slice**

- Interleaved SE measurement
- Multi-slice SE
  - About 60 slices can be measured simultaneously!
Inversion Recovery Sequence

\[ S_{IR} = \rho \cdot \left[ 1 - 2e^{-\frac{TI}{T1}} + e^{-\frac{TR}{T1}} \right] \cdot e^{-\frac{TE}{T2}} \]

\[ M_z \]

source: Reiser and Semmler, "Magnetresonanztomographie" 2002
Inversion Recovery Contrast

- WM and GM contrast dependency on TI, TR and TE
- IR gold standard technique for T1 contrast

source: Reiser and Semmler. "Magnetresonanztomographie" 2002

Gradient-Echo Sequence

- example: $\alpha = 20^\circ$  
  $M_z$ - reduction by 6%  
  $M_{xy}$ - value 34% of $M_z$!!
Gradient-Echo: Phase

\[ 0 \leq t \leq \tau \quad \phi(x, t) = \gamma \cdot \int_{0}^{t} -G_x \cdot x \cdot d\tau = -\gamma \cdot G_x \cdot x \cdot t \]

in rot. frame:

\[ \tau \leq t \leq 2\tau \quad \phi(x, t) = -\gamma \cdot G_x \cdot x \cdot t + \gamma \cdot \int_{\tau}^{t} G_x \cdot x \cdot d\tau \]

\[ = -\gamma \cdot G_x \cdot x \cdot \tau + \gamma \cdot G_x \cdot x \cdot (t - \tau) \]


Gradient-Echo: Steady-State

\[ \alpha \cos \frac{2\pi}{T1} \cdot \sin \frac{2\pi}{M1} \]

\[ M_z \text{ steady-state:} \quad M_{z\text{SS}} = M_0 \cdot (1 - e^{-TR/T1}) / (1 - e^{-TR/T1} \cos \alpha) \]

\[ M_{xy} \text{ steady-state:} \quad S \propto M_{xy} = M_{z\text{SS}} \sin \alpha \cdot e^{-TE/T2^*} \]

example: WM

T1 \sim 600 \text{ ms}

TR = 25 \text{ ms}

source: Reiser and Semmler. "Magnetresonanztomographie" 2002
Gradient-Echo: FLASH

FLASH signal:

\[ S_{\text{FLASH}} = \rho \cdot \frac{(1 - E_1)\sin\alpha}{1 - E_1 \cos\alpha} \cdot e^{-\frac{TE}{T_2^*}} \cdot e^{-\frac{TR}{T_1}} \]

with \( E_1 = \exp(-\frac{TR}{T_1}) \)

Ernst-angle:

\[ \alpha_E = \arccos \left( e^{-\frac{TR}{T_1}} \right) \]

FLASH: “fast low angle shot”

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Gradient-Echo: Measuring Time

**SE**

- \( \alpha = 90^\circ / 180^\circ \)
- TE = 20 ms
- TR = 600 ms

**GE**

- \( \alpha = 25^\circ \)
- TE = 7 ms
- TR = 20 ms

\( T_{\text{aq}}: \text{minutes} \)

\( T_{\text{aq}}: \text{seconds} !! \)
Gradient-Echo: Examples I

spin-echo
TR = 680 ms
TE = 15 ms
$\alpha = 90^\circ$
T1-contrast

2D FLASH
TR = 170 ms
TE = 5 ms
$\alpha = 70^\circ$
T1-contrast

3D FLASH
TR = 60 ms
TE = 40 ms
$\alpha = 25^\circ$
T2*-contrast

- no T2 contrast with gradient-echo technique!

Gradient-Echo: Examples II

CT
TE = 20 ms

SE
TE = 20 ms

GE
TE = 20 ms

normal bone

osteoporosis

susceptibility effect
**Gradient-Echo: FISP**

- FISP: “fast imaging with steady precession”
- steady-state free precession sequence: SSFP
- no spoiler, all phases are compensated
- $M_y$ contributes to $M_z \rightarrow$ more signal!
- FISP signal for $TR \ll T_1$ and $TR \ll T_2^*$:

\[
S_{\text{FISP}} = \rho \left( \frac{\sin \alpha}{1 + T_1/T_2^* + (1 - T_1/T_2^*) \cos \alpha} \right) e^{-\frac{TE/T_2^*}{T_1/T_2^*}}
\]

- FISP contrast: $T_1/T_2^*$
  water: $\sim 1$, all other tissues: $\sim 10$

**Gradient-Echo: FISP Problem**

concepts
- transverse magnetization is not spoiled (as in FLASH)
- complete refocusing of all gradients in one TR

problems
- signal equation yields $T_1/T_2$ contrast
- susceptibility differences can cause artifacts
- high flip angles (SAR)

solutions
- strong gradients
- very short TR ($< 5$ ms)
Gradient-Echo: FISP Contrast

\[ \alpha_{\text{opt}} = \arccos \left( \frac{T_1/T_2 - 1}{T_1/T_2 + 1} \right) \]

- FISP sequence parameters:
  \( TR/TE/\alpha = 2.6 \text{ ms} / 1.4 \text{ ms} / 55^\circ \)

Gradient-Echo: Fat-Water Separation

- chemical shift between protons of water H₂O and fatty tissue CH₃ is about 3.5 ppm or 220 Hz at 1.5 T
  - 1/220 Hz = 4.55 ms →
    - TE = 4.55, 9.1 ... ms  fat / water: "in-phase"
    - TE = 6.8, 11.4 ... ms  fat / water: "opposed-phase"
Spin-Echo: Fat-Suppression

- no fat-water separation possible since refocusing 180° pulse
- preparation by frequency selective 90°-pulse to select only fat resonance (CHESS) and to destroy fat signal by spoiling

no fat-suppression with fat-suppression

Spin-Echo: Contrast Agent

- intravenous injection of 0.1 mmol/kg paramagnetic contrast agent Gd-DTPA
- shortens locally T1 (ca. 1000 ms → 100 ms)
- signal increase at SE imaging by a factor of 2 - 4 !
- detects disruption of blood brain barrier → tumor grading !
- also ferromagnetic nano-particles (SPIO ~ 100 nm, USPIO < 50 nm) available → liver
Contrast Agent: Classification

(by the different changes in relaxation times after their injection)

1. positive contrast agents
   - a reduction in the T1 relaxation time (increased signal intensity)
   - bright on MR images
   - small molecular weight compounds containing gadolinium, iron or manganese
   - unpaired electrons in their outer shells

2. negative contrast agents
   - short T2 relaxation time
   - dark on MRI (decreased signal intensity)
   - small aggregates often termed superparamagnetic iron oxide (SPIO) and ultrasmall superparamagnetic iron oxides (USPIO)
   - crystalline iron oxide core and a shell of polymer (e.g. dextrane)

Contrast Agent: Gd Requirements

- good solubility in water
- high thermodynamic and possibly kinetic stability to ensure against the in vivo release of toxic Gd³⁺ ions and free ligand molecules
- short T1 relaxation time

**gadolinium:**

- large magnetic moment
- long electron spin relaxation time (~10⁻⁹ s at the magnetic field strengths of interest for MRI applications)
- optimum efficiency for nuclear spin relaxation of the interacting nuclei

Parker and Williams, J Chem Soc 1996
- octadentate ligands: one water molecule in the inner coordination sphere
- rapid exchange with the bulk solvent to affect the relaxation of all solvent protons

Paul-Roth and Raymond. Inorg Chem 1995

Contrast Agent: Gd Spherical Models

Gadopentetate (Magnevist)
Gadodiamide (Omniscan)

Gadoterate (Dotarem)
Gadoteridol (ProHance)

courtesy: Weinmann, Schering AG
• octadentate coordination of gadolinium
• one free coordination side is occupied by a water molecule
• relationships between the chemical structure and the factors determining the ability to enhance the water protons relaxation rates
• for a positive CA → short T1 time → high longitudinal relaxation rate

Gd-DTPA Relaxation Mechanism

dipolar interaction between the paramagnetic ion and the proton nuclei of coordinated water molecules

1. the number of metal bound water molecules q
2. molecular reorientation time $\tau_R$
3. electron-spin relaxation time $\tau_S$
4. and chemical exchange time $\tau_M$

described in detail by the Solomon-Bloembergen-Morgan theory

Solomon. Phys Rev 1955
Spin-Echo: Gd-DTPA Example

- typical measuring protocol in brain diagnostics

patient: glioblastoma

intravenous injection of 0.1 mmol/kg Gd-DTPA

Fast Imaging
Fast Spin-Echo Imaging

- “turbo-SE-technique” (TSE) with acceleration-factor 3
- acquired k-space data after first TR

- 1 total k-space line is acquired with every echo

Hennig et al. MRM 1986

PSF: K-Space Inhomogeneity

15 echoes
ΔTE = 10 ms
T2 = 50 ms
Fast Spin-Echo Imaging: Examples

TSE
turbo-factor: 3
TR / TE = 4 s / 11 ms
matrix: 320 x 256
3:36 min
- tissue with long T2 (water) → sharp (see arrow)
- tissue with short T2 (fat) → blurred

TSE
turbo-factor: 33
TR / TE = 4 s / 11 ms
matrix: 320 x 256
16 s
TSE heart
turbo-factor: 23
ECG-triggered breath hold

Fast Spin-Echo Imaging: FLAIR

- "turbo-inversion-recovery"-sequence (TIR) for fluid suppression followed by TSE readout
- "fluid-attenuated-inversion-recovery" (FLAIR)

TSE FLAIR
- patient with brain tumour
TSE: 4000/115 ms, TF = 15
FLAIR: 9000/115 ms, TF = 21, TI = 2500 ms
Fast Spin-Echo Imaging: HASTE

- **HASTE**: “half-Fourier acquisition single-shot turbo spin-echo”

- HASTE lung imaging:
  \[\text{TE} = 29 \text{ ms}, \Delta \text{TE} = 3.6 \text{ ms},\]
  \[N = 50 \text{ echoes}, \text{GRAPPA} = 2,\]
  \[\tau_{\text{aq}} = 200 \text{ ms}!\]

- lung parenchyma is visible!

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Fast Gradient-Echo Imaging: EPI

- “echo-planar imaging” EPI
- multi-gradient imaging technique
- single-shot technique with strong requirements to the gradient power
- strong T2* dependency \(\rightarrow\) susceptibility artifacts!
- fastest imaging technique

Sir Mansfield
2003 Nobel prize in medicine

Mansfield and Pykett. JMR 1978
Fast Gradient-Echo Imaging: EPI Technique

EPI Problem: N/2 Ghosts

gradient echo  EPI

echo shift of odd against even echoes
EPI Problem: Field Inhomogeneities

gradient echo  EPI

Fast Gradient-Echo Imaging: EPI Examples

40 slices in 4 s !
Fast Gradient-Echo Imaging: EPI Methods

classical EPI

spin-echo EPI

SE-EPI

diffusion-weighted EPI

DW-EPI

Fast Gradient-Echo Imaging: 3D FLASH

measured

reconstructed

whole brain imaging: 3D FLASH: 20/6/30°, 256 slices
3D isotropic resolution: 1 x 1 x 1 mm³, t_{iq} ~ 20 min

Haase et al. MRM 1986
3D FLASH: Example

- high resolution heel imaging:
- 3D FLASH: 25/11/30°, 100 slices, $t_{eq} \sim 10$ min
- 3D isotropic resolution: $0.4 \times 0.4 \times 0.4$ mm$^3$ !!!

Fast Gradient-Echo Imaging: MP-RAGE

- MP-RAGE: 3D "magnetization prepared rapid gradient echo" technique
- volunteer whole brain imaging:
  - MP-RAGE: 10/4/10°, TI = 200 ms, 128 slices
  - 3D isotropic resolution: $0.9 \times 0.9 \times 1.2$ mm$^3$
  - $t_{eq} \sim 8$ min

Mugler and Brookeman, MRM 1990

- clinical application: osteoporosis
Fast Gradient-Echo Imaging: PSIF

- PSIF: 3D reversed timing of FISP "noissecr etats ydaets htiw gnigami tsaf" technique

- volunteer whole brain imaging:
  PSIF: 17/7/50°, 128 slices
  - 3D "isotropic" resolution: 0.9 x 0.9 x 1.2 mm³
  - $t_{aq} \sim 10$ min!

Friedlinger et al. Comp Med Imag Graph 1995

Clinical Application: MP-RAGE, PSIF

- brain volumetry (GM, WM, CSF) in Alzheimer disease

Friedlinger et al. Comp Med Imag Graph 1995
Clinical Application: 3D Visualization

- functional MRI overlaid to MP-RAGE
- planning of neurosurgery

Fast Imaging: Hybrid Technique GRASE

- GRASE: "gradient and spin-echo" technique
- TGSE: "turbo-gradient-spin-echo" technique
- TSE technique mixed with GE's
- k-space variability: SE's in center of k-space
  GE's at border of k-space

- volunteer high resolution imaging:
  GRASE: 2030/112/90° ms
  resolution: 0.4 x 0.4 x 2 mm³!

Oshio and Feinberg, MRM 1991
Summary: K-Space Scan Options

- **conventional**
  - 1 echo / TR
  - SE
  - GE / FLASH
  - FLAIR
  - MP-RAGE
  - FISP
  - PSIF

- **hybrid**
  - multiple echoes / TR
  - TSE
  - TGSE / GRASE

- **single-shot**
  - all echoes / TR
  - HASTE
  - EPI

Summary: K-Space / Speed

- **spin-echoes**
  - SE
  - TSE
  - TGSE
  - HASTE

- **gradient-echoes**
  - GRE
  - EPI

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Sequence Family

Sequence Family with Examples
### Babylonian Confusion of Tongues I

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Name</th>
<th>Explanation</th>
<th>Synonyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE-FAST</td>
<td>Contrast enhanced FAST</td>
<td>GRE with SE-part using steady state magnetization</td>
<td>name also PSIF, CE-GRASS</td>
</tr>
<tr>
<td>CE-GRASS</td>
<td>Contrast enhanced GRASS</td>
<td>GRE with SE-part using steady state magnetization</td>
<td>name also PSIF, CE-FAST</td>
</tr>
<tr>
<td>CISS</td>
<td>Constructive interference in steady state</td>
<td>two GRE-sequences with SE-part where single signals are added constructive</td>
<td></td>
</tr>
<tr>
<td>DESS</td>
<td>Double echo steady state</td>
<td>double-GRE-sequence where GRE- and SE-parts are measured separately and added afterwards</td>
<td></td>
</tr>
<tr>
<td>EPI</td>
<td>Echo planar imaging</td>
<td>multiple GRE after one excitation; mostly all raw data in one pulse train</td>
<td></td>
</tr>
<tr>
<td>FAST</td>
<td>Fast acquired steady state technique</td>
<td>GRE using steady state magnetization</td>
<td>name also FISP, FAST</td>
</tr>
<tr>
<td>FFE</td>
<td>Fast field echo</td>
<td>GRE with small angle excitation</td>
<td>FISP</td>
</tr>
<tr>
<td>FISP</td>
<td>Fast imaging with steady precession</td>
<td>GRE using steady state magnetization</td>
<td>name also GRASS, FAST</td>
</tr>
<tr>
<td>FLASH</td>
<td>Fast low angle shot</td>
<td>GRE with small angle excitation</td>
<td></td>
</tr>
<tr>
<td>FLAIR</td>
<td>Fluid attenuated inversion recovery</td>
<td>SE with 180°-pulse at the beginning, long inversion time for fluid attenuation</td>
<td>T1-FFE, Spoiled GRASS</td>
</tr>
<tr>
<td>FSE</td>
<td>Fast spin echo</td>
<td>SE with multiple 180°-pulses, one raw data line per echo</td>
<td>TSE, RARE</td>
</tr>
<tr>
<td>FSPGR</td>
<td>Fast spoiled GRASS</td>
<td>GRE, fast FLASH with preparation pulse for contrast enhancement</td>
<td>name also TURBO-FLASH, TURBO-FFE, Snapshot-FLASH</td>
</tr>
</tbody>
</table>

### Babylonian Confusion of Tongues II

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Name</th>
<th>Explanation</th>
<th>Synonyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRASE</td>
<td>Gradient and spin echo</td>
<td>Turbo-SE-sequence where SE is surrounded by GRE</td>
<td>name also TGSE</td>
</tr>
<tr>
<td>GRASS</td>
<td>Gradient refocused acquisition in the steady state</td>
<td>GRE using steady state magnetization</td>
<td>name also FISP, FAST</td>
</tr>
<tr>
<td>HASTE</td>
<td>Half Fourier single shot turbo spin echo</td>
<td>Turbo-SE with Half-Fourier-Acquisition, all raw data in one pulse train</td>
<td></td>
</tr>
<tr>
<td>IR</td>
<td>Inversion recovery</td>
<td>SE with 180°-pulse at the beginning</td>
<td></td>
</tr>
<tr>
<td>MP-RAGE</td>
<td>Magnetization prepared rapid gradient echo</td>
<td>3D-variant of Turbo-FLASH</td>
<td></td>
</tr>
<tr>
<td>T1-FFE</td>
<td>T1 fast field echo</td>
<td>GRE with small angle excitation</td>
<td>FLASH, Spoiled GRASS</td>
</tr>
<tr>
<td>PSIF</td>
<td>&quot;mirrored&quot; FISP</td>
<td>GRE with SE-part using steady state magnetization</td>
<td>name also CE-FAST, CE-GRASS</td>
</tr>
<tr>
<td>RARE</td>
<td>Rapid acquisition with relaxation enhancement</td>
<td>SE with multiple 180°-pulses, one raw data line per echo</td>
<td>name also TSE, FSE</td>
</tr>
<tr>
<td>SE</td>
<td>Spin echo</td>
<td>90°-180°-pulse train</td>
<td></td>
</tr>
<tr>
<td>snapshotFLASH</td>
<td>Snapshot FLASH</td>
<td>GRE, fast FLASH with preparation pulse for contrast enhancement</td>
<td>name also turbo-FLASH, FSPGR, FFE</td>
</tr>
<tr>
<td>Spoiled GRASS</td>
<td>Spoiled gradient refocused acquisition in the steady state</td>
<td>GRE with small angle excitation</td>
<td>name also FLASH, FFE</td>
</tr>
<tr>
<td>STEAM</td>
<td>Stimulated echo acquisition mode</td>
<td>Pulse train with three 90°-pulses</td>
<td></td>
</tr>
<tr>
<td>STIR</td>
<td>Short TI inversion recovery</td>
<td>SE-sequence with 180°-pulse at the beginning, imaging of absolute signal</td>
<td></td>
</tr>
</tbody>
</table>
Babylonian Confusion of Tongues III

<table>
<thead>
<tr>
<th>TGSE</th>
<th>Turbo gradient spin echo</th>
<th>Turbo-SE-sequence where SE is surrounded by GRE</th>
<th>name also GRASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIR</td>
<td>Turbo inversion recovery</td>
<td>Turbo-SE with 180°-pulse at the beginning</td>
<td></td>
</tr>
<tr>
<td>TIRM</td>
<td>Turbo inversion recovery magnitude</td>
<td>Turbo-SE with 180°-pulse at the beginning, imaging of absolute signal</td>
<td></td>
</tr>
<tr>
<td>trueFISP</td>
<td>True fast imaging with steady precession</td>
<td>GE using steady state magnetization, all gradients are symmetric</td>
<td></td>
</tr>
<tr>
<td>TSE</td>
<td>Turbo spin echo</td>
<td>SE with multiple 180°-pulses, one raw data line per echo</td>
<td>TSE, RARE</td>
</tr>
<tr>
<td>TFE</td>
<td>Turbo fast field echo</td>
<td>GRE, with multiple 180°-pulses, one raw data line per echo</td>
<td>name also turbo-FLASH, Snapshot-FLASH, FSPGR</td>
</tr>
<tr>
<td>TFL</td>
<td>Turbo fast low angle shot</td>
<td>GRE, fast FLASH with preparation pulse for contrast enhancement</td>
<td>name also Snapshot-FLASH, FSPGR, TFE</td>
</tr>
</tbody>
</table>

- the most important MRI-sequences !!

SE / TSE
FLASH / FISP / EPI

MRI: Advantage - Disadvantage

- advantage
  - best soft tissue contrast of all imaging modalities
  - multi-planar slice orientation
  - no ionizing radiation
  - high flexibility of the method due to complex signal dependency of physical parameters

- disadvantage
  - costs
  - availability
  - contraindication

It´s fun !!
Summary I

- essential prerequisites for MRI are:

1. nuclear spin (magnetic moment)
2. strong, homogeneous magnetic field (0.1 - 7 Tesla)
3. nuclear magnetic resonance
   (interaction of magnetization with a high frequency pulse)
4. relaxation (T1, T2)

Summary II

- Larmor-frequency: $\omega = \gamma \cdot B_0$
- magnetic field gradients for spatial encoding
  
  $\omega(x) = \gamma \cdot B(x) = \gamma \cdot B_0 + \gamma \cdot G_x \cdot x$
  
  - slice selection gradient
  - phase encoding gradient
  - frequency encoding gradient (readout gradient)
• pulse sequences are a chronology of RF-pulses and gradients
• the most important basic types of sequences are spin-echo and gradient-echo sequences
• spin-echo sequences are using a 90°-pulse for excitation followed by a 180°-refocussing pulse
• gradient-echo sequences are much faster since they use flip-angles of less than 90° for excitation without using any 180°-refocussing pulse
• EPI sequences are normally single-shot techniques, i.e. the complete image is acquired after one RF excitation

Summary IV

• k-space formalism is a very helpful description in MRI
  \[ k_x = \gamma G_x t \quad k_y = \gamma G_y T_p \]

• the measured signals in MRI are the Fourier transform of the unknown image
  \[
  S(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \rho(x, y) e^{i2\pi(k_x x + k_y y)} \, dx \, dy \\
  \left\lceil \begin{array}{c}
  \text{F.T.}
  \end{array} \right. 
  \]
Summary V