Part 0: What we will not talk about.

- We assume that you know how a magnetic resonance signal comes about and what is required for its detection:
  
  Magnetic field – r.f. pulse – detection free induction decay
  – Fourier transformation
  
- In contrast to NMR spectrometer, magnetic field gradients $(x, y, z)$ are not only a nice thing to have but essential for MRI.
Part 1: Spatial encoding

- How to generate an MR IMAGE?

- How to acquire localized NMR spectra?
2D MR Imaging

- Spatial encoding using magnetic field gradients in x, y and z direction
  -> magnetic field strength varies in each voxel
  -> resonance frequency varies in each voxel ($\nu = (\gamma/2\pi) B_0$)

- Selection of slices (along z-axis) using z-gradient

- Analysis of frequencies/ phases of the resonance frequencies provides a map of local spin distribution (image)

Slice selection

Combination of field gradient with selective excitation pulses
Slice selection

Utilization of a frequency pulse of 42.70 MHz results in selective excitation of spins from one slice.

Slice selection

Signal comes from one slice but we don’t know the position within the slice -> selection of rows.
**Y gradient – phase encoding**

Application of a gradient in y-direction results in Lamor frequency differences of spins according to their position along the y-axis resulting in phase shifts after gradient is switched off.

**X gradient – frequency encoding**

- So far: Signal from a particular slice with phase encoded rows.
- Application of a gradient in x-direction during signal acquisition results in encoding of columns due to frequency differences.
2D Spatial encoding

Due to z-gradient -> slice selection
Due to y-gradient -> different phases
Due to x-gradient -> different frequencies

\[
\{90 - \text{TE}/2 - 180 - \text{TE}/2 - \text{echo} - \text{TR}\}_N
\]

Acquisition time and resolution:
- N pixel in x-direction are encoded by their frequency.
- To reconstruct the phase encoding, excitation of N different y-gradient values are necessary

\(\Rightarrow\) \text{N Excitations are necessary to acquire an } N \times N \text{ matrix!}

Multislice acquisition – spin echo

- N = number of phase encoding steps/ matrix size (64, 128, 256, ...)
- TR = repetition time for each acquisition
- NA = number of acquisitions (1, 2, 3, ...)

\text{Acquisition time} = N \times TR \times NA

(with N = 256, TR = 1s, NA = 1 \Rightarrow 256s = \text{long acquisition time})
More rapid acquisition protocols

Gradient echo sequences (FLASH, FISP, ...)

- Generation of echoes using re-focussing gradients
- Excitation pulse with small flip angle ($\alpha << 90^\circ$)

Why are they rapid?

- Utilization of only a part of $M_z$ -> most still available for excitation
- Rapid pulsing (small TR) is possible
- TR = 10-100ms, TA < 1 minute

Optimization of signal intensity with $\alpha$, TR and $T_1$
Spin echo vs. Gradient echo

<table>
<thead>
<tr>
<th></th>
<th>Gradient echo</th>
<th>Spin echo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Rapid</td>
<td>Slow</td>
</tr>
<tr>
<td>T2* artifacts</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>T1, T2, T2* weighting</td>
<td>mixed</td>
<td>well defined</td>
</tr>
</tbody>
</table>

3D MR imaging

- Excitation of the whole volume of interest (no slice selecting pulses)
- Spatial encoding (z-direction) with a second phase encoding gradient

N = number of phase encoding steps (y-axis)
N’ = number of phase encoding steps in ‘slice direction’ (z-axis)
TR = repetition time for each acquisition
NA = number of acquisitions

Acquisition time = N x N’ x TR x NA
(with N = 256, N’ = 32, TR = 50ms, NA = 1 ⇒ 7 minutes)

Advantages over 2D acquisition:
- High-resolution, true 3D images possible
- Very thin ‘slices’
Localization in NMR spectroscopy

- Low concentration of metabolites -> larger VOI than in MRI

1. Localization by using small surface coils over VOI (bad localization)
2. Localization using slice selective gradients:

- The 90° pulse excites a slice.
- The first 180° pulse refocuses the transverse magnetization in a row within the slice
- The second 180° pulse refocuses the magnetization within a column of the row - single voxel.

The signal represents a combination of spins in that voxel, frequency differences due to different chemical shifts.

Localization in NMR spectroscopy

Different localization techniques possible (STEAM, PRESS, …)

1. Single volume MR spectra

Three slice selective RF pulses select a volume of interest (VOI)

Pulse sequences:
1. Stimulated echo acquisition (STEAM)
2. Point resolved spectroscopy (PRESS)
Localization in NMR spectroscopy

Examples for localized, in vivo, single-voxel brain spectra in humans and rats. And key brain metabolites.

Typical volumes:
4-10mm³  4-10cm³

Chemical Shift Imaging (CSI)
- Phase encoding gradients utilized as in imaging -> spatial encoding
- Single slice defined through the area of interest
- Frequency encoding switched off -> frequency differences = chemical shift
- Process is repeated with various gradients -> full set of phase-encoding
- Fourier transformation -> array of space and frequency encoded signals
Potential problems associated with chemical shift and spatial encoding

- Artifacts due to spatial shift based on frequency differences in metabolites (chemical shift displacement effect)
- Example: shift between water and lipid images ($\Delta = 3.5$ ppm (CH$_2$ lipids))
- Frequency encoding will result in different locations for water and lipids

**Phantom at 7T**
- Inner tube: oil
- Outer tube: H$_2$O

Potential problems associated with chemical shift and spatial encoding

H$_2$O intensity CSI maps, $\nu_{\text{carrier}} = 2.2$ ppm, $\nu_{\text{H}_2\text{O}} \sim 4.7$ ppm

Possible solutions/ suppression:
- Change carrier frequency (middle of the spectrum rather than water)
- Selective suppression (e.g. fat resonance)
- Larger amplitude for frequency encoding gradients ($\Delta x = \Delta B / G_{FE}$); larger bandwidth to keep FOV