(N)MR Imaging

Lab Course Script

FMP PhD Autumn School

Location: C81, MRI Lab B0.03 (basement)

Instructor: Leif Schröder

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Purpose:

Understanding the basic principles of MR imaging and identification of different substances based on image contrast. (You should finally know why Homer did not get an MRI scan).

1 Experiment Preparation

1.1 Safety Aspects

Please follow the guidelines taught for the solution and solid state NMR courses, in particular

- no ferromagnetic objects are allowed close to the 5 Gauss line
- people with pace makers or devices like implanted insulin pumps etc. cannot enter the magnet room.

1.2 Installation of the Gradient Insert

Spatial encoding in MRI is achieved through additional pulsed magnetic fields. This requires a gradient insert that has to be installed prior to the experiment. During the measurement, fast switching of these fields can cause considerable heating of the system. A water chiller system is therefore implemented (see Fig. 1).

- Familiarize yourself with the different connectors of the gradient stack. Which types can you identify?
- Insert the gradient system into the magnet bore and lock it in position.
- Connect the electric cables and the water supply.
- Turn on the chiller system.

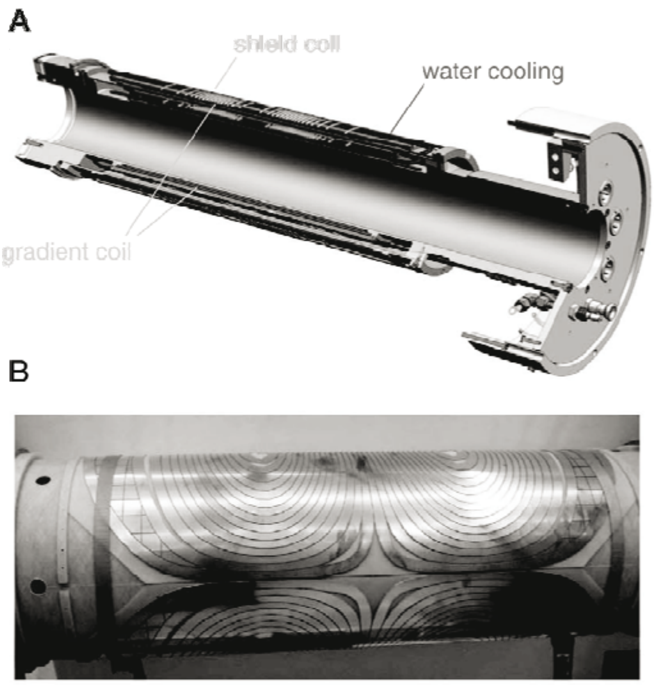

Fig. 1:
Design of the gradient insert.

1.3 Coil Selection

A "phantom" with a mixture of two liquids will be studied in the following. The container will be an NMR tube with 10 mm outer diameter. Different NMR coils (i.e. RF resonators working on the ^{1}H resonance frequency of 400 MHz) are available for this purpose.

- Familiarize yourself with the different resonators and the corresponding probe head (electrical connectors etc.)
- Choose a resonator based on the aspect that the geometry of the object to be studied and the resonator is an important criterion. Which diameter is favourable when you want to receive the radio signal from the sample as good as possible?

  ○ 10 mm ○ 25 mm

  ○ 20 mm ○ 30 mm

  (Note: do you have good reception of a Spanish FM radio station in Berlin?)
- Connect the resonator with the probe head.
- Insert the NMR tube all the way down and fix it in position if necessary.
- Insert the complete probe head into the gradient system, lock it in position and connect the RF cable from the pre-amplifier. IMPORTANT: Avoid breaking off the NMR tube inside the resonator.

1.4 Tuning and Matching

The next step is to prepare the resonator for the RF signal to be expected. You start by tuning it to the right frequency like you do for a radio station. Next, you use the matching knob to adjust the impedance (which changes with the electromagnetic properties of the object inside the resonator) to 50 Ω so that it is the same as for the rest of the RF electronics and transmission losses are minimized.

- Start the tune/match routine with the tool box "Acquisition/Wobble" of Paravision.
- Use the "T" and "M" knobs to adjust the resonator.
- Observe the changes in reflected frequencies on the monitor and try to achieve a narrow absorption line at 400 MHz (see Fig. 2).
- Quit the routine by using "stop" of the spectrometer control tool.

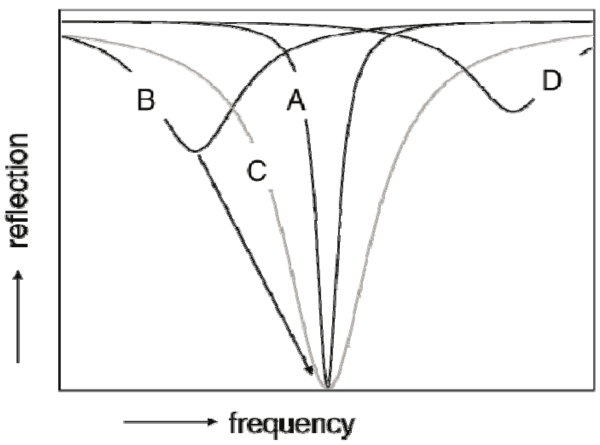

Fig. 2:

A) Well tuned resonator without load. B) Inserting a load changes the resonance frequency and the impedance. C) Broadened profile after tuning with load. D) Effect of inserting a metallic object.

1.5 Positioning of Probehead and Phantom

To achieve good results, the object has to be positioned in the isocentre of the magnet (so-called sweet spot). The gradient insert is already in the right position when it is locked in place.

- Acquire a so-called scout data set (Praktikum_Scout) with images in all three orientations. You will notice a boundary layer that should be aligned with the centre of the magnet.
- What do you notice DURING the measurement?

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  This happens because

  ○ the gradients are switched on and off very quickly and forces are induced onto the gradient stack according to Lenz' rule.

  ○ the magnetic field inhomogeneities are not compensated and forces act upon the sample which therefore starts oscillating in the magnet.
- Decide whether the sample has to be moved upwards/downwards or if a repositioning of the probe head is necessary. Remember that the centre of the gradients is the origin of your coordinate system and that the sensitivity of the resonator decreases towards the top and the bottom.
- The signal distribution may appear predominantly in the upper half of the saggital and coronal images. Therefore,

  ○ the NMR tube has to be shifted upwards.

  ○ the NMR tube has to be shifted downwards.
- Now it can be that the signal is distributed evenly but the boundary layer is not in the image centre.

  ○ You mark the probe head position relative to the gradients and change the position of the sample again.

  ○ The probe head position is changed again without moving the sample inside the resonator.
- Proceed iteratively: one person does the re-positioning, another acquires new images and analyzes the result.
- The grey stripes on the images are caused by the acquisition of the other 2 slices. Parts of the magnetization are already "used up" when the next slice is acquired. Which stripes are more peculiar?

  ○ The horizontal stripes. ○ The vertical stripes.
- Measure the displacement:

  _____________ mm

1.6 Shim

Homogeneity of the static magnetic field is a crucial point for good results because image reconstruction is based on assignments of field changes attributed to the gradients. Hence, unwanted inhomogeneities may cause errors in localization. Additional static fields are used to correct for imperfections of the B0 field to yield a good homogeneity when the sample with its specific magnetic susceptibility is located inside the magnet. Consequently, shimming is performed after the final positioning of the sample.

The criterion used in imaging to quantify the shim quality is the line width of the most intense signal (i.e. water in most cases) because the different frequency components are directly related to the applied net magnetic field ($\omega = \gamma B_0$). This signal has to be optimized.

- Improving the field homogeneity causes
  ○ line broadening of the resonance because this corresponds to a more intense signal.
  ○ a narrow resonance because more spins experience the same magnetic field.
- Start the shim routine Adj_Shim_1st_2nd_z3 in Paravision. An automatic procedure will optimize the currents in the shim coils.
- Note the initial and final values for the more intense resonance:

  Line width FWHM ______________ ______________

  Signal intensity (GS normalized area) ______________ ______________
- You will see 2 resonance lines representing the 2 different substances. How much ist he spectral separation?

  ____________________ Hz

- Earlier you noted the displacement of the grey stripes in the scout images. It is the slice selection gradient that causes a shift of

  ____________________ Hz/mm.

- The combination of gradient strength and frequency selective excitation pulses defines the slice thickness. Knowing that this parameter was 1 mm for the scout images, we can conclude that the bandwidth of the selective Gauss pulse is exciting a spectral range of ca.
  ○ 1700 Hz ○ ca. 2700 Hz ○ 3700 Hz
- Optimization of the shim currents changed the static magnetic field. Hence,
  ○ a re-adjustment of the resonance frequency is required (protocol: Adjust Frequency)
  ○ the sample has to be re-positioned.
- Acquire another scout data set but reduce the slice thickness to 500 µm. This will require a stronger gardient and the displacement of the grey stripes will
  ○ increase ○ decrease ○ remain unchanged
- Knowing that for protons the resonance frequency changes by ca. 42 700 Hz per mT, we conclude that the gradient amplitude was ca.

  ____________________ mT/mm.

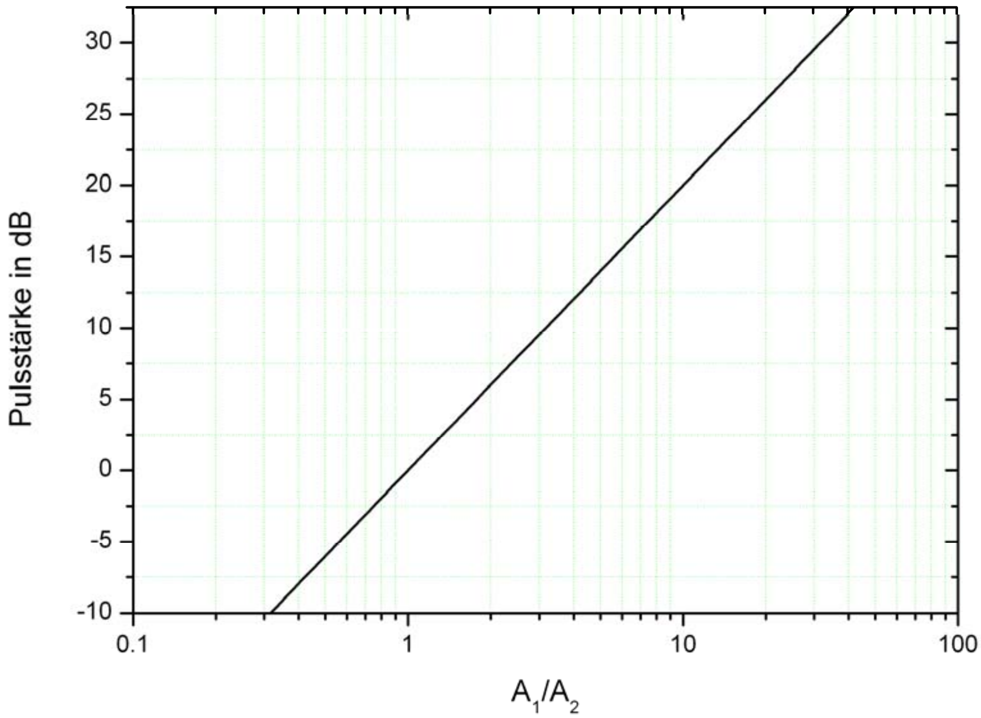
1.7 Reference Gain

The next parameter to be calibrated is the reference pulse that is used to achieve a well defined flip angle for the magnetization. Depending on the load in the RF coil, more or less energy is required to cause a certain excitation of the magnetization. An RF pulse of defined length in time domain can therefore be used with different pulse amplitudes to determine which amplitude yields a maximum NMR signal. We will use the routine Adjust Reference Gain.

- The observed signal corresponds to that fraction of magnetization that is converted from longitudinal orientation (along the z-axis of the magnet) into the transversal plane. Optimum signal is therefore achieved with a flip angle of

  ○ 90° ○ 180°

  ○ 45°
- As you can guess from the name of the routine, the different pulse amplitudes are achieved by adjusting the gain of the amplifier for the RF signal. These amplitudes are usually given in decibel (dB). This is a relative measure that is related to the maximum power of the amplifier (300 W in this case) The difference in dB of two pulse amplitudes A_1 and A_2 is given by: $20 \cdot \log_{10} (A_1/A_2)$ with the following graphical illustration:



The difference in decibel between a 90° and a 180° pulse is therefore

ca. _____ dB.

2 MRI Study of Two-compartment Phantom

(finally!)

2.1 Basic T_2 Contrast

Initially, experiments elucidating the coarse structure of the “phantom” should be done with a spin echo sequence. This sequence is relatively slow but less prone to artefacts.

- Select the sequence Praktikum_T2_saggital.
- Position a 1 mm thick slice in saggital orientation along the centre axis of the phantom.
- Pay attention to the right dimensions of the field of view (full coverage along teh z-axis).
- Enter a resolution of ca. 150 µm by 150 µm.
- Select a repetition time TR = 2 s and echo time TE = 35 ms.
- Start the acquisition.
- Analyze the images in the Image Display and Processing window. Which layer is brighter?
  ○ top ○ bottom ○ no difference
- Start another acquisition but change the echo time to TE = 100 ms. How does the signal contrast change?
  ○ Contrast improves.
  ○ Contrast gets worse.
  ○ Contrast remains unchanged.
- The magnetization of the protons in the darker layer is much more dephased after 100 ms and therefore contributes less signal. The reason for this effect is a more efficient spin-spin interaction compared to the other layer because the correlation time for molecular motion in the darker layer is increased. The upper layer therefore contains
  ○ long chain molecules ○ short molecules.

2.2 Artefact Study

- You will notice a suspicious stripe in the centre of the image. This could be an artefact since the two substances have different resonance frequencies and contributions from both layers overlap in this area. The next measurement should test this hypothesis.
- Select the sequence Praktikum_T2_saggital_swapPE.
- In this sequence, frequency encoding is applied along the short axis and phase encoding along the long one (the encoding schemes are swapped). Consequently, the measurement time
  ○ increases ○ decreases.
- What do you see when you compare these images with the previous set?

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  This confirms that the different resonance frequency is the reason for an artefact along the frequency encoding direction.

2.3 T_2 Quantification with Spin Echo Sequence

Now we want to have a closer look at the T_2 relaxation times of the two substances. This is achieved with a sequence that acquires a set of images with different echo times. A software package can finally fit an exponential signal decay to each pixel and calculate the T_2 time constant.

- Select the sequence Praktikum_MSME-T2-map.
- Enter a geometry of 4 cm x 1 cm.
- Enable a resolution of 80 µm in plane, slice thickness 1 mm.
- Adjust the number of echoes to 25.
- Start the acquisition.
- Export the images to the display window to show the entire data set.
- Define two regions of interest (ROIs).
- Start the Image Sequence Analysis (ISA) Tool
- Select the function “t2vtr“ for fitting.
- Select “More buttons“ in the sub-menu “File”.
- Calculate the intensity values for each ROI and activate the ISA.
  Note the values of the two relaxation times (include the errors):

○ T_2 in top layer ______________ ○ T_2 in bottom layer ______________

2.4 T_2* Effects with Gradient Echo Sequence

Now we want to test another encoding scheme that is more sensitive to magnetic field inhomogeneities and susceptibility transitions as they can occur at surface boundaries. However, this protocol will be much faster.

- Select the sequence Praktikum_FLASH.
- Import the geometry settings from 2.3.
- Enter the following parameters: TE = 7 ms, Flip Angle = 10°, TR = 100 ms.
- Compare the result with the first image of the data set from 2.3.

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2.5 T_1 Contrast with Gradient Echo Sequence

- Start another acquisition of this protocol but change the flip angle to 90°. How does the contrast change?

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- The magnetization cannot relax sufficiently during the 100 ms between two strong perturbations from the large flip angle. Both substances react differently to this effect. Relaxation in the bottom layer is

  ○ slower ○ faster

  because the initial signal difference vanishes.

2.6 High Resolution Study

- Continue with the FLASH sequence but change the resolution to 1024 x 256 pixels and a alice thickness of 250 µm. Increase the number of acquisitions to 16.
- Investigate the top layer and measure the size of some bubbles with the geometry tool

  Bubble size: __________ µm

2.7 Identification of Bubble Content

- In order to assign the bubble content to the left or right resonance in the NMR spectrum, one signal component can be suppressed by selective pre-saturation.
- Use the sequence from 2.6 and activate the magnetization transfer ("MT") tool in the "Research" options.
- Implement a series of 10 Gauss pulses with a flip angle of 90° and a band width of 500 Hz, irradiated at -1550 Hz offset, i.e. directly onto the right signal that you observed during shimming.
- The bubbles

  ○ disappear. ○ remain unchanged.

  This means that the bubble content is assigned to the

  ○ right ○ left

  NMR signal.
- As a control experiment, repeat the acquisition but change the offset for the pre-saturation pulses to 0 Hz offset. Which part of the image disappears?

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- In case the effects are inconclusive, repeat the experiments with an increased bandwidth for the pre-saturation pulses (e.g., 800 Hz)