MRI Lab 3 6.s03 – Spring 2015

2D Projection Reconstruction MRI

1. Preparing to image

1.1 Optimize f_0, transmit amplitudes, and shim settings

In order to acquire spin echoes, we first need to find the appropriate scanner settings using the **FID GUI**. This was all done last week, but these calibration settings should be rechecked before each experiment.

- Insert full water tube (phantom #1) into RF coil. Run FID GUI sequence, by clicking on the "FID_GUI" software interface as you did last week. When you insert or remove phantoms, be careful not to displace the copper-covered coil holder within which the phantom test tube is placed. It is a good idea to remove and insert phantoms by holding the coil cartridge steady by one hand and use the other to position the phantom in the coil

- Use the frequency finder in the software ('find center frequency" box) or check the **6.S03_2015_MRI_Lab_Frequency_and_Shim_Settings.pdf** document on MITx to find the correct Larmor Frequency for your magnet and use this value for "Frequency (MHz)" field in the FID_GUI. Without a correct center frequency you may not see a proper signal (at least an SNR of ~200)

- If you don't see a frequency peak, try a reset on the medusa console. If that doesn't work, then try power cycling. Spend no more than 10 mins on getting a proper signal. If you can't, ask for help from the staff.

- If the peak is not centered at 0 Hz, adjust the system console frequency f_0 ("Frequency (MHz)") until it is. Record this f_0 frequency:_______________

- Stop any ongoing runs, checking the "flip angle calibration" box in the FID_GUI and then click "Run Scan" again. Recall from MRI Lab #1:
  a. The 90^o flip angle occurs when amplitude of the FID signal is maximized.
  b. The 180^o flip angle occurs at the first minimum after the first maximum.
  c. Sometimes there will be a second maximum because a 270^o rotation is achieved.

- Record the 90^o transmit amplitude:_______________, Record the 180^o transmit amplitude:_______________ Enter the 90^o transmit amplitude value into the FID_GUI field "RF TX amplitude (0 to 1)" and use it for the rest of the lab.

- In the GUI, change the current offsets (mA) of the x, y, z gradient coils to apply linear shim fields along each direction. Refer to the document **6.S03_2015_MRI_Lab_Frequency_and_Shim_Settings.pdf** for a good start on the shim values. Try to further increase the magnitude of the frequency peak (i.e. make the line as narrow as possible, equivalently increase the peak) by adjusting these values. You may want to set the number of repetitions to a high enough number so that you don't have to hit run scan every time. Once you optimize the shims, you may or may not have to update the system console frequency to center the frequency peak at 0 Hz. **Save your best shim settings using the "Save shim settings" button**. Also record your center frequency, in some cases with shimming the center frequency may shift slightly.

Record the currents (mA): X shim:____________ Y shim:__________ Z shim:___________

Center frequency f_0: ____________

1.2 Use projections to optimize the coil position along the y-axis

We need to make sure that the RF coil and phantom is centered in the gradient coils by looking at the 1D projection in Y by following these steps:

- Stop any ongoing scans in the "FID GUI" and close this window. Now open the "Spin echo GUI" through the software interface.
- Enter your optimal f_0, shims, and RF transmit amplitudes into the "Spin echo GUI" interface.
- Turn on the Y gradient by selecting "projection along Y" as the acquisition type. This creates a field gradient along the axis of the bore of the magnet (i.e. the long axis of your tube phantom).
- Click "Run Scan" (it is convenient here to type 100 into "number of repetitions" before scanning so that you can see the plots update every TR period). If the Y-projection is not centered around 0 kHz, gently adjust the coil position in or out of the bore until the Y projection is centered around 0 kHz in the frequency domain. To adjust the position of the coil in the bore, you need to first relax by a few turns the fastening screw that secures the coil box. Once you have adjusted the coil position, tighten the screw that holds the coil so that it does not slip out of place during the rest of your experiment
- **CAUTION**: Once the copper clad sample holder is in the right place, be sure not to move it when replacing phantoms! For some of the systems the phantoms fit quite tightly in the coil, so it may be helpful to use one hand to secure the coil in place while you move the phantom into place with the other.
- If the coil position was modified, re-check your shims and update center frequency if necessary: i.e. go back to the "FID GUI", find the best shim settings for this coil position so that the magnitude of the frequency peak is as narrow as possible (and thus, T_2* is at its maximum). Save your best shim settings by clicking the "Save shims settings" button.

MRI Lab 3 6.s03 – Spring 2015
2D Projection Reconstruction MRI

Record the currents (mA): X shim:___________ Y shim:_________ Z shim:__________

Center frequency, f_0: _____________

2. Acquire a small number of projections, P, via PROJRECON_GUI

- On the master GUI selector, open the Projection Imaging GUI and insert the now-familiar **mystery phantom** in the coil while taking care not to disturb the optimized Y-placement of the coil box. Verify that the center frequency, shim settings, and RF amplitudes are set appropriately based on your previous calibration.
- Near the top of the GUI, click to select the check box called "Center frequency correction ON".
- Load shim settings.
- The key acquisition parameters are N, the number of points per projection, and P, the number of projections. This GUI enables us to set both parameters and let the system modulate the Gx and Gz gradient amplitudes to collect projections at a uniform set of P projection angles in the range of 0° to 180° without manually rotating the phantom as was done in MRI Lab #2. For this initial exercise, set these parameter to:
  - "number of projections" to 4, i.e. P=4.
  - readout duration to 4.1 ms, which gives N=128 points per projection for the default readout sampling bandwidth.
  - "number of averages" to 1.
- Run the scan with P=4 projections (projection angles 0°, 45°, 90°, 135°) and N=128 points-per-projection on the mystery phantom. As the scanner loops through the projections, note how the blue and red gradient amplitude settings vary in the pulse sequence diagram (upper left-most plot on the GUI) as they change amplitude from one projection to the next.
- Save the data, and read into Matlab. The important data for this exercise are stored in are **all_angles** and **offrescorrected_data_projrecon**. The vector **all_angles[2:P+1]** contains the projection angles in radians, and the columns of the NxP matrix **offrescorrected_data_projrecon** contain the time-domain values of the data collected in the presence of the G_x and G_z gradients.
- For each projection: Plot the absolute value of the frequency domain data on a separate plot. If these data are (very) noisy to the point that you don't recognize the projections, repeat the scan a few times (e.g. 4 times), save each set under a different name, and then load these sets into Matlab and average before you calculate the projections. (the "number of averages" field does the averaging for the data plotted on the GUI, but does not save them … sorry – we'll fix that bug for next time!).

MRI Lab 3 6.s03 – Spring 2015

2D Projection Reconstruction MRI

Checkoff 1. Explain/show to a staff member:

- Show your plots of the absolute values of the projections. Do these projections correspond to your previously obtained manual rotations of the mystery phantom? Do they make sense given that the mystery phantom contains separate capillary tubes along the Y-axis? How many tubes are in the phantom?
- What is the FOV for each projection and what is the spatial resolution?
- Write expressions for the amplitudes of G_x and G_z gradients for these projections as a function of P if the amplitude of G_x for the 0° projection is G.

3. Dial up the number of projections, P=64

Now it's time to go beyond image reconstruction "by eye" and sample 64 projections and reconstruct the data in Matlab. While the mystery phantom was by design constructed from a small number of capillary tubes aligned with the long axis of the cylinder such that it possible to infer its structure from only a few projections, is not feasible to calculate the intensity of an arbitrary set of 64x64 pixel values from 64 projections by hand.

Recall from lecture that our goal is to solve for the pixel values in the reconstructed image, **M**, as an N x N matrix in Matlab, given the value of our measurements, i.e. the projections at different angles. As demonstrated in class for the (trivial) example of a 2x2 image, one way to estimate the entries of $\boldsymbol{M}$ from the measured projections, $\boldsymbol{p}$, is to set up a linear system of equations of the form

$$\boldsymbol{Em} = \boldsymbol{p}$$

where $\boldsymbol{m}$ is a column vector obtained by stacking up all the columns of the image $\boldsymbol{M}$ <u>and</u> taking the values of that vector that correspond to indices determined by *index_inside.mat*. The indices determined by *index_inside.mat* correspond to the pixels within a circular field-of-view that fits within the NxN image matrix ***M***. In other words, we only care about reconstructing the pixels that are inside this circle in M. $\boldsymbol{p}$ is a column vector obtained by stacking up the $\boldsymbol{P}$ measured projections. Matlab does the stacking up for us rather easily: If *projections* is an NxP matrix of data, then

p = projections(:),

is a column vector obtained from stacking up all P columns of the matrix into one column of size NPx1.

Important: For this reconstruction to work robustly on the currently configured systems, we need to use the **absolute value of the projections** for the vector $\boldsymbol{p}$.

2D Projection Reconstruction MRI

The encoding matrix, $\boldsymbol{E}$**,** is in principle easily obtained as we saw in class for the 2x2 example. However, it takes a while for this to run in Matlab and the book-keeping involved is probably overkill for a 3-hour lab, so we have pre-computed an encoding matrix that correspond to $\boldsymbol{N}$=64 and $\boldsymbol{P}$=64.

On MITx you will find an encoding matrix labeled **E_64_64.mat**, where the first number in the name refers to N, the length of each projection, and the second refers to P, the number of projections. The matrix **index_inside.mat** allows you to reconstitute a 64x64 matrix $\boldsymbol{M}$ from the vector $\boldsymbol{m}$ via

> **M**=zeros(64,64);
> **M**(index_inside) = **m**(:);

To carry out the reconstruction in Matlab, we rely on the same technique as was used earlier in class for a least-squares solution in machine learning. A simple way to reconstruct the image, $\boldsymbol{m}$, is to solve the following optimization problem

$$\min_{\boldsymbol{m}} ||\boldsymbol{Em}-\boldsymbol{p}||_2^2$$

where $\boldsymbol{p}$ is the measured projections, $\boldsymbol{m}$ is the column vector of unknown pixel values in the image, and $\boldsymbol{E}$ is the encoding matrix. This could easily be done in MATLAB using a backslash operation

$$\boldsymbol{m} = \boldsymbol{E}\backslash\boldsymbol{p}.$$

This works when we have a unique and well-defined solution. However, in many cases, we work with ill-posed problems where the direct application of the backslash operator in Matlab will not perform well. As demonstrated earlier in the class, we can amend our approach to consider the least-squares problem with regularization, which in this form is referred to as Tikhonov regularization. Specifically, we solve the following modified optimization problem to reconstruct the image

$$\min_{\boldsymbol{m}} ||\boldsymbol{Em}-\boldsymbol{p}||_2^2 + \gamma||\boldsymbol{m}||_2^2$$

where γ is a (scalar) regularization parameter that balances the data consistency term (how much you believe in your observation), $||\boldsymbol{Em}-\boldsymbol{p}||_2^2$, and the 2-norm of the solutions vector, i.e. the norm of the reconstructed image, $||\boldsymbol{m}||_2^2$. (The fact the symbol γ is used for the regularization parameter has nothing to do with the gyromagnetic ration in MRI! In the current context, γ is a positive scalar value of your choice to regularize a matrix inversion problem). As shown in lecture earlier in the term, this problem is equivalent to

$$\min_{\boldsymbol{m}} ||\widetilde{\boldsymbol{E}}\boldsymbol{m}-\widetilde{\boldsymbol{p}}||_2^2$$

where $\widetilde{\boldsymbol{E}}$ is a modified encoding matrix, and $\widetilde{\boldsymbol{p}}$ is a modified observation defined below as

$$\widetilde{\boldsymbol{E}} = \begin{bmatrix} \boldsymbol{E} \\ -- \\ \sqrt{\gamma}\boldsymbol{I} \end{bmatrix}, \text{ and } \widetilde{\boldsymbol{p}} = \begin{bmatrix} \boldsymbol{p} \\ -- \\ \boldsymbol{0} \end{bmatrix}.$$

$\boldsymbol{I}$ is an identity matrix (where each dimension has the same size as the length of $\boldsymbol{m}$). And the notation "- -" inside the matrix brackets corresponds to concatenating the matrices ***E*** and $\sqrt{\gamma}\boldsymbol{I}$ (in Matlab, you can use the semicolon for this purpose) as well as the vectors ***p*** and ***0.*** Now, for a non-zero γ, the back-slash operator in Matlab may give improved results by estimation of the image via

$$\boldsymbol{m} = \widetilde{\boldsymbol{E}} \backslash \widetilde{\boldsymbol{p}}.$$

We note that there exist other types of regularizations, and the choice of regularization is problem-dependent. Also noteworthy is that there are various ways to solve the least-squares problem more efficiently than the backslash operator.

And now, let's turn to a demonstration of data acquisition and image reconstruction in projection reconstruction:

- Use the mystery phantom for imaging
- Click the check box called "Plot the inverse radon reconstructed image".
- Acquire and save data with P=64 projections with N=64 points per projection (readout duration = 2.05 ms). Set the number of averages to 1.
- Load your data into Matlab, along with **E_64_64.mat**, and **index_inside.mat** from MITx.
- Reconstruct the image, M, from the absolute value of the projections, using first $\boldsymbol{m} = \boldsymbol{E} \backslash \boldsymbol{p}$, and then the regularized version, i.e. $m = \widetilde{\boldsymbol{E}} \backslash \widetilde{\boldsymbol{p}}$, with at least three different positive values for γ.
    - Be aware that the execution time for the backslash operator for matrices of the sizes that we use can be 10s of seconds on the lab computers.
- Replace the mystery phantom with the "star" phantom, acquire a new dataset, save, and then reconstruct this image as you did for the mystery phantom. In contrast to the mystery phantom the individual projections of this phantom are difficult to interpret by eye.

Checkoff 2. Explain/show to a staff member:

- What is the size of the matrix in index_inside.mat? What are the dimensions of the matrices for $\boldsymbol{m}$, $\boldsymbol{E}$, $\boldsymbol{p}$, $\widetilde{\boldsymbol{E}}$, $\widetilde{\boldsymbol{p}}$ and how do they relate to N and P?
- Show your reconstructed images to a staff member. Use e.g. *imagesc()* to display your images. Use *colormap('gray')* and *axis square* commands in Matlab for your image viewing. Explain the effect of regularization, i.e. the value of γ, on the reconstructed image. Which image do you prefer?

Alternative image reconstruction methods: We note that this is not the only way to solve for in image **M** from a set of projections. The PR GUI, for instance, displays an image updated in real time as the data are acquired through a reconstruction that's called the Radon transform, which applies an algorithm called filtered backprojection for image generation and you will run into these terms immediately should scout the literature for projection reconstruction methods. A different approach is to model the acquisition as non-uniformly spaced samples in 2D Fourier space and "regrid" those data onto a Cartesian grid prior to Fourier transform to the image domain. Both of these approaches rely on manipulations with 2D transforms that would take us a bit more time in class to cover adequately for 6.s03 … simply be aware that there is more than one way to proceed as you infer NxN pixels of an MRI image from P projections.

4. Off-resonance effects in projection reconstruction

We have paid particular attention to optimize shim values and center frequency, since those parameters, if poorly calibrated, will cause so-called image artifacts that have detrimental effects on image quality. As a simple demonstration, work with the mystery phantom again and acquire a 64-projection dataset where you uncheck the "Center frequency autocorrect ON" box near the top of the GUI **and** purposefully offset the center frequency value, f_0 by 100 Hz. Acquire another image in the same way but change f_0 by 500 Hz this time.

Acquire these data and save the reconstructed images on the GUI (save a screenshot of them).

Checkoff 3. Explain/show to a staff member:

- Show your images to a staff member and compare with the image of the same phantom but with the center frequency set to its optimal value. Explain the artifacts you observe in the image. As you think this through, it may be helpful to consider what happens to the 0° and 90° projections when the f_0 value is set to the off-resonance frequency.

5. Optional Material: 3D imaging

5.1 MIT Phantom

The MIT Phantom has three layers of plastic structures printed with the letters as seen to the right. When we take a 2D image in the xz plane, we will get a projection through the y direction since that direction is not encoded.

- Insert the MIT phantom. (double check that f_0 is still correct, and the phantom is centered in the y-gradient)

Now we will switch to the 3D imaging GUI. We have covered most of the theory and language required to describe the approach that's implemented in this GUI, including RF excitation and spin-echo pulses and constant gradients to encode projections, but we are missing the general picture of the data as samples acquired in a 2D or 3D Fourier space. In 3D imaging, the k-space (i.e. Fourier space) matrix is now 3D, and this sequence fills in one of the k_x, k_z planes per shot (TR), and then steps through the phase encodes in the k_y axis.

- Open the GUI, "IMAGING_GUI_3" by selecting Gui3 on the master GUI panel.
- Set the number of "slices" to 16 (matrix dimension in the y direction). This will give us 16 slices along the imaging FOV. If the FOV is 3cm, that should cover the full length along the tube seen by the receive coil (detector), and give slices with ~1.875mm thickness. Hopefully, you will see the individual letters in the MIT phantom more clearly, since they will no longer be collapsed.
- Try some different FOV's and some averaging to improve the SNR of your 3D image. Use your newly acquired imaging expertise to try to get the best possible image.

Exploration. Observe and discuss the impact of the relevant scan parameters (spatial resolution, FOV, number of averages) on the images that pop up on the screen given what you know about the phantom.

5.2 Mouse Brain Phantom

The mouse brain phantom has … a mouse brain! Try the same 3D imaging method you used for the MIT phantom to see slices of the mouse brain. Play with imaging parameters (number of averages, etc.) to see some structure inside the mouse brain.