Class Business

- Homework 1 will be due on 4/26
- Office hours
  • Instructors: Fri 10-12 noon
  • TAs: Thursday 3-5pm
  • Emails beforehand would be helpful
- Papers and Slides
Today’s Topics

- Recap of excitation k-space
- 2D excitation pulses
  - 2D EPI pulse design
  - Spatial-spectral pulse design
- Matlab exercise

Summary for Excitation k-space
Small-Tip Approximation

\[ M_{xy}(t, \vec{r}) = i \gamma M_0 \int_0^t B_1(s) e^{i2\pi \vec{k}(s, t) \cdot \vec{r}} ds \]

\[ \vec{k}(s, t) = -\frac{\gamma}{2\pi} \int_s^t \vec{G}(\tau) d\tau \]

Small-Tip-Angle Solution as a k-space Integral

\[ M_{xy}(t, \vec{r}) = i M_0 \int_{\vec{k}} p(\vec{k}) e^{i2\pi \vec{k} \cdot \vec{r}} d\vec{k} \]

\[ p(\vec{k}) = W(\vec{k}) S(\vec{k}) \]

\[ W(\vec{k}) = \frac{\gamma B_1(s)}{|k'(s, t)|} \quad k\text{-space weighting} \]

\[ S(\vec{k}) = \int_{-\infty}^t 3 \delta(\vec{k}(s, t) - \vec{k}) |k'(s, t)| ds \quad k\text{-space sampling} \]
2D Pulse Design

\[ M_{xy}(t, \vec{r}) = iM_0 \int_{\vec{k}} W(\vec{k})S(\vec{k})e^{i2\pi \vec{k} \cdot \vec{r}} d\vec{k} \]

1. Choose a k-space trajectory
2. Choose a weighting function
3. Design the RF pulse

\[ B_1(s) = \frac{1}{2\pi} |\vec{G}(s)|W(\vec{k}) \]

2D Spatial Pulse Design

- EPI
  - Non-isotropic resolution
  - Sidelobes in one dimension
  - Spectral-spatial pulses

- Spiral
  - Unity aspect ratio
  - Minimum length
  - Circular sidelobe
2D EPI Pulse Design

Designing EPI k-space Trajectory

- Ideally, an EPI trajectory scans a 2D raster in k-space

Resolution? / FOV?
Designing EPI k-space Trajectory

- Resolution: 
  \[ \Delta x = \frac{\text{TBW}}{2k_{x,\text{max}}} \quad \Delta y = \frac{\text{TBW}}{2k_{y,\text{max}}} \]

- FOV = \(1/\Delta k_y\)
  \[ \Delta k_y = \frac{2k_{y,\text{max}}}{L \cdot 1} \]

- Ghost FOV = FOV/2
  - Eddy currents & delays produce this

Designing EPI k-space Trajectory

- Refocusing gradients
  - Returns to origin at the end of pulse
Designing EPI Gradients

- Designing readout lobes and blips
  - Flat-top only design

- RF only played during flat part (simpler)

To the board ...
Designing EPI Gradients

- Easy to get k-space coverage in $k_y$
- Hard to get k-space coverage in $k_x$
- We can get more k-space coverage by
  - making blips narrower
  - playing RF during part of ramps

Blipped EPI

- Rectilinear scan of k-space
- Most efficient EPI trajectory
- Common choice for spatial pulses
- Sensitive to eddy currents and gradient delays
Continuous EPI

- Non-uniform k-space coverage
- Need to oversample to avoid side lobes
  • Less efficient than blipped
- Sensitive to eddy currents and gradient delays
  • Only choice for spectral-spatial pulses
Continuous EPI

Gradient Waveforms

$k_x, k_y$

$k$-Space Trajectory

$2k_{x,max}, 2k_{y,max}$

Flyback EPI

- Can be blipped or continuous
- Less efficient since retraces not used (depends on gradient system)
- Almost completely immune to eddy currents and gradient delays
Designing 2D EPI Spatial Pulses

- Two major options
  - General approach, same as 2D spiral pulses
  - Separable, product design (easier)

- General approach
  - Choose EPI k-space trajectory
  - Design gradient waveforms
  - Design $W(k)$, k-space weighting
  - Design $B_1(t)$
Separable, Product Design

- Assume,

\[ W(k_x, k_y) = A_F(k_x) \cdot A_S(k_y) \]

\( A_S(k_y) \): weighting in the slow, blipped direction
\( A_F(k_x) \): weighting in the fast oscillating direction

- Each impulse corresponds to a pulse in the fast direction, \( A_F(k_x) \)
1 ms subpulses
14 subpulses
Flattop only (0.5 ms)
4 cm x 4 cm mainlobe
Sidelobes at +/- 13 cm
Spectral Spatial Pulse

Spatial-Spectral Pulses

- 2D pulses selective in space and frequency
- Excite a slice at a limited band of frequencies
- Clinical applications
  - High speed imaging (spiral/EPI)
  - Robust lipid suppression
  - Spectroscopic imaging (MRSI)
- Gy gradient simply establishes a linear relationship between position and frequency
  • Spatial selectivity in $y \Rightarrow$ Frequency selectivity

\[
M_{xy}(t, \tau) = i\gamma M_0 \int_0^t B_1(s) e^{i2\pi \vec{k}(s,t) \cdot \vec{\tau}} ds
\]

\[
M_{xy}(t, y) = i\gamma M_0 \int_0^t B_1(s) e^{i2\pi k_y(s,t) y} ds
\]

\[
\vec{k}(s, t) = -\frac{\gamma}{2\pi} \int_s^t \vec{G}(\tau) d\tau
\]

\[
k_y(s, t) = -\frac{\gamma}{2\pi} G_y(t - s)
\]
Basic Idea

\[ M_{xy}(t, y) = i\gamma M_0 \int_0^t B_1(s)e^{i2\pi \frac{(\frac{\gamma G y y}{2\pi})(s-t)}{k_f}} ds \]

\[ M_{xy}(t_0, f) = i\gamma M_0 \int_{-t_0}^0 B_1(k_f)e^{i2\pi f k_f} dk_f \]

\[ M_{xy}(f) = i\gamma M_0 \int_{-\infty}^0 B_1(k_f)e^{i2\pi f k_f} dk_f \]

Note that \( k_f \) is time!

Spectral Pulses

\[ M_{xy}(f) = i\gamma M_0 \int_{-\infty}^0 B_1(t)e^{i2\pi f t} dt \]
Add Spatial Selectivity to a Spectral Pulse

- Hard pulses

$B_1(t)$

"Hard" pulses

Slice selective subpulses

$G_z(t)$

Each sub pulse starts and ends at $k_z = 0$

To the board ...
**Flyback Design**

- 1.1 ms sublobes
- 8 sublobes
- 250 Hz spectral passband
- 15 ms length

**Opposed Null Design**

- 2.2 ms sublobes
- 8 sublobes
- 250 Hz spectral passband
- 13.2 ms length
True Null Design

1.1 ms sublobes
16 sublobes
250 Hz spectral passband
15ms length

Source of Bipolar Sidelobes

• Interference between excitations from positive and negative gradient lobes
Matlab Exercise

Windowed Sinc RF Pulse

%%% Design of Windowed Sinc RF Pulses

```matlab
% tbw = 4;
samples = 512;
rf = wsinc(tbw, samples);

function h = wsinc(tbw, ns)
    % rf = wsinc(tbw, ns)
    %
    % tbw -- time bandwidth product
    % ns -- number of samples
    % h -- windowed sinc function, normalized so that sum(h) = 1

    xm = (ns-1)/2;
    x = [-xm:xm]/xm;
    h = sinc(x*tbw/2).*((0.54+0.46*cos(pi*x)));
    h = h/sum(h);
```
RF Pulse Scaling

\[ \theta = \int_{0}^{\tau} \gamma B_1(s) ds \]

\[ \theta_i = \gamma B_1(t_i) \Delta t \]

\[ B_1(t_i) = \frac{1}{\gamma \Delta t \theta_i} \]

RF Pulse Scaling

%% Plot RF Amplitude
r\(f = (\pi/2) \cdot \text{wsinc}(tbw,\text{samples});\)

pulseduration = 1; %ms
rfs = rfscaleg(rf, pulseduration); % Scaled to Gauss

function rfs = rfscaleg(rf,t)

% rfs = rfscaleg(rf,t)
% rf -- rf waveform, scaled so sum(rf) = flip angle
% t -- duration of RF pulse in ms
% rfs -- rf waveform scaled to Gauss

gamma = 2*pi*4.257; % kHz*rad/G
dt = t/length(rf);
rfs = rf/(gamma*dt);
%% Simulate Slice Profile
tbw = 4;
samples = 512;

rf = (pi/2)*wsinc(tbw,samples);
pulseduration = 1; % ms

rfs = rfscaleg(rf, pulseduration); % Scaled to Gauss
bl = [rfs zeros(1,samples/2)]; % in Gauss
G = [ones(1,samples) -ones(1,samples/2)]; % in G/cm

x = (-4:.1:4); % in cm
f = (-250:5:250); % in Hz
dt = pulseduration/samples/1e3;
t = (1:length(bl))*dt; % in usec

% Bloch Simulation
[mx,my,mz] = bloch(bl,g,t,1,.2,f,x,0);
mxy=mx+1i*my;

---

Slice Thickness

- Pulse duration = 1 ms
- TBW = 4
- $G_z = 1 \text{ G/cm}$

\[
\Delta z = \frac{BW}{\frac{\gamma}{2\pi} G_z}
\]

\[
\frac{\gamma}{2\pi} = 4.257 \text{ kHz/G}
\]
Summary

- Adiabatic Pulse Design
- 2D Pulse Design
  - Examples:
    - EPI pulse design
    - Spatial-Spectral Pulses
- Matlab Exercise

Thanks!

- Homework 2
  - 2D EPI design
  - SPSP design
- Next time:
  - Pulse sequences

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