6.1 MR Image Formation

Matrix, Gradients & Signals

Image formation & k-pace

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Outline

- Imaging Matrix
- Gradients & Signals
- Phase, Frequency and Amplitude
- Slice selection
- Phase encoding
- Frequency encoding

Objectives

Upon completion of this course, the attendee should…

1. Learn about the matrix.
2. Understand the MR signals and how they are affected by gradients
3. Learn the concept phase, frequency & amplitude.
4. Understand image formation, slice selection, phase encoding, frequency encoding
5. Understand the concept of k-space.

Imaging Matrix

- Digital images are created with a matrix
- Smallest unit of the digital image is a pixel

Pixel, Voxel

- In MRI slices are acquired
- The voxel is a 3d volume element
- The face of the voxel is the pixel

What makes up a digital image?

- The size of the area imaged in MRI is the field of view (FOV)
- The number of pixels (rows x columns) is the matrix
- The depth is the slice thickness
Calculating pixel size
- to calculate the pixel size
- to calculate the voxel size

Calculating pixel & voxel size
- Isotropic voxel
- Pixel size
- Area of the Pixel (mm²)
- Voxel Volume (mm³)

Pixel Size and Matrix
- higher matrix
- smaller pixel
- less tissue in the pixel
- higher resolution

Pixel Size and FOV
- smaller FOV
- smaller pixel
- less tissue in the pixel
- higher resolution

Pixel Size and Slice thickness
- smaller thickness
- smaller pixel
- less tissue in the pixel
- higher resolution

Imaging Planes
- What Views (Planes)
  - Sagittal
  - Axial
  - Coronal
  - Oblique
- What Contrast
  - TR
  - TE
To Create MR Images

- The patient is placed in the magnetic field to align the spins.
- The RF pulse is applied to excite the spins at the Larmor Frequency.

Timing Diagrams – RF & Gradient Pulses

TR (Repetition Time)

These lines represent gradient pulses.

MR signal induced in the receiver coil.

TE (Echo Time)

Short & Long TR Imaging

Short TR

90° 180°

Long TR

90° 180°

MR Excitation Relaxation

Alignment

Excitation

Relaxation

90° RF Pulse

MR Signal

MRI Signal

FID echo

T2 decay

Proton density-TE1

T2WI-TE2

Timing Diagram

TR (Repetition Time)

TE (Echo Time)

Image with artifact

Cleaned up the "SIC"

Timing Diagram -TE

90° 180° 190°

Proton density-TE1

T2WI-TE2

FID

T1 echo

TE 1

TE 2
Imaging Planes

- What Views (Planes)
  - Sagittal
  - Axial
  - Coronal
  - Oblique
- What Contrast
  - TR
  - TE

Timing Diagram – Gradients- logical coordinate system

Slice Selection

- If the magnetic field is homogeneous, the frequency is the same... head to feet
- If the RF is applied... in this case the entire body would be excited

Selective Excitation

- To excite a location within the imager, within the body...
- A magnetic field gradient is applied
- The RF pulse is applied that matches a location

Selecting an Axial Slice – Physical Coordinate System
Selecting a Coronal Slice - Physical Coordinate System

Y gradient
Anterior to Posterior

Coronal slice

Selecting a Sagittal Slice - Physical Coordinate System

X gradient
Right to Left

Sagittal slice

Phase & Frequency Encoding

- Once the slice is selected...
- Encoding along the other axes,
  - With gradients
    - R to L
    - A to P
  - For encoding
    - Phase encoding
    - Frequency encoding

Outline

- Imaging Matrix
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Periodic signals

- Phase
- Frequency
- Amplitude
- Wavelength

Amplitude

- Low Amplitude Signal
- Medium Amplitude Signal
- High Amplitude Signal

Enhanced Brain Image
Frequency

- Periodic signal
- Sine wave
- Frequency = # times it repeats in a period of time cycles per second or Hertz (Hz)
  - or million cycles per second, or megahertz (MHz)
- Revolutions along the precessional path

Phase

- What phase of the precession where along the precessional path
- In phase
- Out of phase

Phase & Frequency

- 0 degrees
- 90 degrees
- 180 degrees
- 270 degrees
- 360 degrees

Frequency is the rate of precession
Phase is a position along a precessional path

Phases of Periodic Signals

- 0 degrees
- 90 degrees
- 180 degrees
- 270 degrees

Changing the Frequency and Phase

- Steep Gradient
  - High Amplitude Gradient
  - High changes in frequencies
  - Big changes in phase
- Low Gradient
  - Low Amplitude Gradient
  - Small changes in frequencies
  - Small changes in phase
- In phase
- High signal
- High amplitude signal
- Out of phase
- Low signal
- Low amplitude signal

Signal Amplitude

- Phase & Frequency = Where
- Amplitude = What color
- Black – Low Amplitude
- Gray – Medium Amplitude
- White – High amplitude
Phase & Frequency

Phase & Frequency = Where
- Same frequency – different phase
- Same phase different frequency
- Same phase and frequency, different amplitude

K-Space & MR Imaging

Amplitude = What color
- Black, low
- Gray, med
- White, high amplitude signal

Phase & Frequency = Where
- Phase lines in k-space
- Frequency – points along each line

CT Image Acquisition

Back Projection

In CT, the x-ray tube rotates around the “phantom”
In this case the x-ray beam is attenuated by the water in the phantom
and therefore “projects” a “shadow” within the detectors...

Back Projection - Reconstruction

Where the lines intersect, there could be water in the phantom
Two projections are not enough

MR Image Formation

- In order to define a point in space, we need three coordinates X, Y & Z
- To define these three coordinates, we do 3 jobs
  - slice selection
  - phase encoding
  - frequency encoding
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Timing Diagram - Logical Coordinate System

RF Pulse
Slice selection gradient
Phase Encoding gradient
Frequency encoding gradient
MR signal

Homogeneous magnetic field

Slice Selection

- If the magnetic field is homogeneous, the frequency is the same... head to feet
- If the RF is applied... in this case the entire body would be excited

Selective Excitation

- To excite a location within the imager, within the body...
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Slice Thickness & Transmitter Bandwidth

- If only one frequency is “sent in” or transmitted for excitation, we get a slice as thin as tissue paper.
- For a thicker slice a range of frequencies is “transmitted” known as the Transmit Bandwidth

FYI... This is not the bandwidth that we typically "set" during image acquisition. That is the receiver bandwidth. Receive bandwidth will be discussed later in this section

Slice Thickness & Gradient Amplitude

- Steep Gradients (high amplitude) slice selection gradient, produce thin slices.
- Flatter Gradients (low amplitude) slice selection gradient, produce thicker slices.
- "Steep things make skinny things!"
**Imaging Planes & Slice Selection Gradients**

- RF pulses for spin-echo Z gradient
- Slice selection
- Phase encoding Y gradient (A-P)
- Frequency encoding X gradient (R-L)

**Physical vs Logical Gradients**

**Logical Gradients**
- Slice Selection
- Y gradient (A-P) (coronal)

**Physical Gradients**
- Phase Encoding
  - Depends upon the plane
  - Smaller word
  - Smaller anatomy (motion)
  - Smaller matrix (time)

**Spatial Encoding within the Slice**

- Once the slice is selected
- Encoding along the other axes
  - With gradients
    - R to L
    - For encoding
  - Phase encoding
  - Frequency encoding

**Fourier Transformation – Step #1**

- Let’s take one sine wave and try to produce a “ramp”
- Not Even close...

**Fourier Transformation – Step #2**

- Let’s take another sine wave with lower amplitude and higher frequency
- And try again
- Better...
**Fourier Transformation – Step #3**

- Let's take another sine wave with lower amplitude and higher frequency
- And try again

- Better but no cigar!

**Fourier Transformation – step #4**

- Let's take another sine wave with lower amplitude and higher frequency
- And try again

- Not Bad!

**Truncation Artifact – 2D Fourier Transform (2DFT)**

- Less Samples
- More Samples
- Brain image 128 phase matrix
- Brain image 256 phase matrix
- Virtually no visible truncation Artifact

**K-space - Sampling**

- Center of K-space for Contrast
- Signal to Noise
- Edges of K-space Detail
- Resolution

**Image Formation & K-space filling**

- K-space for Mona Lisa
  - All lines filled
  - Resolution
  - But no contrast...
Image Formation & K-space filling

- K-space for Mona Lisa
  - Center lines filled
  - Contrast but No resolution...

Fourier Transformation

- K-space for Mona Lisa
  - All lines filled
  - Fourier transformer will do FT, one at a time
  - Array processor will to an “array” of FT’s

Let’s Make an MR Image…

- Select a slice
- Encode along the other axes,
  - With gradients
    - R to L
    - A to P
- Encoding Steps
  - Phase encoding
  - Frequency encoding

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Image Acquisition & Image Formation

- RF
- SS (Z)
- PE (Y)
- FE (X)
- Signal
- Timing Diagram

Sampling MR Signal

- Signals are created by a 90° and a 180° pulse
- Signals are sampled during “readout” at TE
- Points are “stored” in k-space for until enough points are sampled to create an MR Image

K-space sampling points
Nyquist Theorem
• Signals must be sampled at least twice per cycle
• This means that they must be sampled at the highest frequency
• Sampling is performed at a given time interval (t) based on the frequency

Aliasing
• If signals are not sampled at the appropriate time interval
• Signals are not sampled properly
• This results in aliasing

K-Space
• K-space has lines, # Phase encoding steps
• And points along each line, # Frequency steps

Image Formation
• Less Steep (-) phase encoding gradient
• Sample the echo
• "Store" in k-space
Image Formation

- Less Steep (-) phase encoding gradient
- Sample the echo
- "Store" in k-space

Points stored in the bottom of k-space

Less Steep negative gradient

Sample points along the echo

Frequency

Points stored in the middle of k-space

Flat gradient

Points stored in the top of k-space

Less Steep negative gradient

Points stored in the top line of k-space

Steeper positive gradient

Higher positive amplitude positive

Points stored in the top line of k-space

Steepest positive gradient

Points stored in the top line of k-space

Scan Time

TR x # of Phase Views x NSA

K-space & Image Formation
Motion Artifact

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- Frequency encoding
- k-space manipulation

Filling k-space

*Assume 256 phase matrix for this entire module

Remember:
The amplitude of the phase encoding gradient applied during the FID "encodes" the sampled echo for a particular phase "line" or "profile" in k-space

If we desire a final image with 256 pixel resolution in the phase direction of our FOV, then we will need to acquire 256 distinctive lines of acquisition filling the data points in k-space

Linear Filling

Fills from "bottom" up

Remember:
X = Frequency
Y = Phase
Z = Slice

Centric Filling

This technique acquires high signal data "lines" first
Often used in Contrast Enhanced MRA studies

Elliptic Filling

This technique acquires the most "central" data points first
3D acquisition used for Contrast Enhanced MRA to minimize venous filling

These techniques fill k-space in either a "symmetrical" fashion as shown here, or in a random pattern from the center data points outward
Number of Signals Averaged (NSA)

Scan Time = TR x Ny x NSA

Think of the NSA as "coats of paint". It's the number of times each line or phase view of k-space is sampled.

Reducing NSA

Scan Time = TR x Ny x NSA

Reducing NSA reduces scan time. DOES NOT reduce spatial resolution. Increases noise (reduces SNR) and increased flow/motion artifacts.

Partial Fourier

Scan Time = TR x Ny x NSA

Partial Fourier reduces scan time at the cost of increased noise (reduced SNR). Spatial resolution is unaffected.

Reducing Ny

Scan Time = TR x Ny x NSA

Reducing Ny reduces scan time. Reduces spatial resolution. Increased SNR. Increases truncation artifact.

* Note: the number of phase encodings may be selected by scan percentage.
Rectangular FOV
Scan Time = TR x Ny x NSA

Reduces Ny - reducing scan time
Increasing "step" between phase views reduces FAOV

Parallel Imaging
* Scan time is reduced by using a rectangular FOV (therefore spatial resolution is maintained)
* Data from multi-channel / phased-array coils is used in the image reconstruction process
* Some techniques require a "reference" or "calibration" scan prior to the actual scan
* Image is reconstructed with the prescribed FOV

Conventional Spin Echo
+128 ky
0 ky
-128 ky

Fast Spin Echo
4 ETL Example

-128, -127, -126,...,-1, 0, +1, +2,...,+126, +127, +128

Scan Time
Conventional Spin Echo
Fast Spin Echo
ETL

Scan time increases with increasing spatial resolution (phase)
Scan time shortens with reduction in spatial resolution (phase)

Image "blurring" can increase with increasing ETL

Image Courtesy Siemens Medical Systems
Benefits of Fast Spin Echo

**Sample Scan Time**

TR x Ny x NSA

- 500 TR
- 1500 TR
- 3000 TR
- 5000 TR

Images with bright fluid often show pathology best due to presence of water. The long T1-relaxation time of water requires longer TR times to obtain images with bright fluid. Scan time increases with increasing TR.

**EPI Speed Compared to FSE**

<table>
<thead>
<tr>
<th></th>
<th>FSE</th>
<th>EPI</th>
<th>SS-EPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>180</td>
<td>180</td>
<td>4 sec</td>
</tr>
<tr>
<td>90</td>
<td>180</td>
<td>echo</td>
<td>whole brain (1.5T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FSE 25 sec whole brain (3T)</td>
</tr>
</tbody>
</table>

3000 TR x 256 phase x 2 NSA = 25.6 minutes!

Same scan with FSE and ETL of 16 = 1.6 minutes!!

**Summary**

Scan Time = TR x Ny x NSA

- How many lines of acquisition?
- Zero-fill
- Reduced NSA
- Partial Fourier
- Rectangular FOV (Parallel Imaging)

Reducing scan time by altering the way k-space is filled typically reduces either spatial resolution or SNR.

Since reduced spatial resolution is almost always undesirable, therefore, most advanced imaging techniques are SNR starved.

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6.1 MR Image Formation

Matrix, Gradients & Signals
Image formation & k-space

Thank you for your attention!