Slide 1

MRI In Stereotactic Procedures

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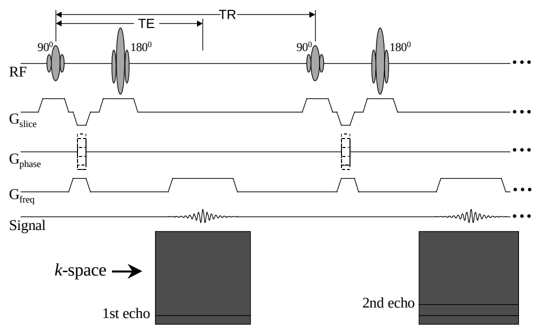
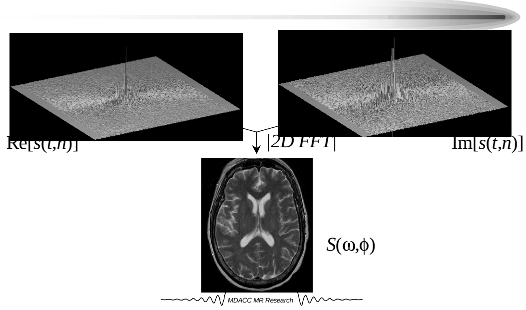
Slide 2

Spin Echo Imaging Sequence



Slide 3

Image Formation



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In-Plane Spatial Encoding in MRI

- Recall that the linear magnetic field gradients relate frequency and phase to spatial position.

  Assuming the frequency- and phase-encoding directions are *x* and *y*, respectively, then

  $$\omega_x = \gamma (B_o + G_x x) \text{ and } \phi_y = \gamma (B_o + G_y y)\, t_y$$

- Therefore, anything that results in a spatially varying magnetic field inhomogeneity, *i.e.*, $\Delta B_o(x,y,z)$, results in distortion of the image.

  $$\omega_x = \gamma \{B_o + [G_x + \Delta B_o(x)]\, x\} \text{ and } \phi_y = \gamma \{B_o + [G_y + \Delta B_y(y)]\, y\}\, t_y$$

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Sources of Geometric Distortion

- System Limitations
  - Poor B_o homogeneity
  - Linear scale factor errors in the gradient fields
  - Field distortion due to induced eddy currents
  - Nonlinearities of the gradient fields
- Object-Induced
  - Chemical shift effects
  - Magnetic susceptibility variations (patient induced)

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Sources of Geometric Distortion

- Poor B_o Homogeneity
  - Modern magnet designs and field engineering tools have made the error due to inhomogeneous B_o fields quite small.
- Linear Scale Factor Errors in the Gradient Fields
  - Usually due to miscalibration of the gradients. Readily fixed by careful calibration using a phantom.
- Field Distortion Due to Induced Eddy Currents
  - Usually negligible in systems with actively-shielded gradients, and can be made negligible in non-actively shielded gradient systems by pre-emphasis techniques.

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Sources of Geometric Distortion

Most significant causes of geometric distortions in MRI:

- *Gradient Field Nonlinearities*
  - Barrel Aberrations
  - "Potato Chip Effects"
  - "Bow Tie Effects"
- *Resonance Offsets*
  - Chemical Shift Induced
  - Local Magnetic Field Inhomogeneity Induced (Susceptibility Effects)

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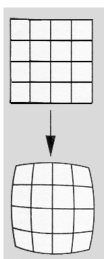
Gradient Field Nonlinearity Effects In-Plane Distortion



Barrel Aberration

- Due to nonlinearities in the gradient fields used for phase- and frequency-encoding.
- Results in a "warping" of the image space.
- Can result in errors up to ~4mm on a 20 x 20 cm FOV (without correction).
- Typically corrected during reconstruction (to within 1 mm near isocenter) using the known error fields of the gradient coils.

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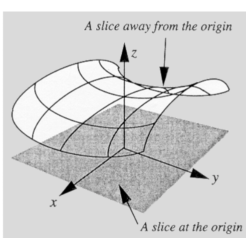
Gradient Field Nonlinearity Effects Slice Distortion



Reference: Sumanaweera TS *et al.*, Neurosurgery 35(4):696-703, 1994.

"Potato Chip" Distortion

- Due to nonlinearities in the gradient field used for slice selection.
- Results in a "warping" of the slice.
- Can result in errors up to ~4mm on slices ~10cm from isocenter with a 20 x 20 cm FOV (without correction).
- Very difficult to correct when using 2D imaging techniques.
- Not an important issue when using 3D (volume) imaging techniques.

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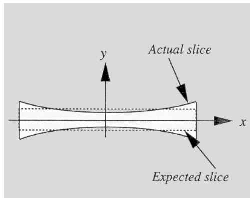
Gradient Field Nonlinearity Effects
Slice Distortion



Reference: Sumanaweera TS *et al.*, Neurosurgery 35(4):696-703, 1994.

"Bow Tie" Distortion

– Due to nonlinearities in the gradient field used for slice selection.
– Results in a "warping" of the slice.
– Not as important as potato chip or barrel aberrations.
– Difficult to correct when using 2D imaging techniques.
– Not an important issue when using 3D (volume) imaging techniques.

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Gradient Field Nonlinearity Effects

To minimize spatial inaccuracy due to nonlinearity of the gradient fields:

– Use 3D imaging techniques (typically T_1-weighted gradient recalled echo sequences) to eliminate "potato chip" and "bow tie" slice distortions.
– Make sure barrel aberration is being corrected for during image reconstruction.
– To the extent possible, place the region of interest at or very near the isocenter of the magnet, where the gradient field nonlinearities are minimum.

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Resonance Offset Effects

The effects of resonance offsets result in spatial inaccuracy in the frequency-encoded direction only. The phase-encoded information is not effected by these effects.

– *Chemical shift effects*

– *Magnetic susceptibility effects*

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Resonance Offset Effects
Chemical Shift

- The chemical shift between the water and methylene fat resonances is ~210 Hz at 1.5T, and scales linearly with B_o.
- The difference in resonance frequency gives rise to an apparent difference in spatial location of the fat and water protons since spatial position and frequency are related in the presence of an applied gradient field.
- Two primary effects:
  - Fat and water pixels are mis-registered in-plane.
  - Fat and water excitation slices are slightly offset.

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Resonance Offset Effects
Chemical Shift

The magnitude of the in-plane chemical shift-induced spatial errors are:

- Directly proportional to B_o
- Inversely proportional to the amplitude of the frequency-encoding gradient field (G_v)
- Inversely proportional to the sampling bandwidth, since decreasing BW results in decreasing G_v (for the same FOV)

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Resonance Offset Effects
Chemical Shift

Good news:
Chemical shift induced artifacts can be eliminated by applying fat suppression techniques during image acquisition.

Bad news:
You may suppress some of the anatomy of interest.

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Resonance Offset Effects
Chemical Shift

In-between news:

Effects can be reduced by anything that increases the amplitude of the frequency-encoding gradient, including (while keeping all other parameters fixed):
- decreasing the FOV
- increasing the sampling bandwidth
- increasing the frequency-encoding matrix size

Each of these options, however, decreases SNR!

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Resonance Offset Effects
Susceptibility Effects

- Magnetic susceptibility effects are patient-induced.
- Modified Larmor equation: $B = (1 + \chi) B_o$, where χ is the magnetic susceptibility. A concomitant χ-dependent spatial shift will occur in the image.
- Interfaces between two substances with differing magnetic susceptibilities result in an *apparent* B_o inhomogeneity. Such areas give rise to local spatial errors in the image.

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Resonance Offset Effects
Susceptibility Effects

Material	Signal	ρ (g/cm^3)	χ (ppm/cm^3)
Air	No		0.0
H_2O	Yes	1.0	-9.05
Bone (Cortical)	No	1.7-2.0	-8.86
$Cu(SO)_4 + H_2O$ (0.12 g/ml)	Yes		3.52
Pyrex	No	2.25	-13.91

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Resonance Offset Effects
Susceptibility Effects

The modified Larmor equation provides a means of calculating the theoretical error in the frequency-encoding direction, Δ_v, in terms of the frequency-encoding gradient amplitude, G_v, applied static field, B_o, and $\Delta\chi$:

$$\Delta_v \sim \Delta\chi\ B_o / G_v$$

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Resonance Offset Effects
Susceptibility Effects

- The most significant errors due to susceptibility changes occur for
  - Air/bone interface $|\Delta\chi| = 8.86$ ppm/cm^3
  - Air/tissue interface $|\Delta\chi| = 9.05$ ppm/cm^3
- Only minor errors occur for
  - Bone/tissue interface $|\Delta\chi| = 0.19$ ppm/cm^3
- For a 1.5 T scanner with G_v = 3.1 mT/m, FOV=24cm, and 256 pixels, this gives rise to theoretical errors of
  - Air/bone interface $|\Delta| = 2.10$ mm
  - Air/tissue interface $|\Delta| = 2.15$ mm
  - Bone/tissue interface $|\Delta| = 0.05$ mm

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Resonance Offset Effects
Susceptibility Effects

Minimizing Susceptibility-Induced Effects:

As in the case of chemical shift-induced spatial errors, susceptibility-induced errors can be reduced by anything that increases the amplitude of the frequency-encoding gradient, including (while keeping all other parameters fixed):
- decreasing the FOV
- increasing the sampling bandwidth
- increasing the frequency-encoding matrix size

Again, each of these options decreases SNR!

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Resonance Offset Effects Susceptibility Effects

Various investigators have published correction algorithms to reduce the magnitude of the susceptibility-induced errors. (Such algorithms will be outlined during this session at AAPM.) At this time, however, vendors have not incorporated such algorithms into commercial products.

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Comparisons of Theoretical Errors with Measured Data

- Most comparisons of the theoretical magnitudes of measurement errors presented here with measured data have been performed using phantoms with known geometry. Other measurements have been made in cadavers.
- Several comparisons have also been made using CT imaging as the gold standard.
- In most cases, measured errors have agreed well with the theoretically predicted results.

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Summary

- While CT typically yields images that are spatially accurate to within a pixel (~1 mm), MR images can have errors that are up to 5 times worse.
- MRI imaging *can* yield quite similar accuracy to CT if:
  - B_0 homogeneity is maintained by shimming on a regular basis
  - Gradient field calibrations and eddy current corrections are maintained
  - 3D acquisition sequences are used and the volume of interest is positioned as close as possible to the isocenter of the magnet to minimize the errors due to nonlinearity of the gradient fields
  - Fat suppression is utilized, if possible, to minimize chemical shift effects
  - The FOV is made as small as practical and the sampling bandwidth as large as possible to reduce both chemical shift- and susceptibility-induced errors

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