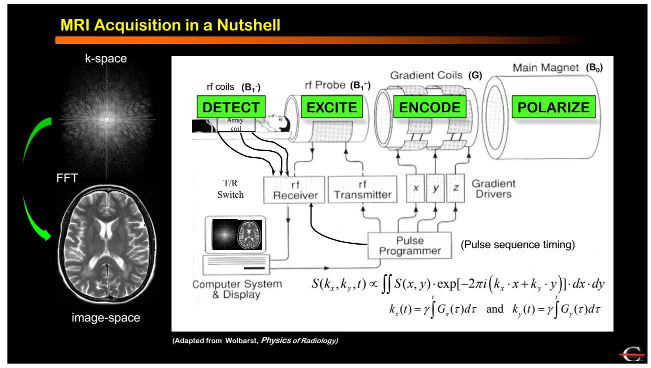
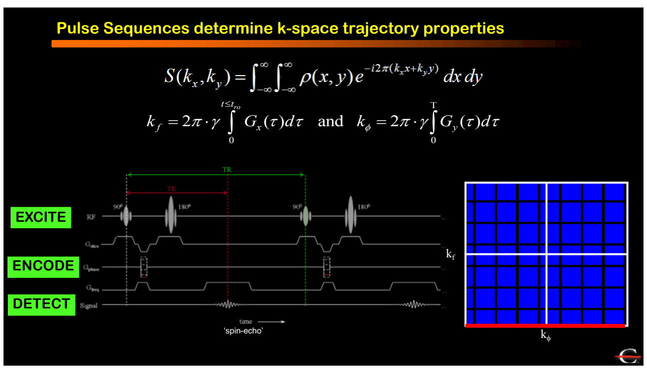
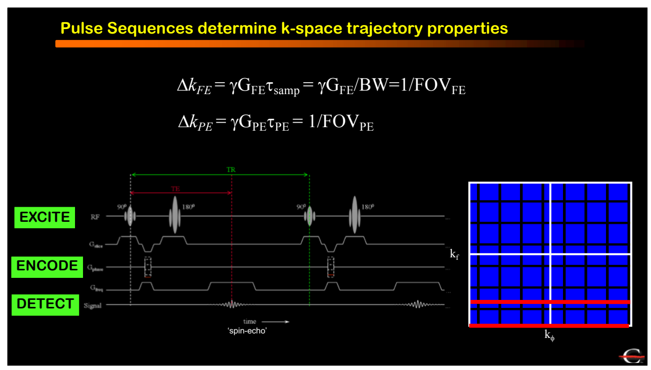

Imaging Artifacts - CT, MRI, and Mammography
MR Artifacts: A Different Spin
R. Jason Stafford, Ph.D.
Department of Imaging Physics
The University of Texas
MD Anderson Cancer Center
WE-HI-207 - AAPM 60th Annual Meeting & Exhibition – Nashville, TN


MRI Acquisition in a Nutshell
k-space
FFT
image-space
rf coils (B_1^-)
rf Probe (B_1^+)
Gradient Coils (G)
Main Magnet (B_0)
DETECT
EXCITE
ENCODE
POLARIZE
T/R Switch
rf Receiver
rf Transmitter
x
y
z
Gradient Drivers
Pulse Programmer
(Pulse sequence timing)
Computer System & Display
$S(k_x,k_y,t) \propto \iint S(x,y)\cdot \exp[-2\pi i(k_x\cdot x + k_y \cdot y)]\cdot dx\cdot dy$
$k_x(t)=\gamma\int G_x(\tau)d\tau$ and $k_y(t)=\gamma\int G_y(\tau)d\tau$
(Adapted from Wolbarst, Physics of Radiology)


Pulse Sequences determine k-space trajectory properties
$S(k_x,k_y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\rho(x,y)e^{-i2\pi(k_x x+k_y y)}\,dx\,dy$
$k_f=2\pi\cdot\gamma\int_0^{t\le t_{acq}} G_x(\tau)d\tau$ and $k_\phi=2\pi\cdot\gamma\int_0^T G_y(\tau)d\tau$
EXCITE
ENCODE
DETECT
RF
Signal
'spin-echo'
k_f
k_ϕ


Pulse Sequences determine k-space trajectory properties
$\Delta k_{FE}=\gamma G_{FE}\tau_{samp}=\gamma G_{FE}/BW=1/FOV_{FE}$
$\Delta k_{PE}=\gamma G_{PE}\tau_{PE}=1/FOV_{PE}$
EXCITE
ENCODE
DETECT
RF
Signal
'spin-echo'
k_f
k_ϕ

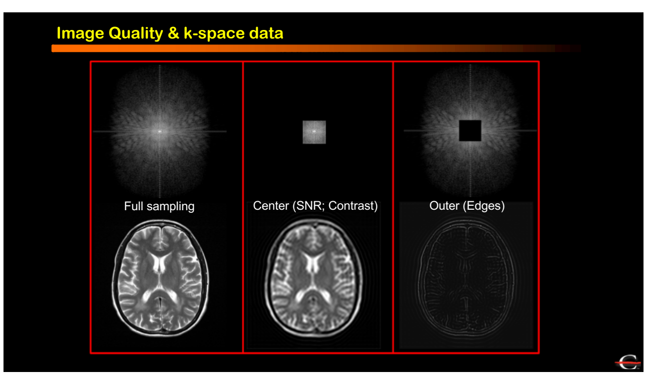
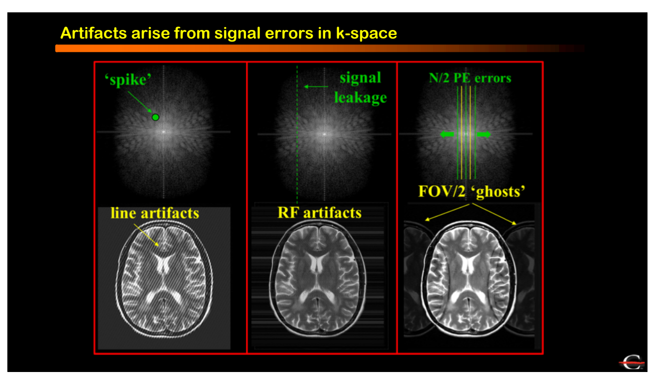


Image Quality & k-space data
Full sampling
Center (SNR; Contrast)
Outer (Edges)


Artifacts arise from signal errors in k-space
'spike'
signal leakage
N/2 PE errors
line artifacts
RF artifacts
FOV/2 'ghosts'

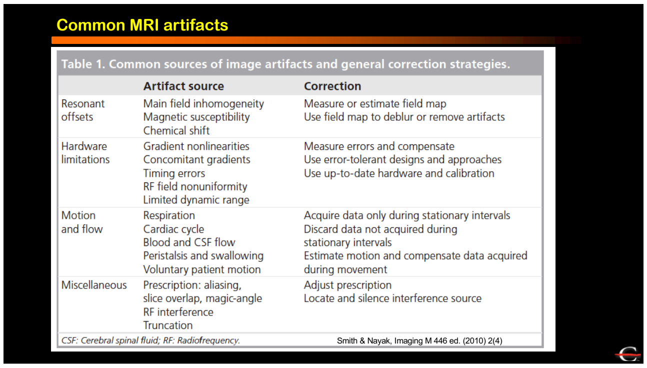
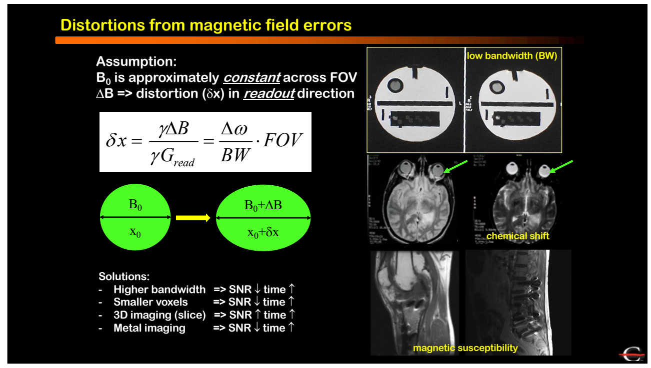
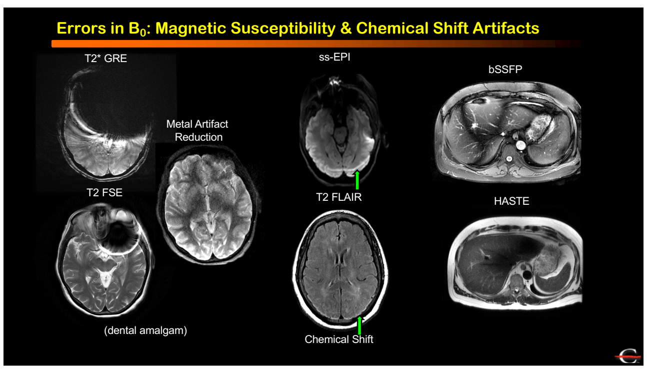


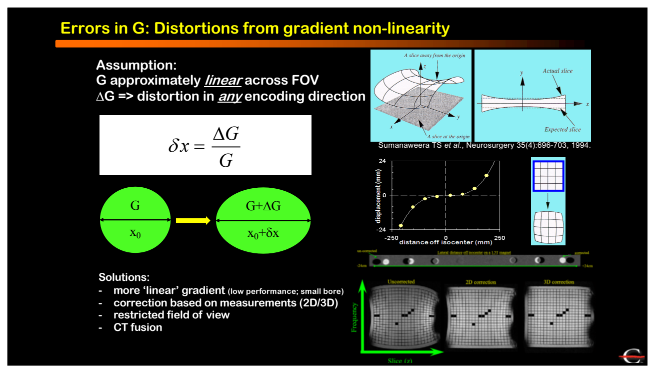
Table 1. Common sources of image artifacts and general correction strategies.

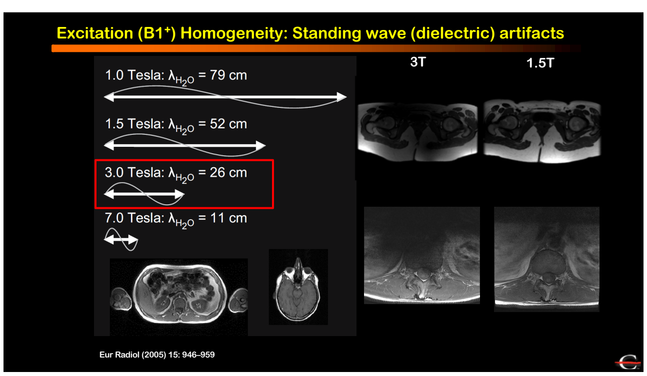
	Artifact source	Correction
Resonant offsets	Main field inhomogeneity Magnetic susceptibility Chemical shift	Measure or estimate field map Use field map to deblur or remove artifacts
Hardware limitations	Gradient nonlinearities Concomitant gradients Timing errors RF field nonuniformity Limited dynamic range	Measure errors and compensate Use error-tolerant designs and approaches Use up-to-date hardware and calibration
Motion and flow	Respiration Cardiac cycle Blood and CSF flow Peristalsis and swallowing Voluntary patient motion	Acquire data only during stationary intervals Discard data not acquired during stationary intervals Estimate motion and compensate data acquired during movement
Miscellaneous	Prescription: aliasing, slice overlap, magic-angle RF interference Truncation	Adjust prescription Locate and silence interference source

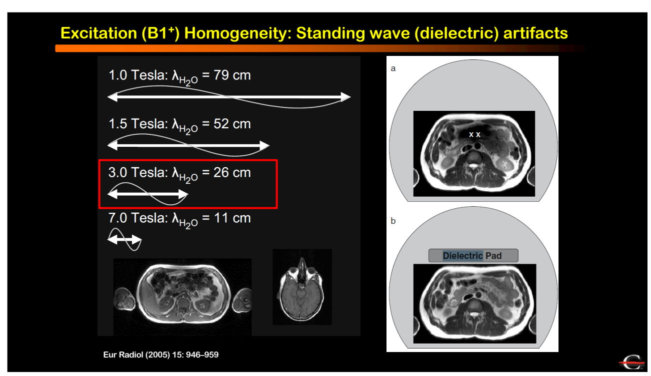
CSF: Cerebral spinal fluid; RF: Radiofrequency. Smith & Nayak, Imaging M 446 ed. (2010) 2(4)

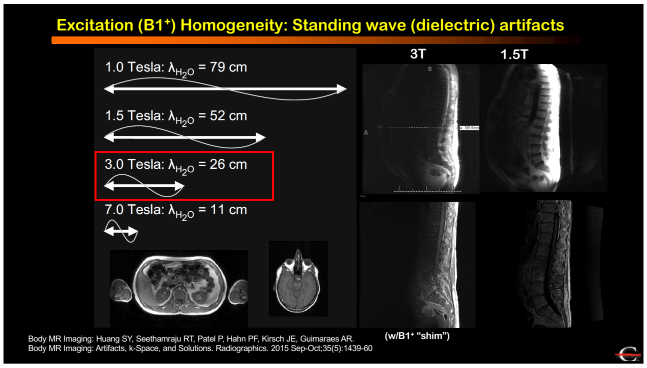




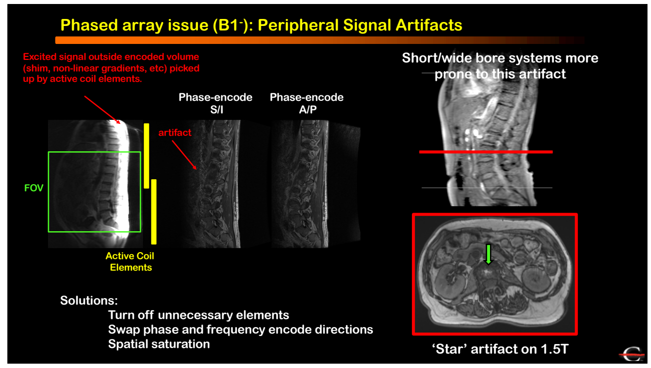




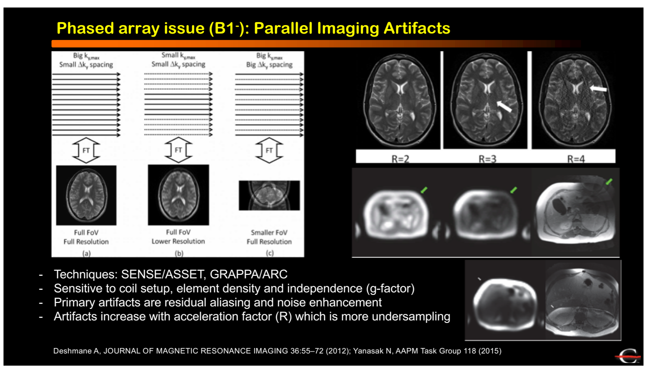




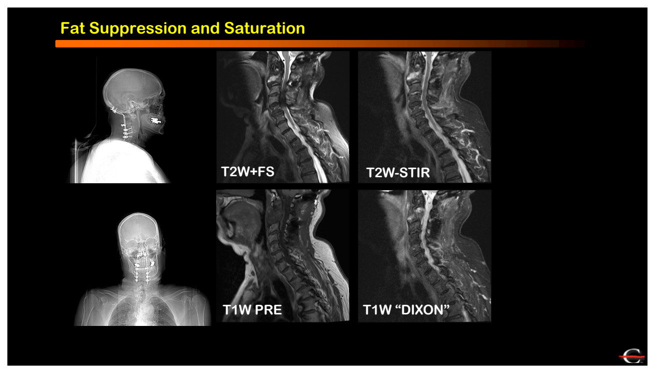
Excitation (B1+) Homogeneity: Standing wave (dielectric) artifacts
1.0 Tesla: λ_{H_2O} = 79 cm
1.5 Tesla: λ_{H_2O} = 52 cm
3.0 Tesla: λ_{H_2O} = 26 cm
7.0 Tesla: λ_{H_2O} = 11 cm
3T
1.5T
(w/B1+ "shim")
Body MR Imaging: Huang SY, Seethamraju RT, Patel P, Hahn PF, Kirsch JE, Guimaraes AR.
Body MR Imaging: Artifacts, k-Space, and Solutions. Radiographics. 2015 Sep-Oct;35(5):1439-60



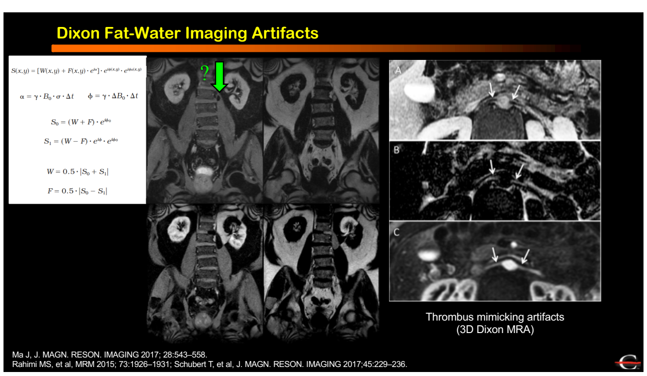
Phased array issue (B1-): Peripheral Signal Artifacts
Excited signal outside encoded volume (shim, non-linear gradients, etc) picked up by active coil elements.
FOV
artifact
Active Coil Elements
Phase-encode S/I
Phase-encode A/P
Short/wide bore systems more prone to this artifact
Solutions:
Turn off unnecessary elements
Swap phase and frequency encode directions
Spatial saturation
'Star' artifact on 1.5T



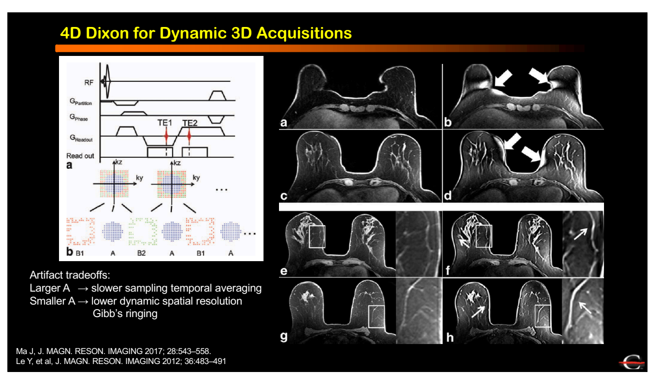
Phased array issue (B1-): Parallel Imaging Artifacts
Full FoV Full Resolution (a)
Full FoV Lower Resolution (b)
Smaller FoV Full Resolution (c)
R=2
R=3
R=4
- Techniques: SENSE/ASSET, GRAPPA/ARC
- Sensitive to coil setup, element density and independence (g-factor)
- Primary artifacts are residual aliasing and noise enhancement
- Artifacts increase with acceleration factor (R) which is more undersampling
Deshmane A, JOURNAL OF MAGNETIC RESONANCE IMAGING 36:55–72 (2012); Yanasak N, AAPM Task Group 118 (2015)



Fat Suppression and Saturation
T2W+FS
T2W-STIR
T1W PRE
T1W "DIXON"

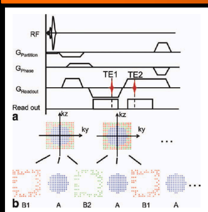


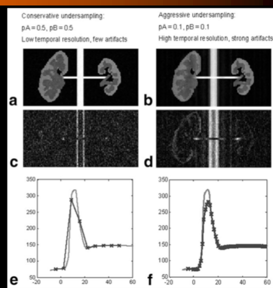
Dixon Fat-Water Imaging Artifacts
$S_0 = (W + F) \cdot e^{i\phi_0}$
$S_1 = (W - F) \cdot e^{i\phi} \cdot e^{i\phi_0}$
$W = 0.5 \cdot |S_0 + S_1|$
$F = 0.5 \cdot |S_0 - S_1|$
Thrombus mimicking artifacts (3D Dixon MRA)
Ma J, J. MAGN. RESON. IMAGING 2017; 28:543–558.
Rahimi MS, et al, MRM 2015; 73:1926–1931; Schubert T, et al, J. MAGN. RESON. IMAGING 2017;45:229–236.



4D Dixon for Dynamic 3D Acquisitions
Artifact tradeoffs:
Larger A → slower sampling temporal averaging
Smaller A → lower dynamic spatial resolution
Gibb's ringing
Ma J, J. MAGN. RESON. IMAGING 2017; 28:543–558.
Le Y, et al, J. MAGN. RESON. IMAGING 2012; 36:483–491

4D Dixon for Dynamic 3D Acquisitions





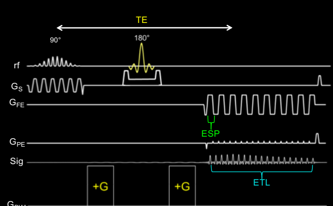
Artifact tradeoffs:
Larger A → slower sampling temporal averaging
Smaller A → lower dynamic spatial resolution
Gibb's ringing

Ma J, J. MAGN. RESON. IMAGING 2017; 28:543–558.
Le Y, et al, J. MAGN. RESON. IMAGING 2012; 36:483–491; Song T, MRM 2009 May ; 61(5): 1242–1248

Echo-Planar Imaging (EPI)

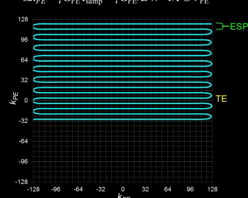
- Echo Planar Imaging is a fast imaging technique that utilizes an echo-train readout for subsecond image acquisition
- The sequence k-space trajectory and sequencing determine a lot of its imaging properties (and artifacts)
- The sequence is a workhorse for a variety of advanced imaging used clinically
  - Diffusion Weighted Imaging (DWI) and Diffusion Tensor Imaging (DTI
  - Blood Oxygen Level Dependent (BOLD) contrast (e.g., fMRI)
  - Dynamic Susceptibility Contrast (DSC) imaging
  - MR Elastography (MRE)
  - Chemical Exchange Saturation Transfer (CEST)

Spin-Echo Echo-Planar Imaging (SE-EPI) for DWI



ETL = Echo Train Length
ESP = Echo Spacing

$\Delta k_{FE} = \gamma G_{FE}\tau_{samp} = \gamma G_{FE}/BW = 1/FOV_{FE}$

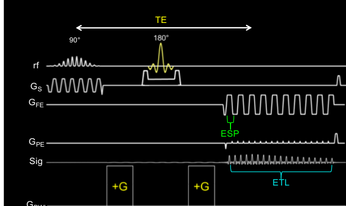


Strong diffusion gradients → long TE

High readout bandwidth to reduce ESP
Ramp Sampling to reduce ESP
→ effective bandwidth
→ effective ESP

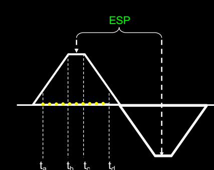
Schmitt F, Stehling M, Turner R, Echo-Planar Imaging Theory, Technique and Application (1998)
Wu W, Miller KL. J Magn Reson Imaging. 2017 Sep;46(3):646-662.

Spin-Echo Echo-Planar Imaging (SE-EPI) for DWI



ETL = Echo Train Length
ESP = Echo Spacing

$\Delta k_{FE} = \gamma G_{FE}\tau_{samp} = \gamma G_{FE}/BW = 1/FOV_{FE}$

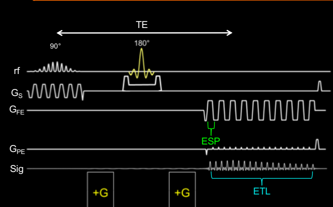


Strong diffusion gradients → long TE

High readout bandwidth to reduce ESP
Ramp Sampling to reduce ESP
→ effective bandwidth
→ effective ESP

Schmitt F, Stehling M, Turner R, Echo-Planar Imaging Theory, Technique and Application (1998)

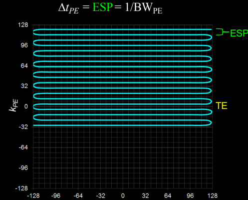
Spin-Echo Echo-Planar Imaging (SE-EPI) for DWI



ETL = Echo Train Length
ESP = Echo Spacing

$\Delta k_{PE} = \gamma G_{PE}\tau_{PE} = 1/FOV_{PE}$

$\Delta t_{PE} = ESP = 1/BW_{PE}$



dk/dt important in EPI for controlling a

No RF pulse between echoes to reset phase!
=>Phase accrual over time
=>Distortions along PE direction (NOT FE!)

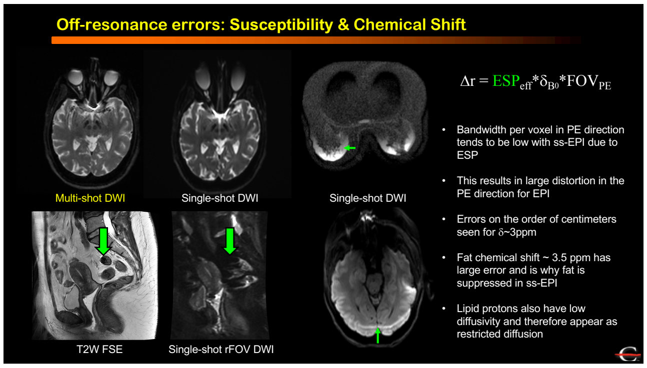
$\Delta y = ESP_{eff} * \delta_{B0} * FOV_{PE}$

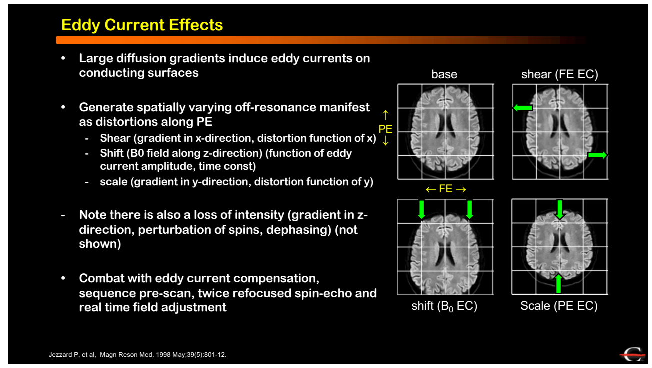
Schmitt F, Stehling M, Turner R, Echo-Planar Imaging Theory, Technique and Application (1998)

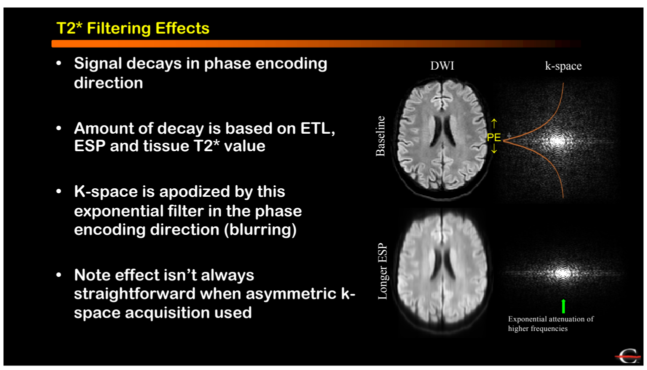
Common ss-EPI DWI artifacts

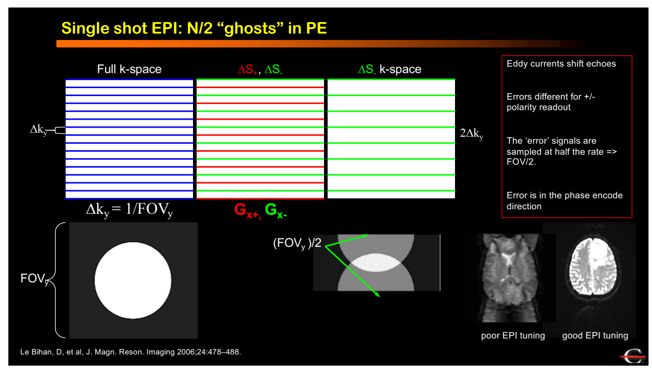
- Artifacts in phase encoding direction due to long ETL readout
  - susceptibility
  - Eddy current
  - Chemical shift
  - T2* filtering
  - N/2 Ghosting
- Artifacts in DWI & ADC map contrast
  - T2 "shine through"
  - Motion

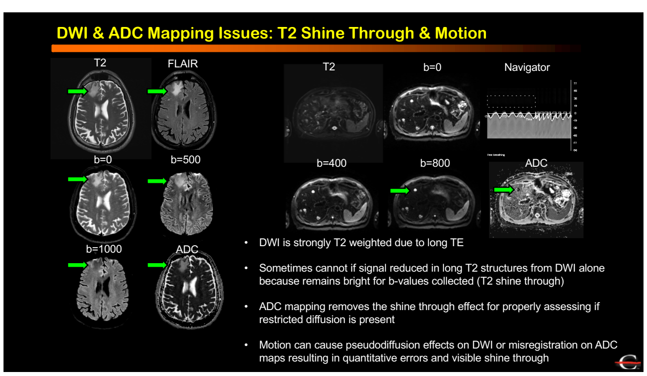
Wu W, et al, J. MAGN. RESON. IMAGING 2017;46:646–662; Huang SY, et al, Radiographics. 2015 Sep-Oct;35(5):1439-60.

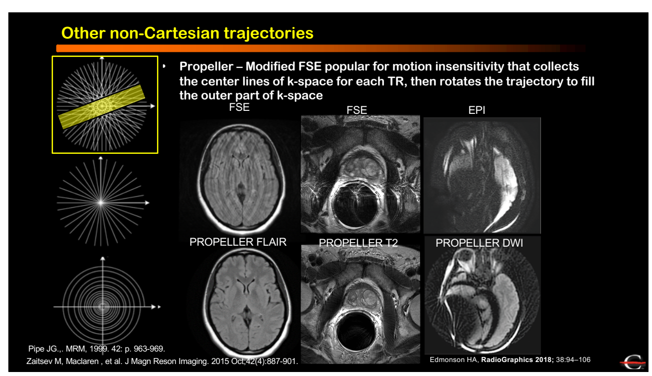

Off-resonance errors: Susceptibility & Chemical Shift
Multi-shot DWI
Single-shot DWI
Single-shot DWI
T2W FSE
Single-shot rFOV DWI
$\Delta r = ESP_{eff} * \delta_{B0} * FOV_{PE}$
Bandwidth per voxel in PE direction tends to be low with ss-EPI due to ESP
This results in large distortion in the PE direction for EPI
Errors on the order of centimeters seen for δ~3ppm
Fat chemical shift ~ 3.5 ppm has large error and is why fat is suppressed in ss-EPI
Lipid protons also have low diffusivity and therefore appear as restricted diffusion


Eddy Current Effects
Large diffusion gradients induce eddy currents on conducting surfaces
Generate spatially varying off-resonance manifest as distortions along PE
Shear (gradient in x-direction, distortion function of x)
Shift (B0 field along z-direction) (function of eddy current amplitude, time const)
scale (gradient in y-direction, distortion function of y)
Note there is also a loss of intensity (gradient in z-direction, perturbation of spins, dephasing) (not shown)
Combat with eddy current compensation, sequence pre-scan, twice refocused spin-echo and real time field adjustment
base
shear (FE EC)
PE
← FE →
shift (B_0 EC)
Scale (PE EC)
Jezzard P, et al, Magn Reson Med. 1998 May;39(5):801-12.


T2* Filtering Effects
Signal decays in phase encoding direction
Amount of decay is based on ETL, ESP and tissue T2* value
K-space is apodized by this exponential filter in the phase encoding direction (blurring)
Note effect isn't always straightforward when asymmetric k-space acquisition used
DWI
k-space
Baseline
PE
Longer ESP
Exponential attenuation of higher frequencies

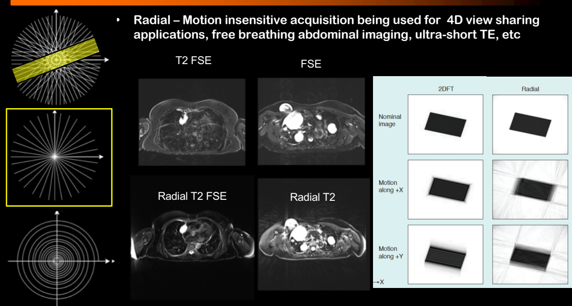

Single shot EPI: N/2 "ghosts" in PE
Full k-space
ΔS_+, ΔS_-
ΔS_- k-space
Δk_y
$2\Delta k_y$
$\Delta k_y = 1/FOV_y$
G_{x+}, G_{x-}
FOV_y
$(FOV_y)/2$
Eddy currents shift echoes
Errors different for +/- polarity readout
The 'error' signals are sampled at half the rate => FOV/2.
Error is in the phase encode direction
poor EPI tuning
good EPI tuning
Le Bihan, D, et al, J. Magn. Reson. Imaging 2006;24:478–488.


DWI & ADC Mapping Issues: T2 Shine Through & Motion
T2
FLAIR
b=0
b=500
b=1000
ADC
T2
b=0
Navigator
b=400
b=800
ADC
DWI is strongly T2 weighted due to long TE
Sometimes cannot if signal reduced in long T2 structures from DWI alone because remains bright for b-values collected (T2 shine through)
ADC mapping removes the shine through effect for properly assessing if restricted diffusion is present
Motion can cause pseudodiffusion effects on DWI or misregistration on ADC maps resulting in quantitative errors and visible shine through


Other non-Cartesian trajectories
Propeller – Modified FSE popular for motion insensitivity that collects the center lines of k-space for each TR, then rotates the trajectory to fill the outer part of k-space
FSE
FSE
EPI
PROPELLER FLAIR
PROPELLER T2
PROPELLER DWI
Pipe JG,. MRM, 1999. 42: p. 963-969.
Zaitsev M, Maclaren , et al. J Magn Reson Imaging. 2015 Oct;42(4):887-901.
Edmonson HA, RadioGraphics 2018; 38:94–106

Other non-Cartesian trajectories

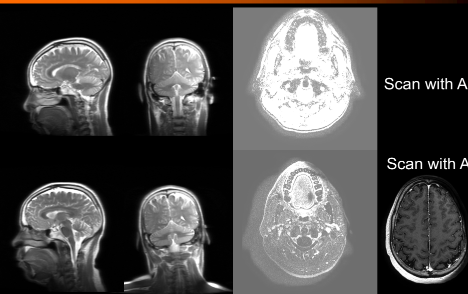
- Radial – Motion insensitive acquisition being used for 4D view sharing applications, free breathing abdominal imaging, ultra-short TE, etc



Zaitsev M, Maclaren , et al. J Magn Reson Imaging. 2015 Oct;42(4):887-901.

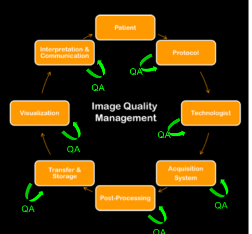
Smith & Nayak, Imaging M 446 ed. (2010) 2(4)

Just for fun …



Summary

- Knowledge of system components and image synthesis is essential to understanding and minimizing or remediating artifacts in MRI
- Violations to key assumptions assumed in our image reconstruction process propagate into the image as artifacts
- Despite this, management of image quality issues, including artifacts, should focus on identifying the step(s) in the imaging chain in which specific teams can intervene to control



THE UNIVERSITY OF TEXAS
MD Anderson ~~Cancer~~ Center

Thank you for your time!

Email: jstafford@mdanderson.org