State-Of-the Art Technology and Protocols

Trevor Andrews, PhD, DABMP(MRI), MRSE(MRSC™)

trevor.andrews@wustl.edu

April 18, 2021

Washington University in St. Louis
School of Medicine

MIR Mallinckrodt Institute of Radiology

Barnes-Jewish Hospital
BJC HealthCare

Disclosure

- Chair: *WG for MR Testing and Quality Assurance (WGMRQA)*
- Member: *Diagnostic Radiology Resident Physics Curriculum Working Group (DRRPCWG)*
- Member: *QIBA Diffusion-Weighted Imaging MR Biomarkers Committee*
- Worked for Philips Healthcare for 9 yrs
- Used Philips for 15 yrs
- Used GE for 11 yrs
- Used Siemens for 2 yrs
- Never used Toshiba/Canon or Hitachi (or others)

Disclosure

- <u>By necessity</u> many vendors and products are mentioned here
- ALL these are FDA approved and worth considering

- More importantly:

  <u>Many of these details will likely change in the future as these products improve</u>

Introduction: The Scope is Too Big!

“State of the Art” MRI is huge!

Today I we will cover MR techniques which are:

- Not “traditional” acquisitions, hardware, or reconstruction (i.e. the stuff on the ABR exam)
- Commercially available (no WIPs or patches)
- Multiple vendors

Photo Courtesy of Mallie's Sports Grill and Bar, Southgate, Michigan

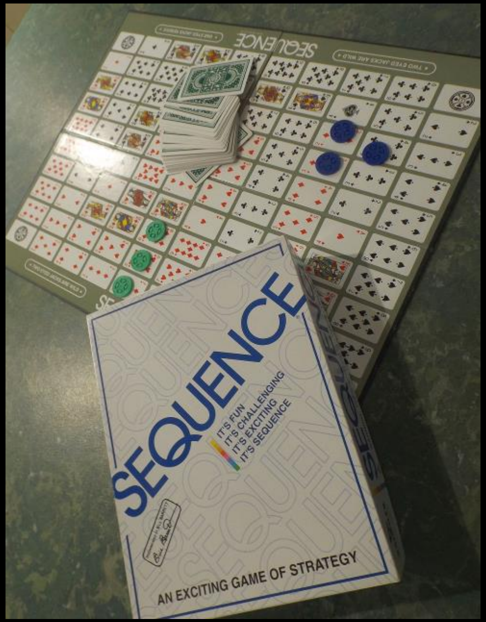
Introduction: What We Will Cover

Intended Audience:

Knows the basics of MRI physics but NOT experts with MRI applications

I will try to cover big points less likely to change:

- Basic concepts and clinical needs
- Pulse sequence basics
- Main advantages and obstacles (currently!)



I will avoid most vendor-specific differences

- E.g. parameter values, vendor performance comparisons

Outline

- Introduction
- Speed Improvements

Simultaneous Multi-Slice (SMS)
Compressed Sense (CS)

- Image Quality Improvements

Golden Angle Free Breathing MR
View Angle Tilting/SEMAC/MAVRIC
RF Shimming
DIXON

- Quantitative Mapping

MR Elastography (MRE)
T1 Mapping
Fat Fraction/T2* Mapping
QIBA

This still leaves out a lot of major state-of-the-art clinical MRI
And I will still leave out most of the math and simplify a LOT!!

Basic Tips for Advanced Applications

Main Tip:

Find vendor-specific guidance, and start there

For example, note:

Scan parameters in a paper might not translate easily from vendor to vendor

Basic Tips for Advanced Applications

Scenario 1:

When planning a purchase:

- What exact licenses must be purchased? (Maybe you already have some.)
- What scanner software version is needed? What do I have?
- Do I have all the required hardware installed?
- Is offline processing needed? Do I need new hardware (e.g. workstation) for that? New software? What kind of support does this need (maintenance, processing, etc.)?
- What vendor apps training is needed and provided?

Basic Tips for Advanced Applications

Scenario 2:

When troubleshooting, consider:

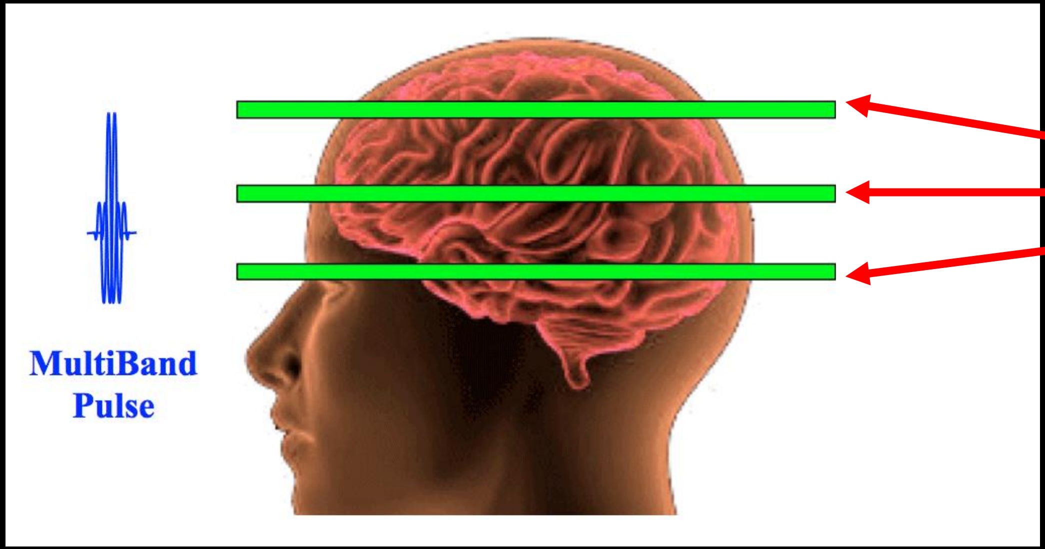
- Do I have all the required licenses installed?
- Do I have all the required hardware installed?
- What does the default scan look like using vendor-supplied scan parameters?

For any IQ problem, vendors will always tell you to go back to the vendor-supplied scan parameters!

Speed Improvement #1: Simultaneous MultiSlice (SMS)

Excite multiple slices (2-4) at the same time.

Unlike parallel imaging, there is <u>minimal SNR penalty for SMS acceleration</u>!



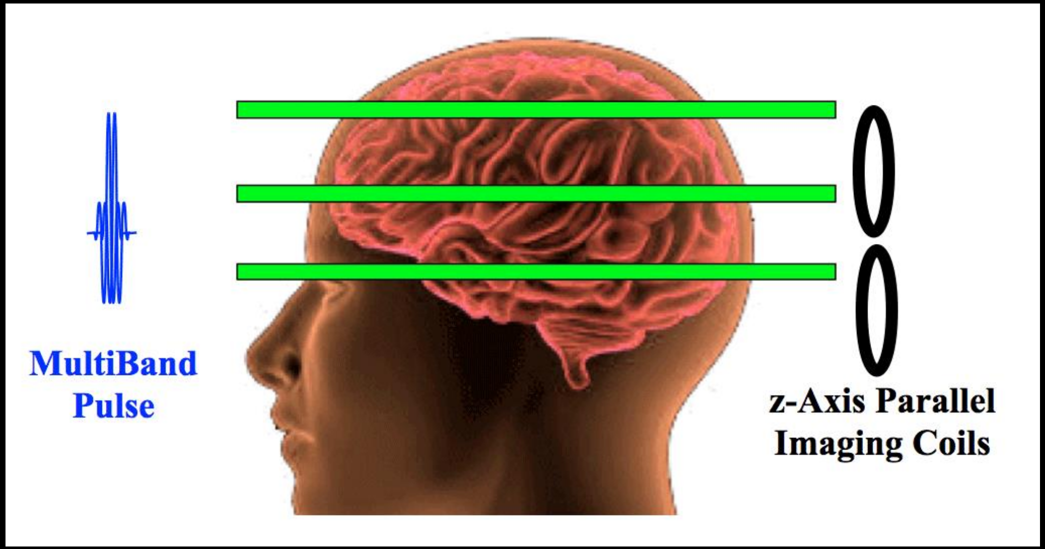
Each slice has different phase offset to <u>shift it inplane</u>

<u>The recon can unwrap this</u>

Image courtesy of Allen D. Elster, MRIquestions.com

Speed Improvement #1: Simultaneous MultiSlice (SMS)

Adding parallel imaging (PI) acceleration is possible



- Need coil with multiple elements in acceleration direction (not 8ch head coil for axial)
- Use large gaps between simultaneous slices
- Interleave slices

Note: Recon may be slow enough to affect workflow (vendors getting better rapidly)

Speed Improvement #1: Simultaneous MultiSlice (SMS)

Trade Names:

Siemens: SMS (using "blipped CAIPI")

GE: HyperBand

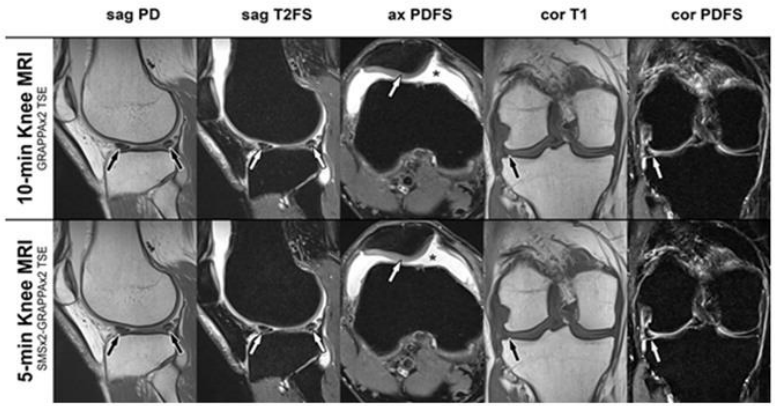
Philips: MultiBand

Initially introduced for speed improvements for EPI-based scans (e.g. DTI and fMRI)

Can potentially be used for long 2D scans (e.g. axial t-spine)

Speed Improvement #1: Simultaneous MultiSlice (SMS)

Five-minute Five-Sequence Knee MRI Using Combined Simultaneous Multisection and Parallel Imaging Acceleration: Comparison with 10-minute Parallel Imaging Knee MRI



Images from a 10-minute MRI protocol (top row) compared with a 5-minute SMS-PI (bottom row) in a patient with a tear of the anterior and posterior segments of the lateral meniscus (arrows), a joint effusion (∗), and intact patella cartilage (arrows).

- Combined simultaneous multisection (SMS) technique and parallel imaging (PI) enables fourfold-accelerated, 5-minute, five-sequence turbo spin-echo knee MRI at 1.5 and 3 T.
- Five-minute SMS-PI–accelerated and 10-minute PI-accelerated knee MRI had high reader agreements for detecting structural abnormalities at 1.5 T ($\kappa > 0.71$) and 3 T ($\kappa > 0.85$).
- Five-minute and 10-minute MRI protocols had similar diagnostic performances for internal derangement (AUCs >78%, $P > .32$).

Del Grande F et al. Published Online: April 6, 2021
https://doi.org/10.1148/radiol.2021203655
Radiology

5min session vs. 10min session

Similar diagnostic performance

Speed Improvement #1: Simultaneous MultiSlice (SMS)

Potential problems:

- **High SAR**
  - **Could force ↑ TR, or limit use w/ implants**
- **Residual aliasing artifacts**
  - **similar to SENSE ghost artifact**

Speed Improvement #2: Compressed Sensing

When you save a BMP of an MR image as a JPG, it might be ~<u>1/10 the size</u> with modest reduction in image quality.

Question:

- **Are we saving more MR image data than we need for similar IQ?**
- **If so, <u>can we acquire less data to get similar IQ? Yes, we can!</u>**

For a deeper discussion by Miki Lustig:
https://www.youtube.com/watch?v=AP6JczMW8C8

Speed Improvement #2: Compressed Sensing

<u>To increase speed we:</u>

1) **<u>Skip some (random) lines in k-space, and</u>**
2) **<u>Use new recon methods (w/machine learning)</u>**

This study found <u>33% reduction</u> in scan duration for a 3D FSE with no significant IQ reduction (GE, Discovery MR750, 8ch T/R coil).

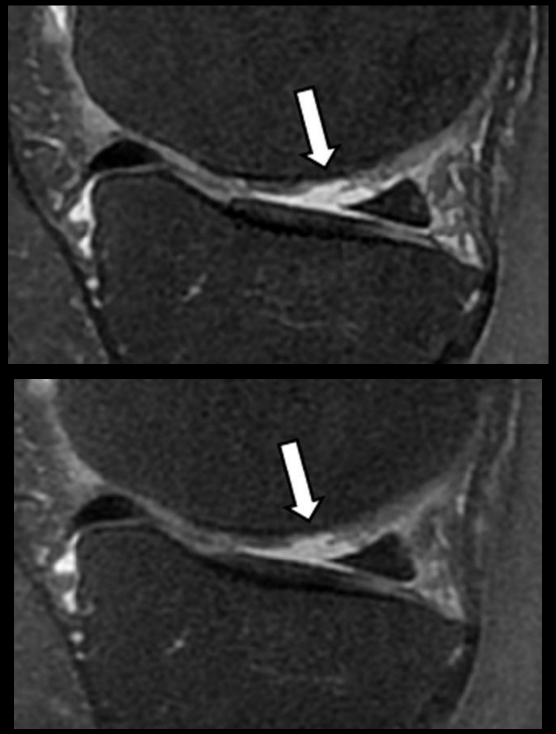
<u>Vendor claims closer to 50% can be found</u>

<u>Trade names (w/ PI):</u>

<u>Siemens:</u> Compressed Sensing

<u>GE:</u> Hyper SENSE

<u>Philips</u>: Compressed SENSE



Lee, et al "**Accelerating knee MR imaging: Compressed sensing in isotropic three-dimensional fast spin-echo sequence**" MRI, 2018

Speed Improvement #2: Compressed Sensing

CS Tips:

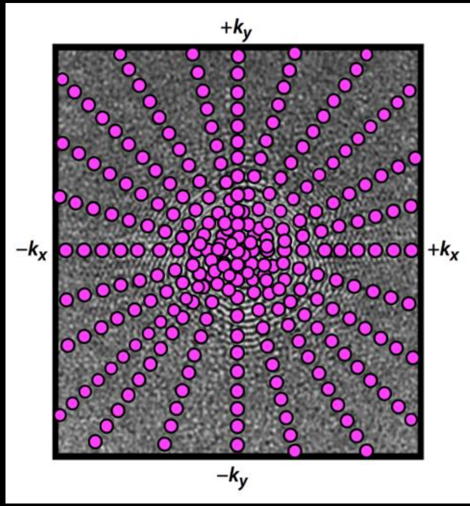
- Biggest clinical benefits: greatly shortened breath holds, more flexible schedule for add-ons/inpatients
- CS is not available for all sequences for all vendors
- 3D generally shows bigger improvements than 2D (~%40 vs ~%20)
- CS can often combine with parallel imaging (PI) for faster scan
  - CS and PI acceleration commonly lumped together in to 1 acceleration factor
- Biggest acceleration often with spatially or temporally “sparse” data
  - E.g. Time-of-flight often quoted (total acceleration factors 10-24).

IQ Improvement #1: Free Breathing Imaging

<u>Golden Angle "Stack-Of-Stars":</u>

Especially for abdominal <u>free-breathing</u> scans

"Stack of stars" filling of k-space can be used with the "golden angle" (111.25°) between each radial line in k-space to <u>reduce gross motion artifacts</u>.



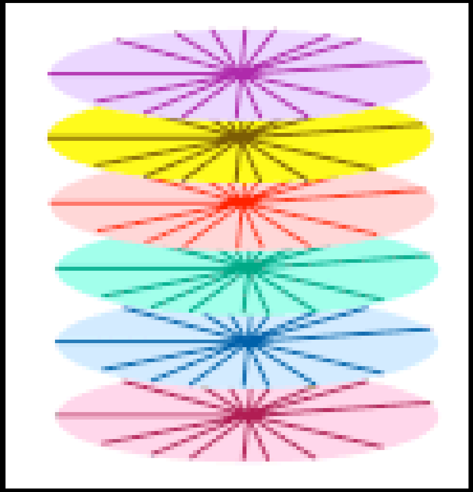


Image courtesy of Allen D. Elster, MRIquestions.com

IQ Improvement #1: Free Breathing Imaging

<u>Trade names:</u>

Siemens: GRASP

Philips: 3D VANE XD

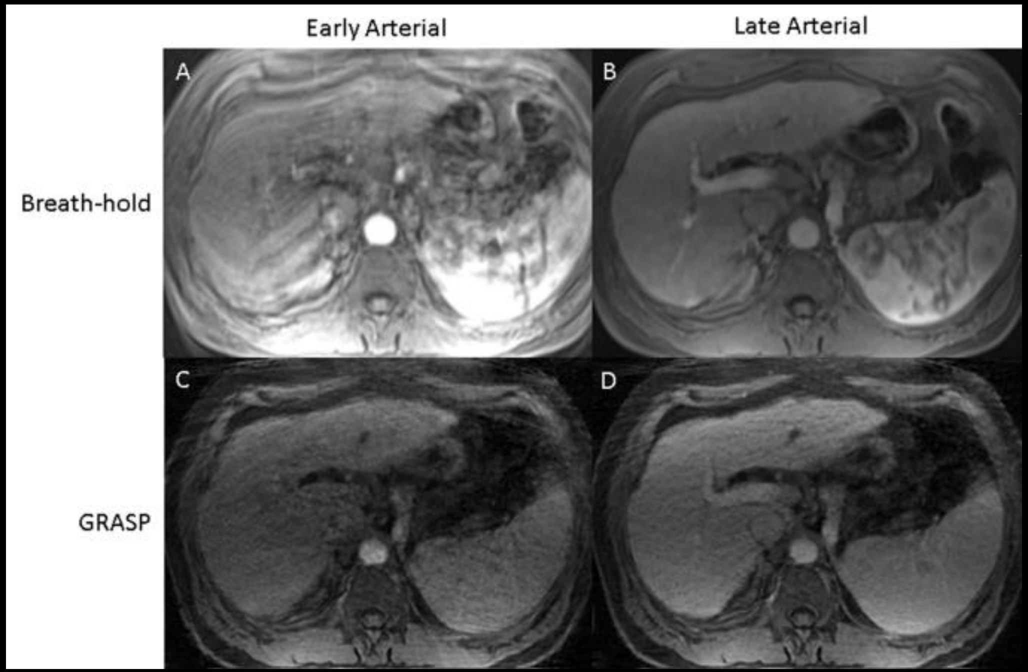
GE: ?

Generally uses CS recon

Produces diagnostic quality images

Especially useful for **<u>abdominal imaging compared to conventional BH</u>**

Note: <u>Eovist</u> is known to induce significant motion in some patients (even during BH).

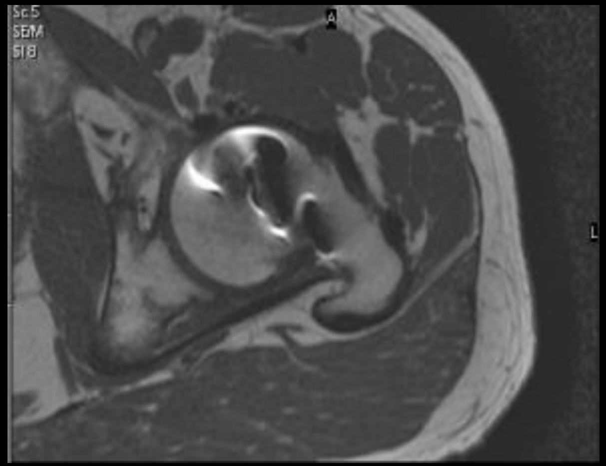


Chadarana, et al, "Respiratory Motion-Resolved Compressed Sensing Reconstruction of Free-Breathing Radial Acquisition for Dynamic Liver MRI " Invest. Radiol 2015

IQ Improvement #2: Metal Artifact Reduction

Problem:

Metal in the FOV causes magnetic field inhomogeneities which result in geometric distortion, voids, and signal pile-up nearby.



IQ Improvement #2: Metal Artifact Reduction

Solutions:

Several new methods reduce this problem significantly:

- Siemens/GE/Philips:
  - View Angle Tilting (VAT): for in-plane distortions
- GE: MAVRIC: for through-plane distortions
- Siemens/Philips: SEMAC: for through-plane distortions

VAT can be added to MAVRIC or SEMAC for better improvements

IQ Improvement #2: Metal Artifact Reduction

Through plane distortions:

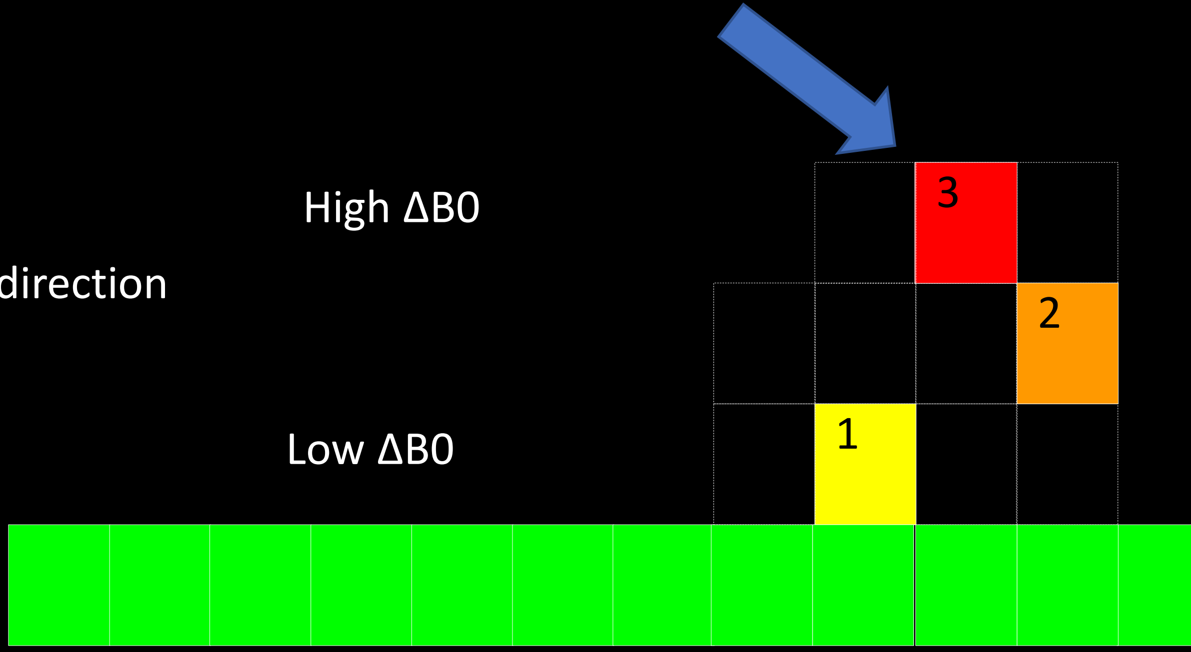
Nearby metal shifts frequencies of distant spins

BEFORE
SCAN STARTS

High ΔB0

Slice selection direction

Low ΔB0



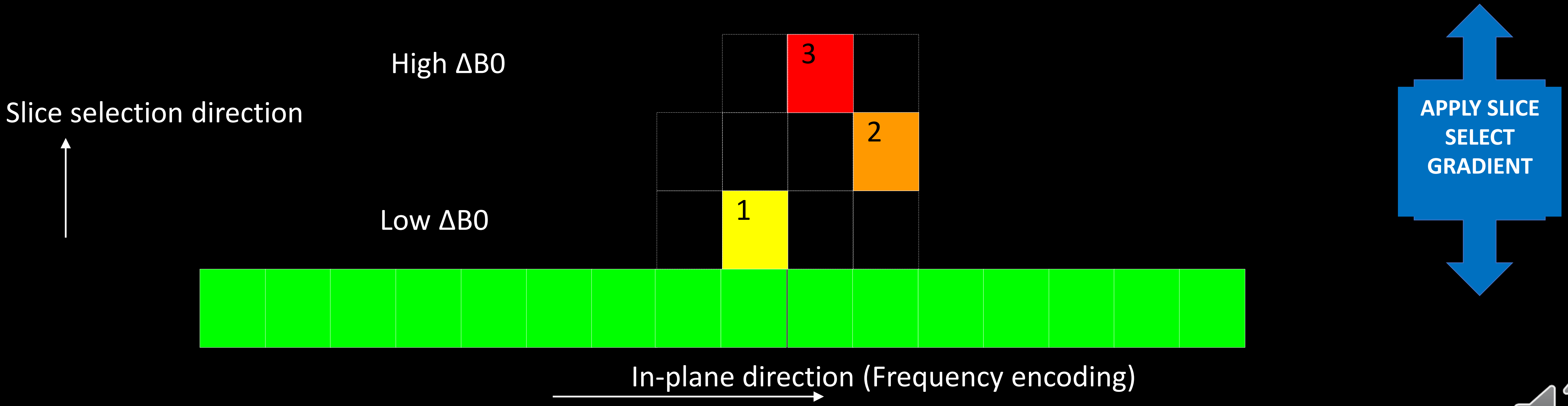
INTENDED
SLICE

In-plane direction (Frequency encoding)

IQ Improvement #2: Metal Artifact Reduction

Through plane distortions:

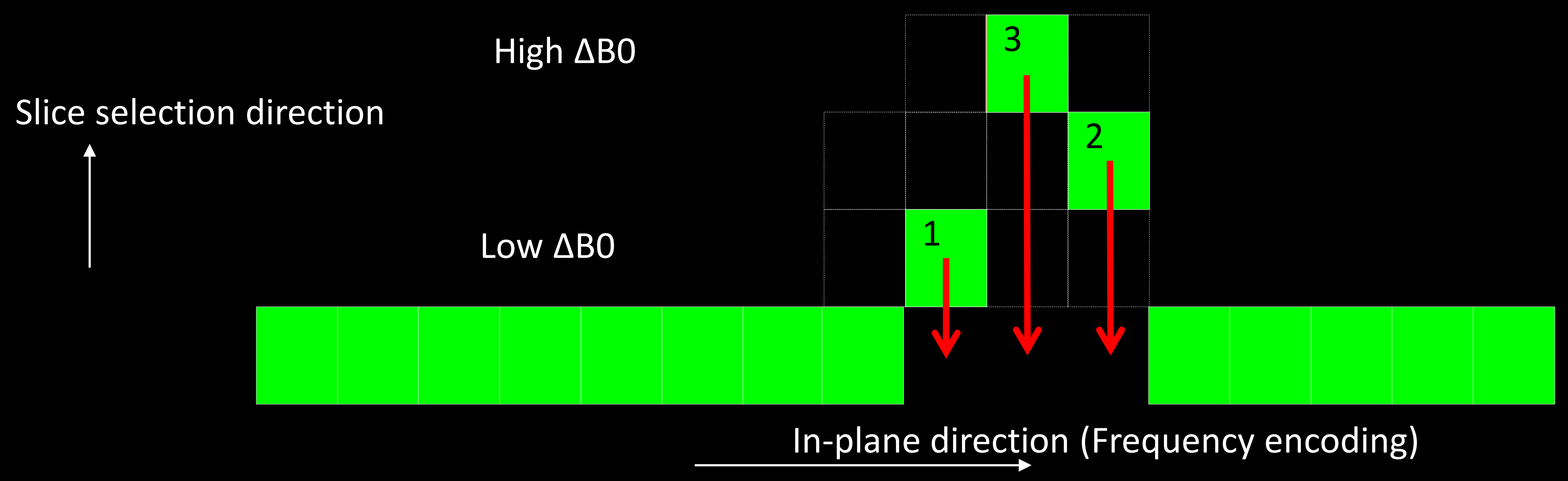
Imaging gradients cause distant volumes to match RF excitation frequencies during slice selection.



IQ Improvement #2: Metal Artifact Reduction

Through plane distortions:

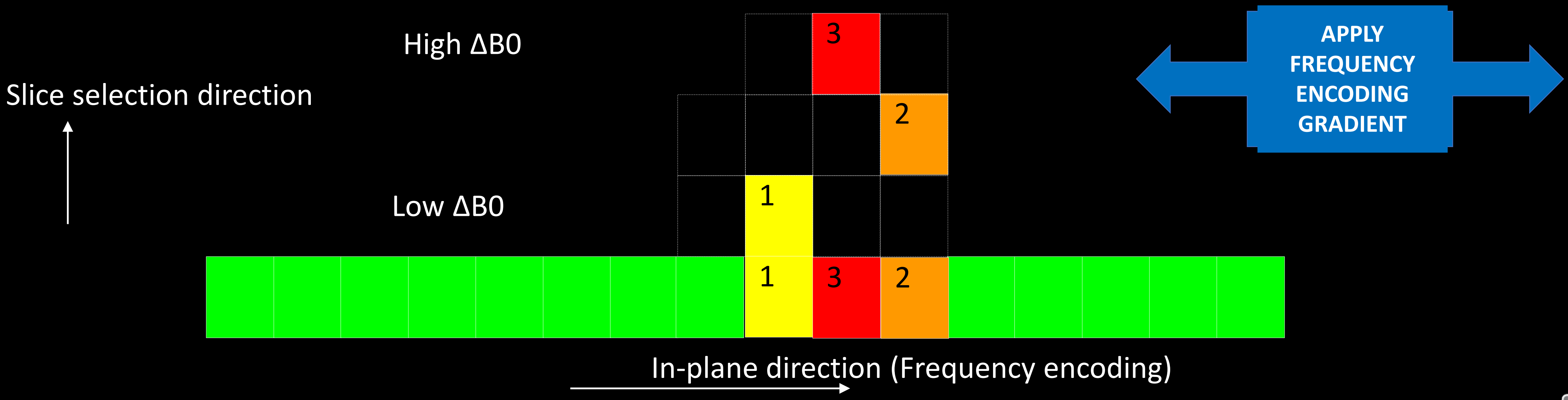
Distant spins mistaken for spins in flat slice.



IQ Improvement #2: Metal Artifact Reduction

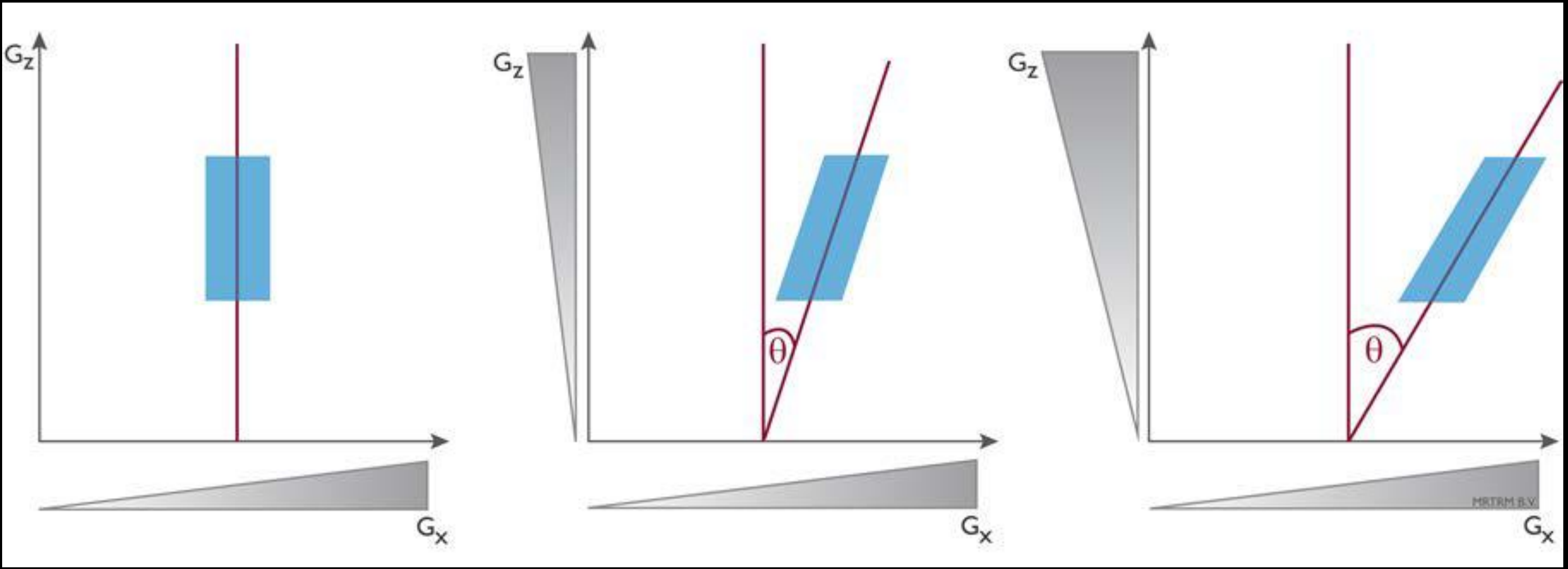
In-plane distortions:

During FE, off resonance spins mimic spins w/ frequency offset and shift along FE direction



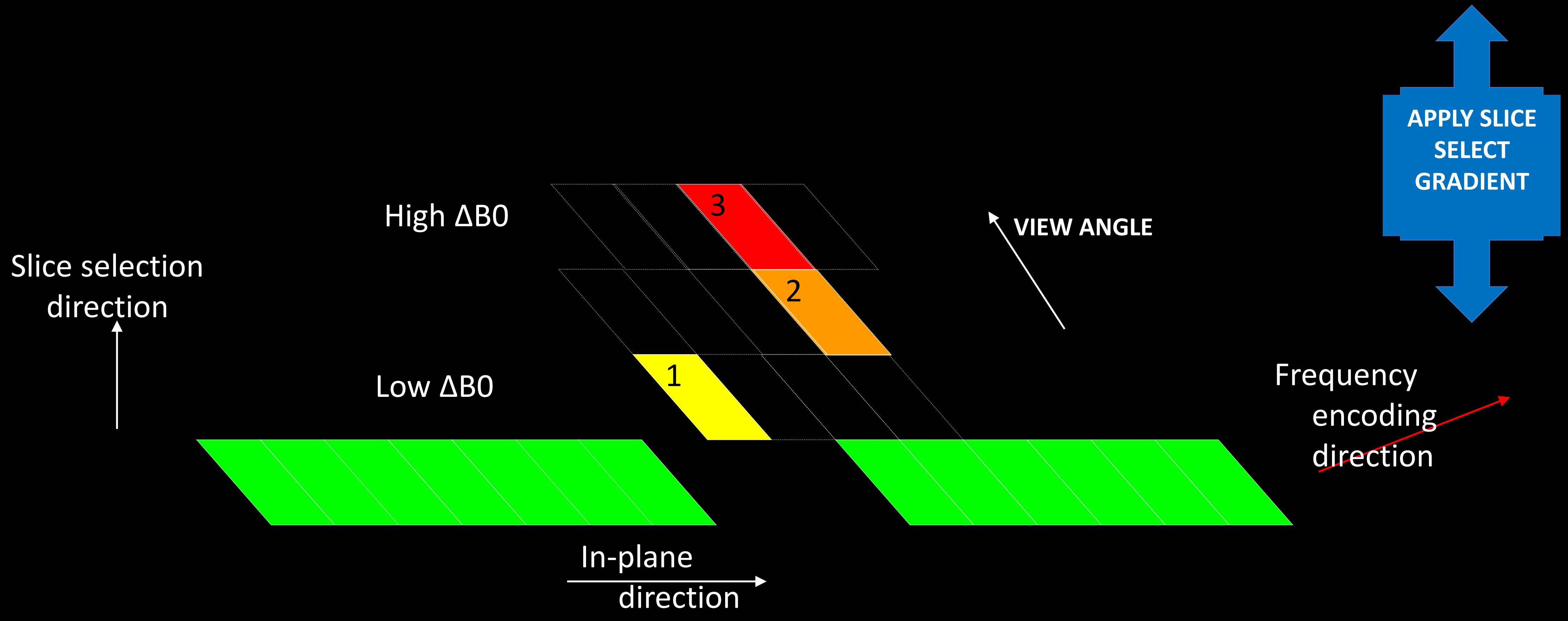
IQ Improvement #2: Metal Artifact Reduction View Angle Tilting (VAT)

To correct this we will <u>change the "view angle" (the angle between the slice select direction and the FE direction):</u>

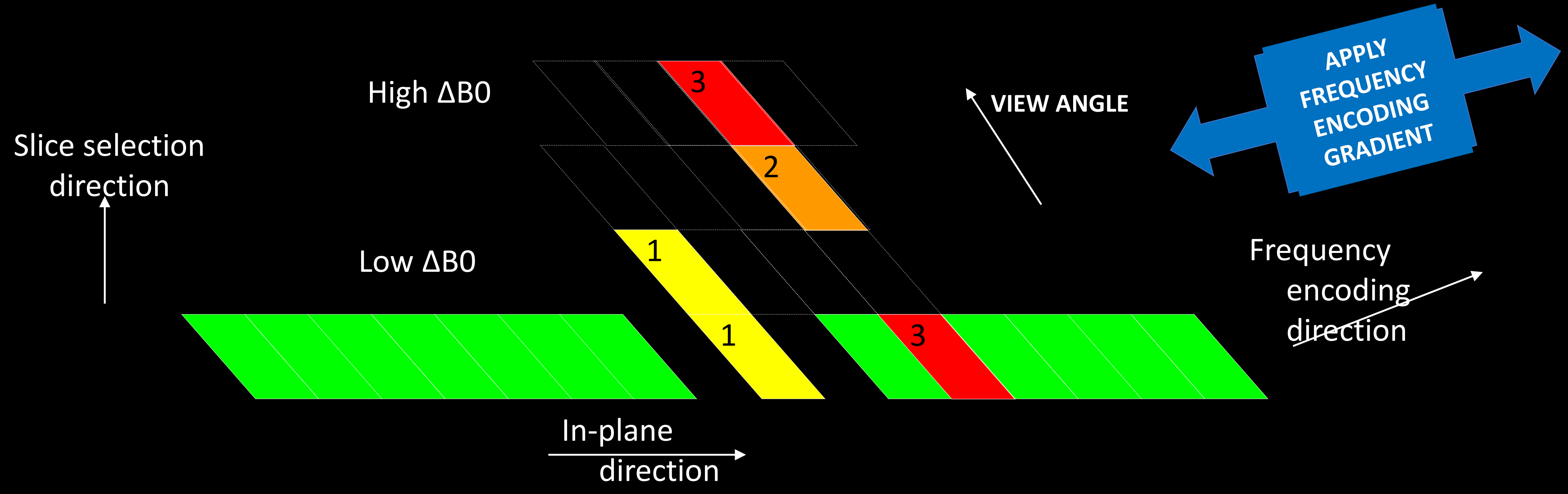


"Total inhomogeneity correction including chemical shifts and susceptibility by view angle tilting". Z. H. Cho, D. J. Kim, and Y. K. Kim Medical Physics 15, 7 (1988);

IQ Improvement #2: Metal Artifact Reduction View Angle Tilting (VAT)

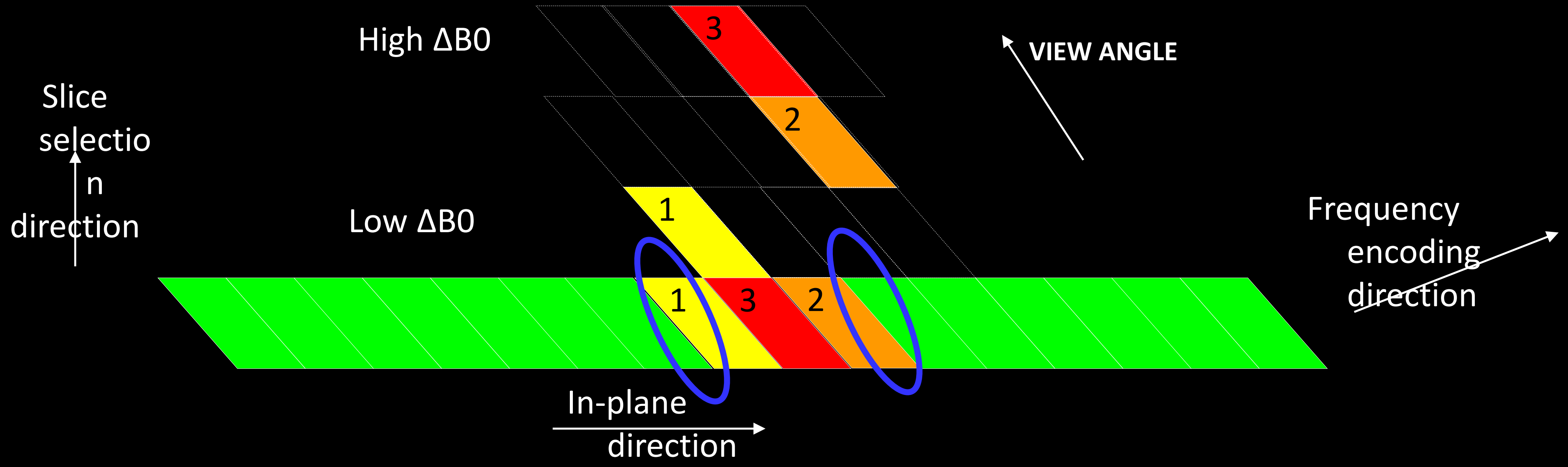


IQ Improvement #2: Metal Artifact Reduction
View Angle Tilting (VAT)



IQ Improvement #2: Metal Artifact Reduction
View Angle Tilting (VAT)

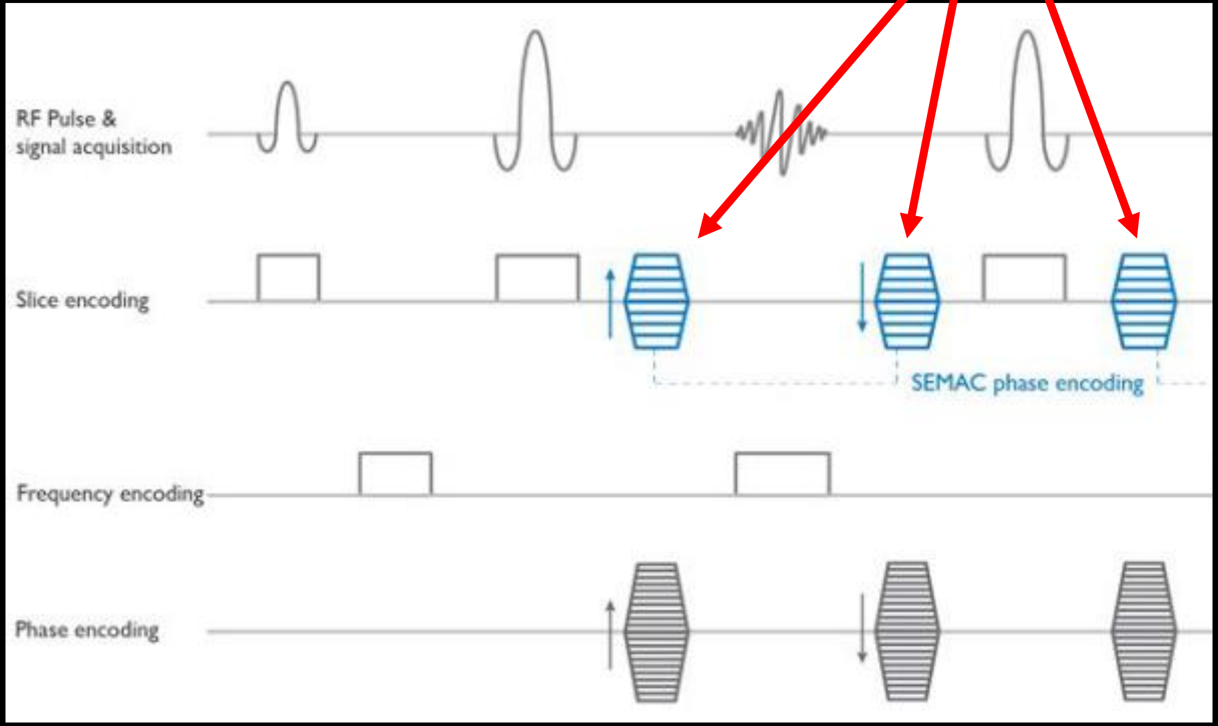
- Disadvantage: Can result in a blurring at the edges of tissues.
- Mitigation: reduce slice thickness, increase BW



IQ Improvement #2: Metal Artifact Reduction

Slice Encoding for Metal Artifact Correction (SEMAC)

This 2D scan is repeated with different "SEMAC encodings", making the pulse sequence look a bit like a 3D



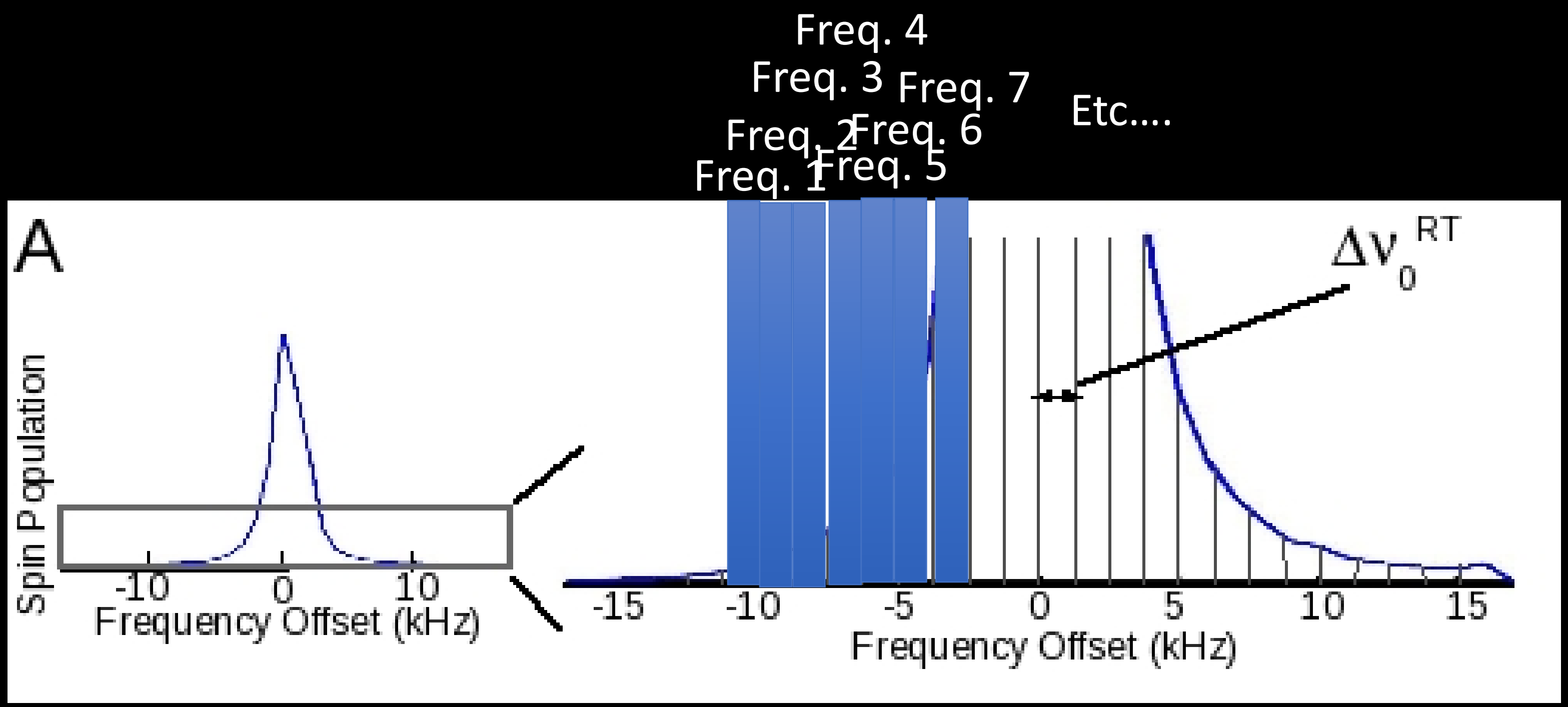
This makes the scan potentially <u>very long</u>.

IQ Improvement #2: Metal Artifact Reduction

MultiAcquisition Variable-Resonance Image Combination (MAVRIC)

MAVRIC performs a short 3D FSE, repeating it several times with a shifted transmit and receive frequency.

The idea is to use this to cover the entire range of frequencies.



Koch et.al., MRM;61:381 (2009)

This makes the scan potentially very long.

IQ Improvement #2: Metal Artifact Reduction

Tips:

- MAVRIC and SEMAC are **powerful methods for tough cases, but may not be needed for many implants**

- For more practical scan durations:
  - Spatial resolution is reduced
  - Recently, Compressed Sensing has been added

IQ Improvement #2: Metal Artifact Reduction

Tips:

- Small metal or titanium: VAT or just parameter optimization
- Big metal artifacts: VAT + (SEMAC or MAVRIC) + CS

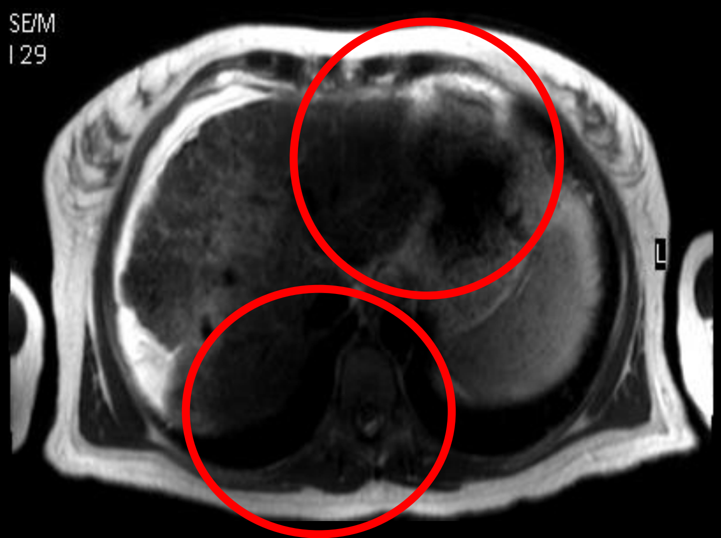
- For Siemens use 30-40% VAT; for Philips it automatically picked
- Check EPIC to see if you know in advance the type of metal!
  - May help guide you in your choice of methods

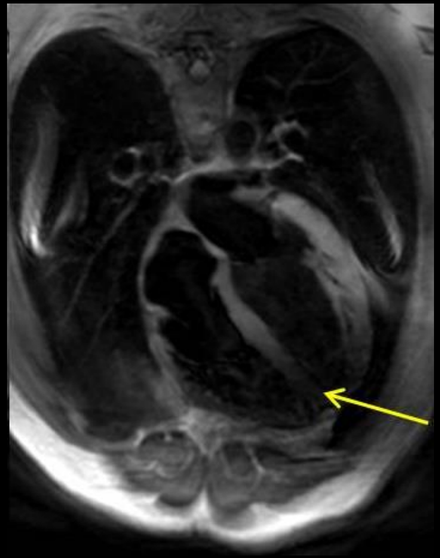
IQ Improvement #3:
RF Shimming

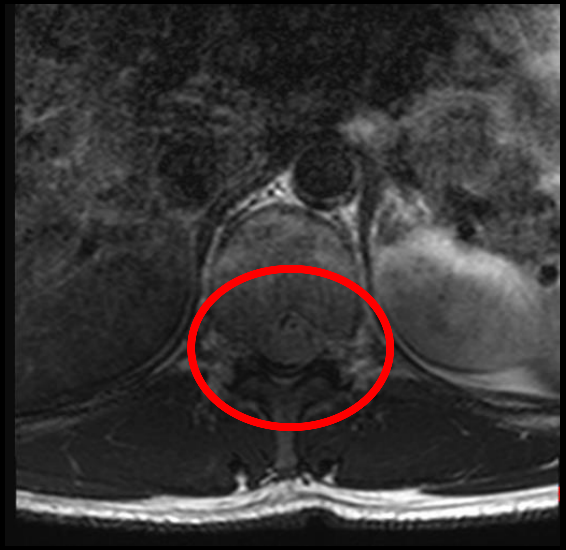
Problem:

Shading artifacts primarily at 3T or higher , mainly in chest/abdomen

Classic example: ascites







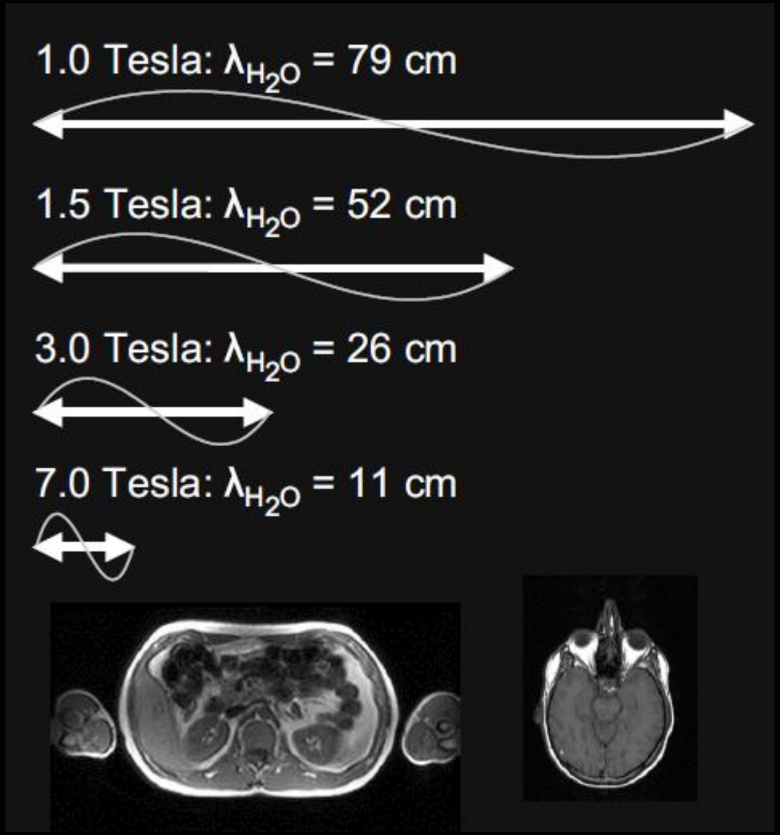
IQ Improvement #3: RF Shimming

Problem:

Wavelength cut to **~ 1/10** in water or soft tissue

Table 1 Radio frequency wavelength in air and in water for several biologically important nuclei at 1.5, 3 and 7 T

Field strength (T)	Nucleus	Wavelength in air (cm)	Wavelength in water (cm)
1.5	^{1}H	470	52
	^{13}C	1,870	210
	^{23}Na	1,780	200
	^{31}P	1,160	129
3.0	^{1}H	235	26
	^{13}C	940	105
	^{23}Na	890	100
	^{31}P	580	64
7.0	^{1}H	100	11
	^{13}C	400	45
	^{23}Na	380	42
	^{31}P	250	28



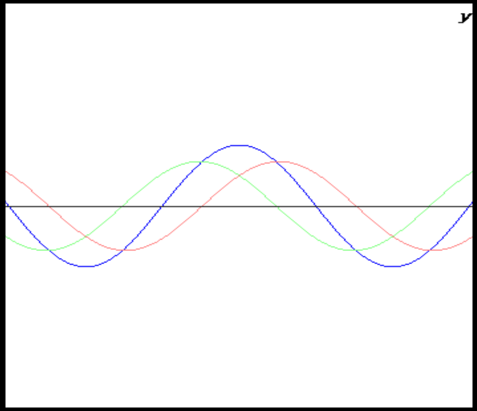
Schick, F. Whole-body MRI at high field: technical limits and clinical potential. *Eur Radiol* **15,** 946–959 (2005).

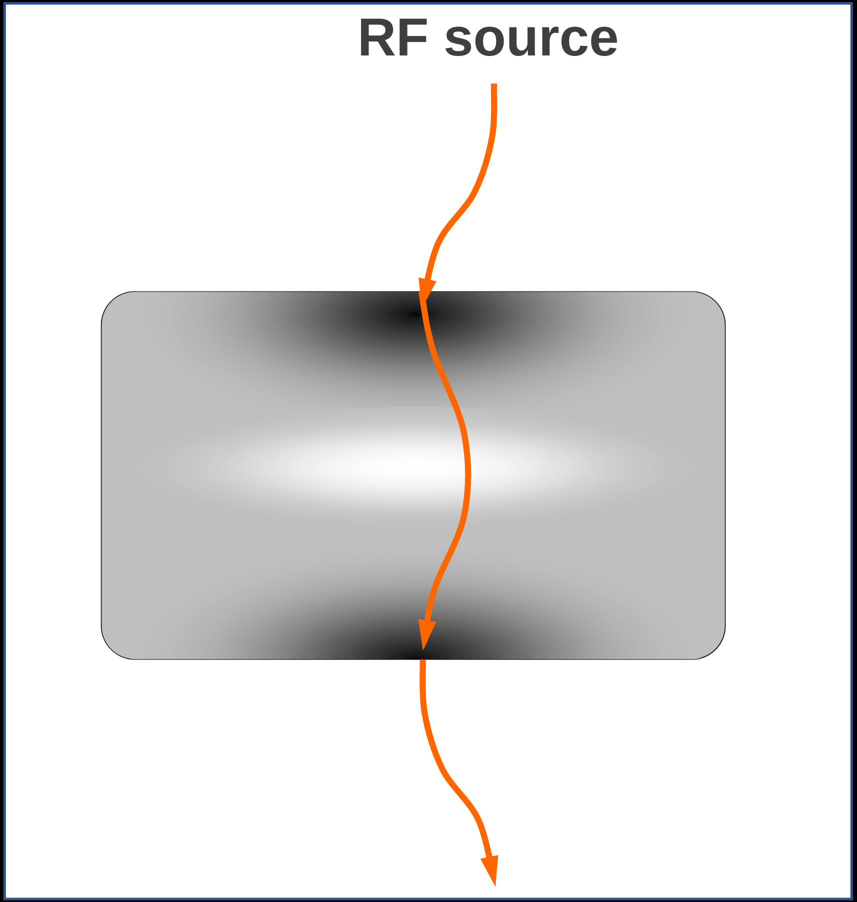
IQ Improvement #3: RF Shimming

<u>Problem:</u>

This is commonly mislabeled as purely a “dielectric effect”

RF reflects in body creating “standing waves”(see blue wave below)





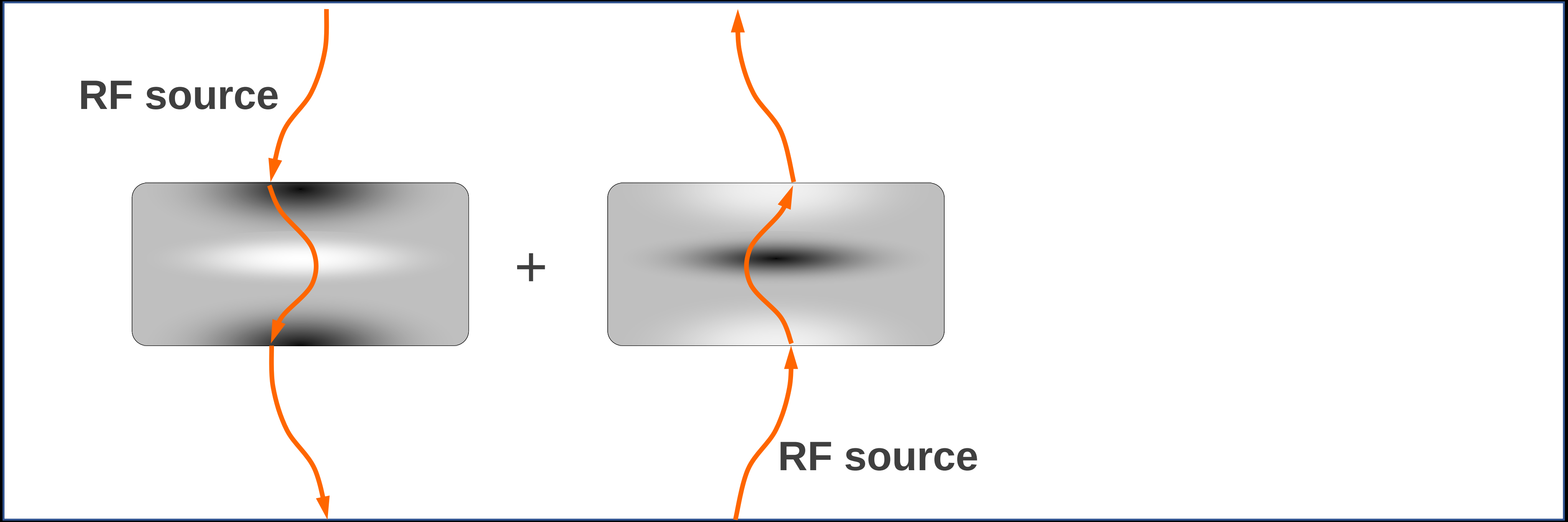
IQ Improvement #3: RF Shimming

Solution:

- "RF shimming" (AKA, "parallel transmission" or "parallel transmit"
- Change phase and amplitude of at least 2 RF transmissions
- Makes RF transmit field more uniform.

Analogous to noise cancelling headphones

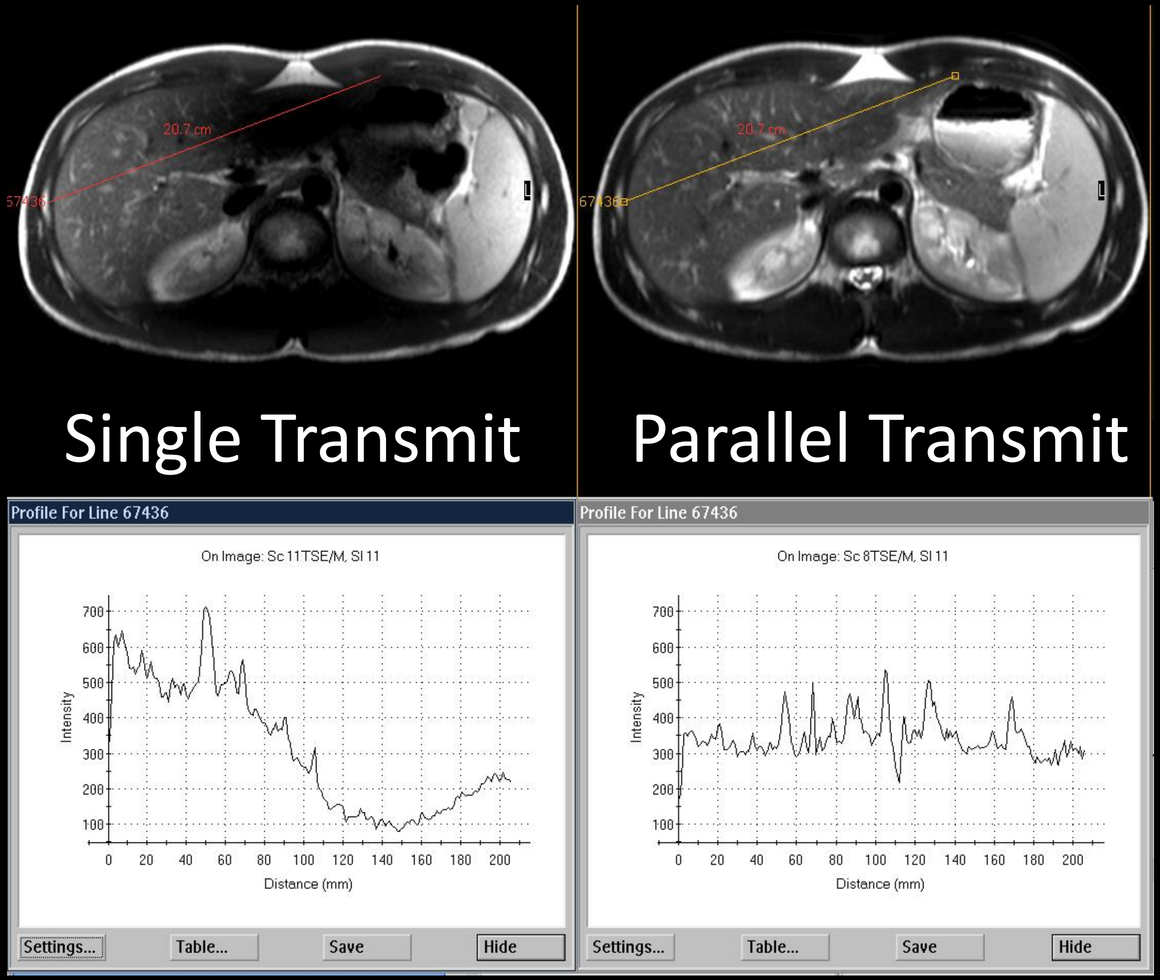
http://mriquestions.com/uploads/3/4/5/7/34572113/mr_achieva_tx_whitepaper_multitransmit.pdf



IQ Improvement #3: RF Shimming

Is this a window/level trick?

Corrected an <u>85% signal drop</u> in left lobe of liver.



Andrews T, Ghostine J, Gonyea JV, Ebert GM, Braff SP, Filippi CG, "Reduction in Dielectric Shading in Liver on Clinical 3T Parallel Transmission MR System", ISMRM Proc., 2010.

IQ Improvement #3: RF Shimming

Tips:

No parameters to really tweak, BUT

- For 2 transmitters this reduces RF hot spots, reducing whole body average SAR
  - This might allow for faster scanning (in RF Normal Mode)
- RF shimming is in x-y plane (i.e. axial plane), extending slightly z-direction
  - So may not help much with coronal or sagittal, esp. at edge of FOV

IQ Improvement #4: Dixon Fat Suppression

Fat suppression is critically valuable but historically difficult to achieve for many pathologies studied with clinical MR.

The Dixon Method has been recently made more robust with several new improvements (details vary by vendor approach):

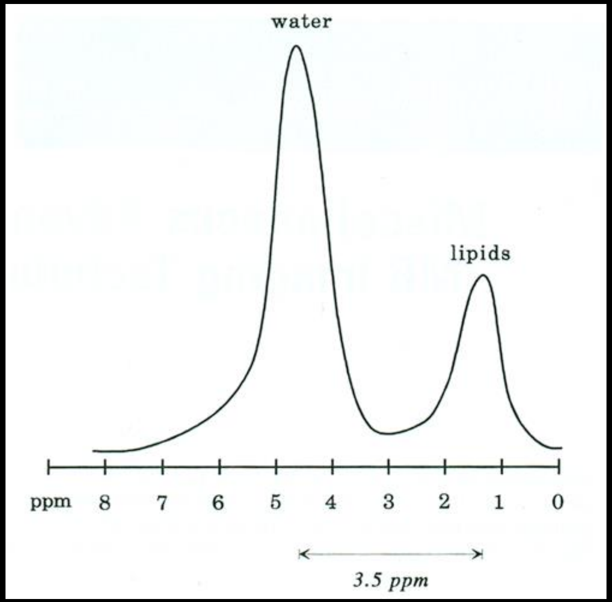
- good fast B0 mapping and corrections at edge of FOV
- better eddy current corrections
- multi-peak fat models (and greater TE selection flexibility)
- faster reconstruction, etc.

Artifacts far less common than in the past

IQ Improvement #4:
Dixon Fat Suppression

Dixon Method

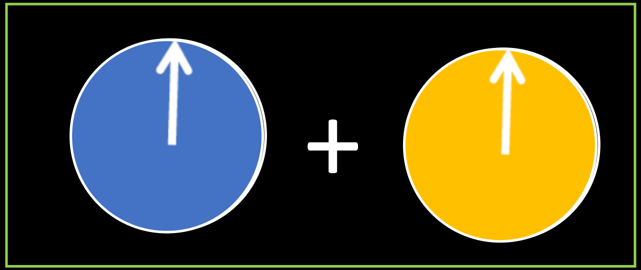
Hydrogen spins in fat precess slower than those in water molecules.



Graph courtesy of Allen D. Elster, MRIquestions.com

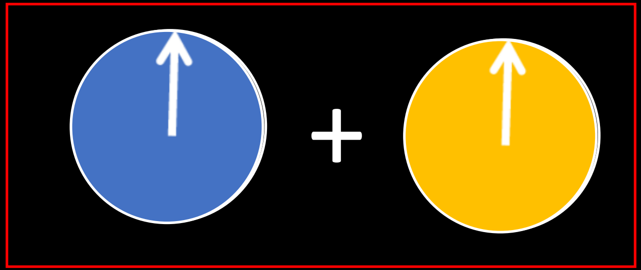
<u>At 1.5T:</u>

TE=2.2ms



= Fat and water IN PHASE

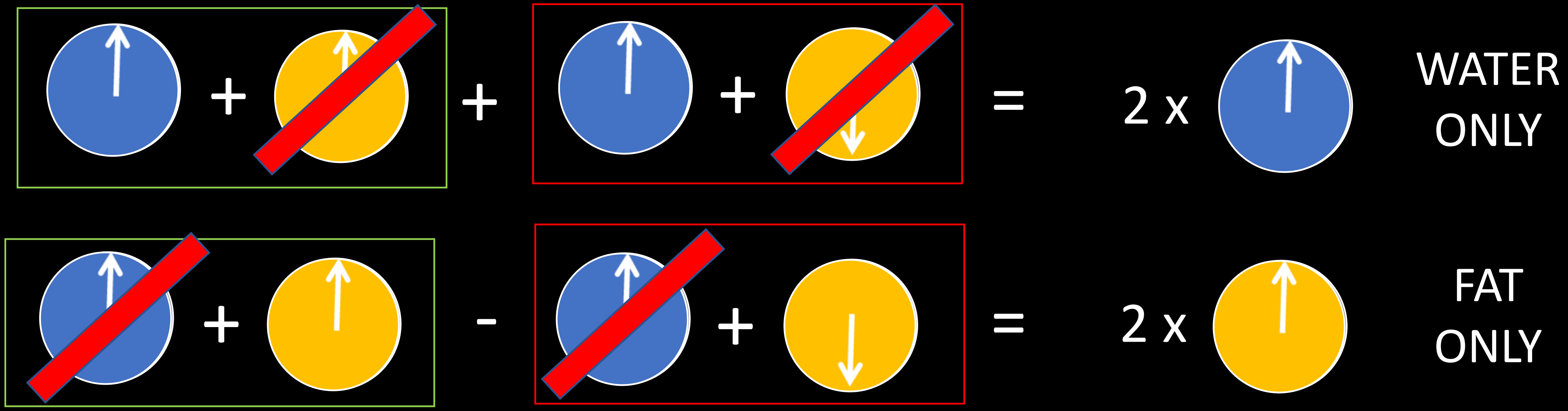
TE=4.4ms



= Fat and water OPPOSED PHASE

IQ Improvement #4: Dixon Fat Suppression

Dixon Method



TE=4.4ms

TE=2.2ms

IQ Improvement #4: Dixon Fat Suppression

So you get 4 image sets:

- In-phase
- Opposed-phase
- Water only
- Fat only

Non-fat suppressed image

Fat suppressed image

2 for the price of 1 !

IQ Improvement #4:
Dixon Fat Suppression

Pulse sequences

- Gradient echo (usually w 2 or 3 echoes)
  - Usually w/ 2 or 3 echoes
  - Liver scans
- Fast spin echo
  - 2 acquisitions w/ different echo times,
  - Double scan duration
  - MSK scans

- Might help for T1W post Gd near metal
- "Fat water swap" artifacts can sometimes occur

Glocker, et al "Correction of Fat-Water Swaps in Dixon MRI" MICCAI 2016

Quantitative Imaging #1: MR Elastography

Tissues stiffness has long been assessed superficially by palpation.

By attaching an external pneumatic "driver" to a patient, phase mapping methods can be used to map elastic properties (esp. shear stiffness).

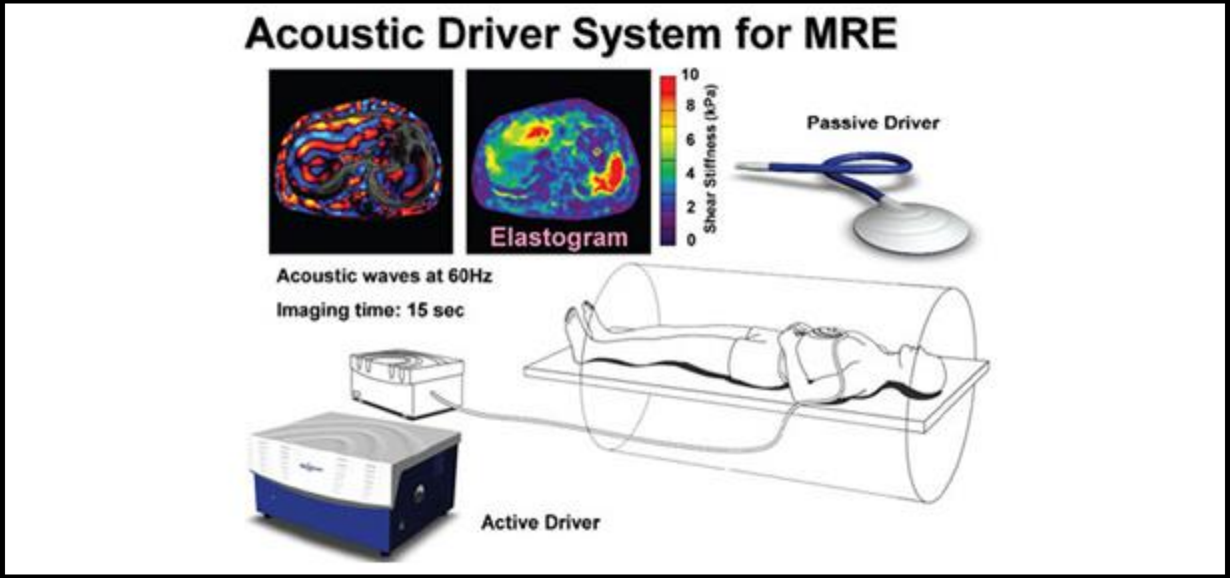
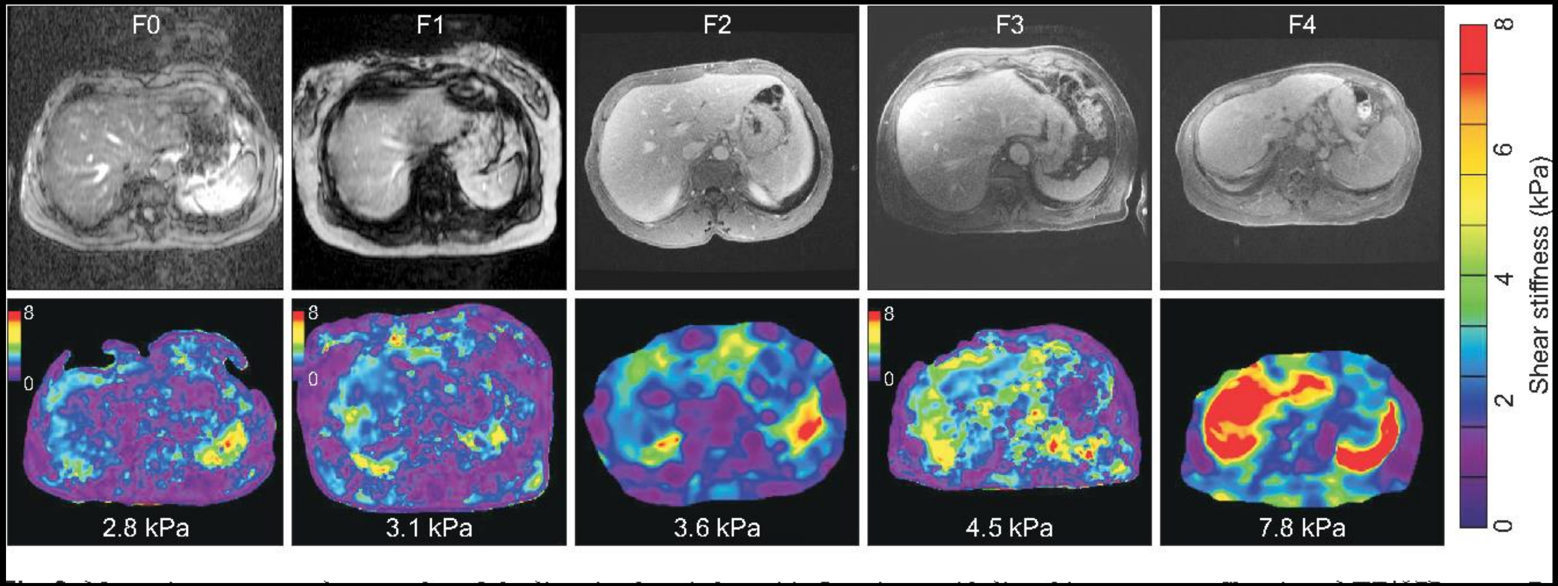


Image: https://blog.cincinnatichildrens.org/cms/radiology/mri-elastography

Quantitative Imaging #1: MR Elastography

5 2 9

Primary use: liver fibrosis assessment for chronic liver disease



Pulse sequence: Gradient echo, but increasingly EPI (for speed)

Troubleshooting tip: Check source images for signal dropout/poor mask

Tan, et al "**Magnetic Resonance Elastography and Other Magnetic Resonance Imaging Techniques in Chronic Liver Disease: Current Status and Future Directions" Gut and Liver, 2016**

Quantitative Imaging #2: T1 Mapping

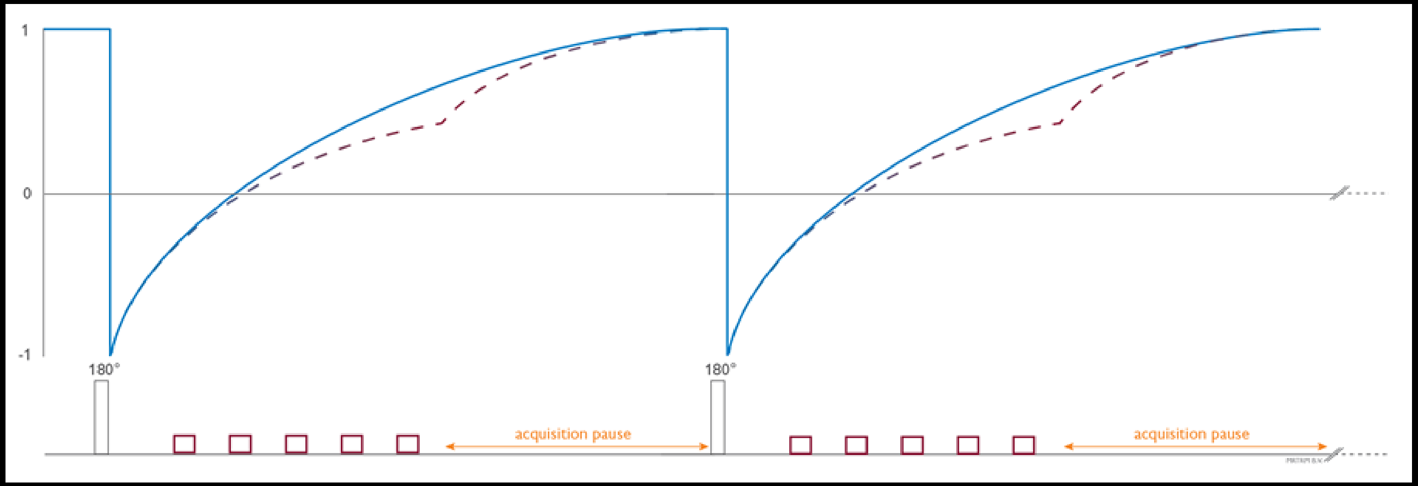
Clinical need:

- Diffuse myocardial fibrosis and global myocardial edema are an important part of a non-invasive diagnostic assessment of cardiac disease.
- Need to differentiate between myocardial infarction, focal scar, and fibrosis
- T1-weighted IR cardiac MR can miss diffuse myocardial fibrosis if myocardial signal is nulled (which looks like healthy tissue)
- Fast accurate mapping of T1 values would avoid this

Quantitative Imaging #2: T1 Mapping

Pulse sequence (Siemens and Philips)

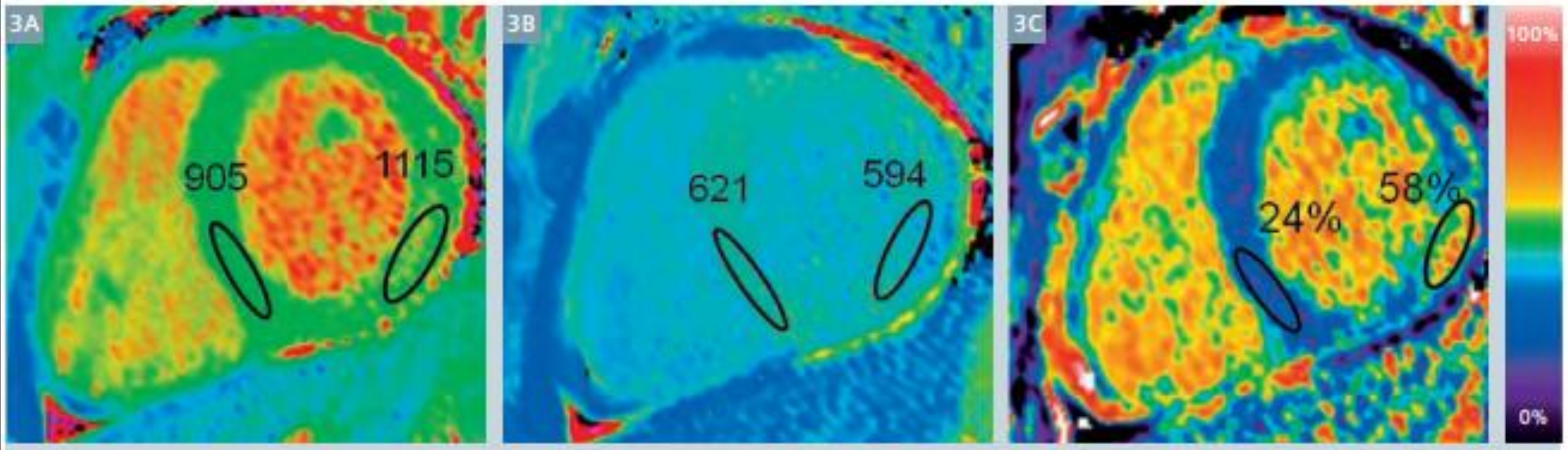
MOdified Look-Locker Inversion recovery (MOLLI): IR pulse followed by multiple small FA excitations and measurements during inversion recovery w/ cardiac triggering modifications.



Pre-Contrast Enhancement (CE): "native T1"

Post-CE "enhanced T1"

Quantitative Imaging #2: T1 Mapping



3 A patient with myocarditis. On the left side a native T1 map showing the higher T1 value in the inferolateral wall (1115 ms); in the centre, a post-contrast T1 map showing the shortened T1 value after contrast administration (594 ms); on the right side the derived ECV map showing higher value of ECV (58%) compared to remote myocardium.

- Post- used for late-Gd enhancement (LGE) assessment of non-enhancing scars
- Subtraction of pre- and post- w/ a hematocrit correction results in an estimated <u>extracellular volume (ECV) map</u> (probing the interstitium for edema, fibrosis, or amyloid).

Maestrini, et al "New Generation Cardiac Parametric Mapping: the Clinical Role of T1 and T2 Mapping", FLASH Magnetom 2013

Quantitative Imaging #2: T1 Mapping

GE uses a series of saturation recovery scans w/ a balanced SSFP readout to try to avoid underestimates of T1 inherent to MOLLI.

- Trade names:
  - Siemens (MyoMaps)
  - GE (SMART1 Map)
  - Philips (CardiacQuant)

5
2 9

Quantitative Imaging #3: Fat Fraction/T2* Mapping

Non-Alcoholic Fatty Liver Disease (NAFLD)

↓

Non-Alcoholic SteatoHepatitis (NASH)

↓

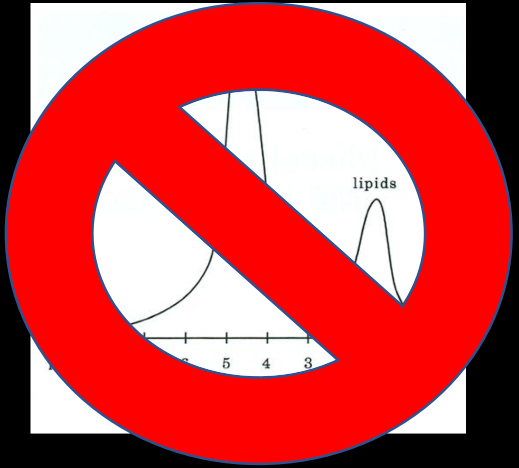
Cirrhosis

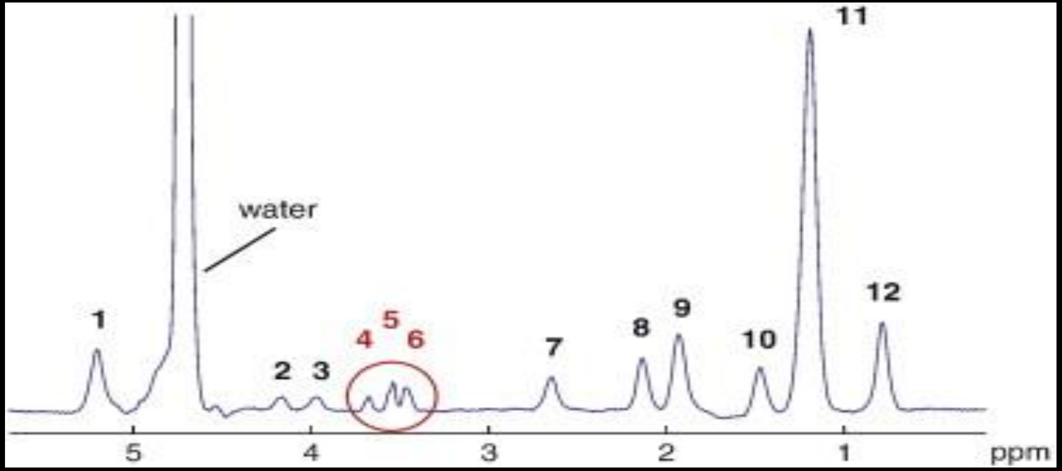
NAFLD is most common chronic liver disease in the US

Liver fat content is an early marker of development of NASH and cirrhosis

Quantitative Imaging #3: Fat Fraction/T2* Mapping

<u>Fat doesn't have 1 peak, it has MANY</u>





W/multipeak models (and multi-echo Dixon acquisitions) can obtain proton density fat fraction (PDFF) maps with accuracy of 1 or 2%!

At <u>least 6 echoes</u> for T2* map for correction of fat fraction data.

Quantitative Imaging #3: Fat Fraction/T2* Mapping

T2* maps can also be used to estimate iron content, critical to assessing hereditary HFE hemochromatosis, thalassemia, sickle cell anemia, aplastic anemia, and myelodysplasia.

Trade names: Siemens (MapIT), GE (Star-Map), Philips (StarQuant/CardiacQuant), Hitachi (T2*RelaxMap)

For detailed parameter/processing:

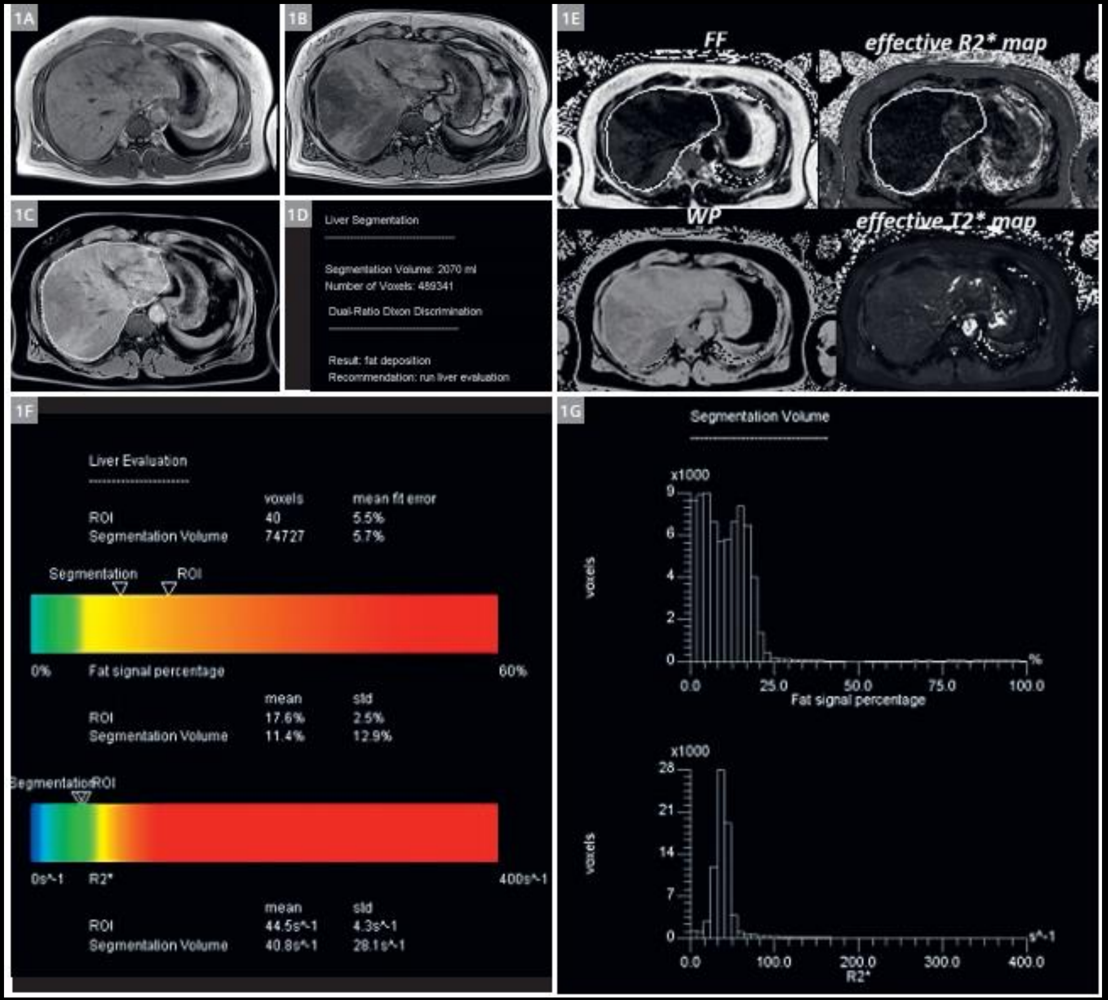
Henninger, et al "**Practical guide to quantification of hepatic iron with MRI" Euro. Radiol. 2020.**

Quantitative Imaging #3: Fat Fraction/T2* Mapping

Fat Fraction Mapping

Trade names:

- Siemens (LiverLab),
- GE (IDEAL IQ),
- Philips (mDIXON Quant)



LiverLab Screen w/ FF maps And T2* maps

Quantitative Imaging:
Quantitative Imaging Biomarkers Alliance (QIBA)

RSNA project to foster development and adoption of hardware and software standards for quantitative imaging

Scanning protocols are described in “profiles” for specific applications

<u>**MRI Profiles:**</u>

MR Dynamic Contrast Susceptibility (DSC)
MR Diffusion-Weighted Imaging (DWI)
MR Elastography of the Liver (MRE)
MR Dynamic Contrast Enhancement (DCE)/
MR DCE MRI Quantification
MR MSK cartilage for joint disease

Each of these needs advanced QC

Could this lead to more billable work?

Thank You and Stay Safe!

Washington University in St. Louis
School of Medicine

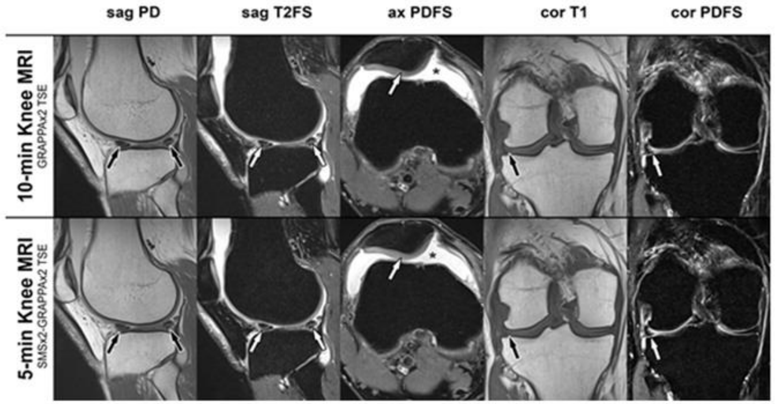
MIR Mallinckrodt Institute of Radiology

Barnes-Jewish Hospital
BJC HealthCare

Bonus Slides

Speed Improvement #1:
Simultaneous MultiSlice (SMS)

Five-minute Five-Sequence Knee MRI Using Combined Simultaneous Multisection and Parallel Imaging Acceleration: Comparison with 10-minute Parallel Imaging Knee MRI



Images from a 10-minute MRI protocol (top row) compared with a 5-minute SMS-PI (bottom row) in a patient with a tear of the anterior and posterior segments of the lateral meniscus (arrows), a joint effusion (∗), and intact patella cartilage (arrows).

- Combined simultaneous multisection (SMS) technique and parallel imaging (PI) enables fourfold-accelerated, 5-minute, five-sequence turbo spin-echo knee MRI at 1.5 and 3 T.
- Five-minute SMS-PI–accelerated and 10-minute PI-accelerated knee MRI had high reader agreements for detecting structural abnormalities at 1.5 T ($\kappa > 0.71$) and 3 T ($\kappa > 0.85$).
- Five-minute and 10-minute MRI protocols had similar diagnostic performances for internal derangement (AUCs >78%, $P > .32$).

Del Grande F et al. Published Online: April 6, 2021
https://doi.org/10.1148/radiol.2021203655
Radiology

5min session vs. 10min session

Similar diagnostic performance