

RF Pulse Design

Multi-dimensional Excitation I

M229 Advanced Topics in MRI

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Today's Topics

- Review of adiabatic pulses
- Applications of adiabatic pulses
- Small tip approximation
- Excitation k-space interpretation

Summary for Adiabatic Pulses

Adiabatic Pulses

- Flip Angle $\neq \int_0^T B_1(t) dt$
- Amplitude and frequency modulation
- Long duration (8-12 ms)
- High B1 amplitude ($>12 \mu\text{T}$)
- Generally NOT multi-purpose (inversion pulses cannot be used for refocusing, etc.)

Non-adiabatic Pulses

- Flip Angle $= \int_0^T B_1(t) dt$
- Amplitude modulation with constant carrier frequency
- Short duration (0.3-1 ms)
- Low B1 amplitude
- Generally multi-purpose (inversion pulses can be used for refocusing, etc.)

Bloch Equation

$$\frac{d\vec{M}}{dt} = \vec{M} \times \gamma \vec{B}_{eff}$$

Non-selective vs. Selective Excitation

$$\vec{B}_{eff} = \begin{pmatrix} B_1(t) \\ 0 \\ B_0 - \frac{\omega}{\gamma} \end{pmatrix} \quad \vec{B}_{eff} = \begin{pmatrix} B_1(t) \\ 0 \\ B_0 - \frac{\omega}{\gamma} + G_z z \end{pmatrix}$$

Adiabatic Pulses

$$\vec{B}_{eff} = \begin{pmatrix} A(t) \\ 0 \\ B_0 - \frac{\omega}{\gamma} + \frac{\omega_1(t)}{\gamma} \end{pmatrix}$$

To the board ...

```

%%% User inputs:
mu = 5;      % Phase modulation parameter [dimensionless]
beta1 = 672; % Frequency modulation parameter [rad/s]
pulseWidth = 10.24; % RF pulse duration [ms]
A0 = 0.12;   % Peak B1 amplitude [Gauss].

%%%%%%%%

nSamples = 512; % number of samples in the RF pulse
dt = pulseWidth/nSamples/1000; % time step, [seconds]
tim_sech = linspace(-pulseWidth/2,pulseWidth/2,nSamples)./1000';
% time scale to calculate the RF waveforms in seconds.

% Amplitude modulation function B1(t):
B1 = A0.* sech(beta1.*tim_sech);

% Carrier frequency modulation function w(t):
w = -mu.*beta1.*tanh(beta1.*tim_sech)./(2*pi);
% The 2*PI scaling factor at the end converts the unit from rad/s to Hz

% Phase modulation function phi(t):
phi = mu .* log(sech(beta1.*tim_sech));

% Put together complex RF pulse waveform:
rf_pulse = B1 .* exp(1i.*phi);

% Generate a time scale for the Bloch simulation:
tim_bloch = [0:(nSamples-1)]*dt;

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Applications of Adiabatic Pulses

Adiabatic Pulses

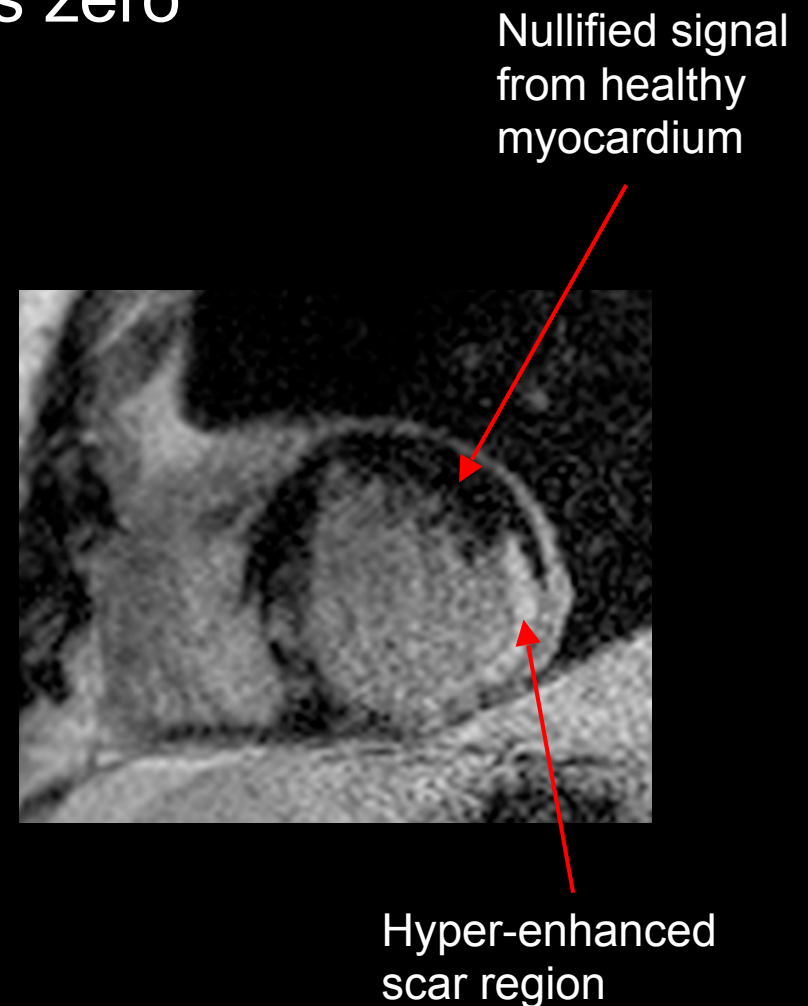
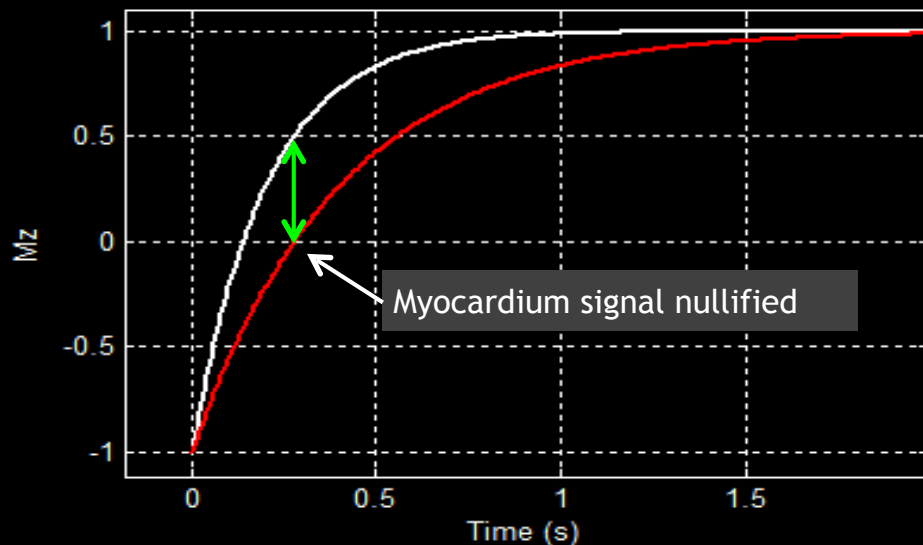
- Fat suppression (STIR)
- CSF suppression (FLAIR)
- Myocardium suppression in cardiac scar imaging (LGE)
- Black blood cardiac imaging (DIR TSE)
- T1 Mapping

Late Gadolinium Enhancement (LGE)

- Gold standard for detection of scar/myocardial fibrosis
- Spoiled gradient echo (SPGR) sequence with an inversion pulse (inversion recovery SPGR)
 - Inversion pulse is usually hyperbolic secant pulse
 - Healthy myocardium is nulled with the inversion pulse
 - Scar tissue (which has shorter T1 than healthy tissue) appear bright

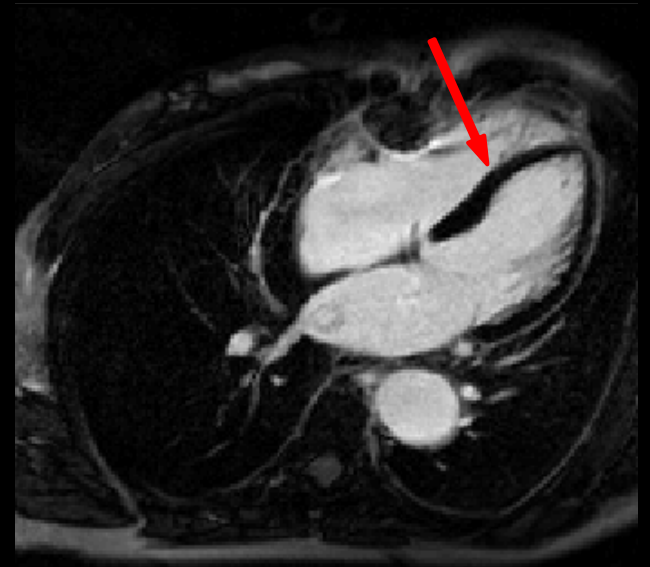
- The conventional LGE sequence uses an RF-spoiled gradient echo (FLASH) readout with an inversion recovery (IR) pulse as a preparation pulse
- The readout is acquired at a time after inversion at which the healthy myocardium signal reaches zero

Inversion recovery curves of postcontrast scar (white) and myocardium (red)

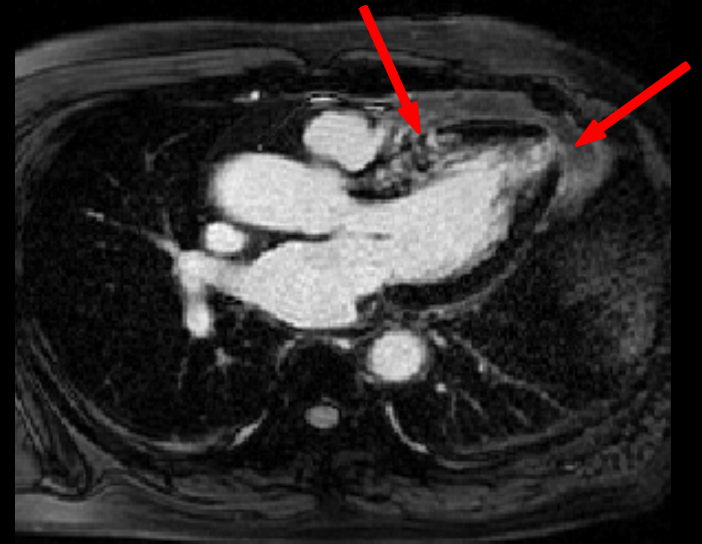
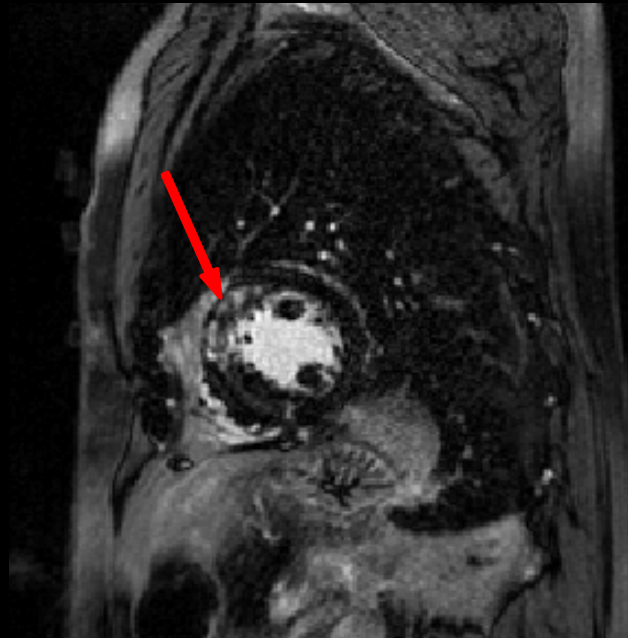


Clinical Example

Patient with healthy myocardium



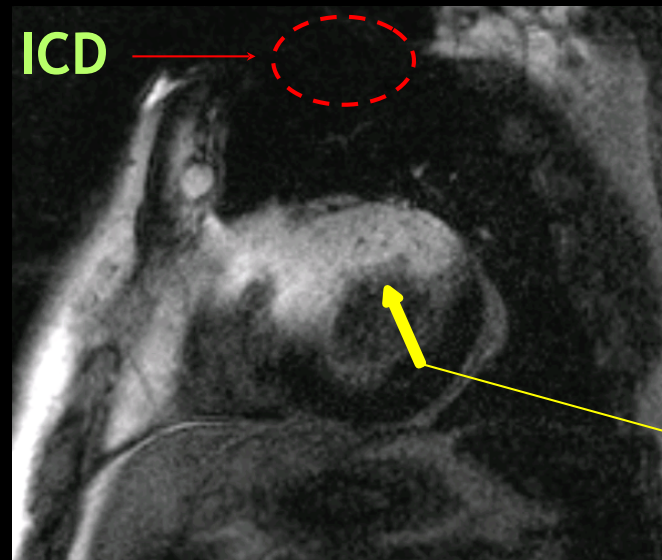
Patient with scar tissue



Clinical Example

Late Gadolinium Enhancement (LGE) in patients with implantable cardiac devices

- Presence of an implantable cardiac device in the patients produces an interesting off-resonance artifact



**Hyper-
intensity
Artifacts**

Hyper-intensity artifact

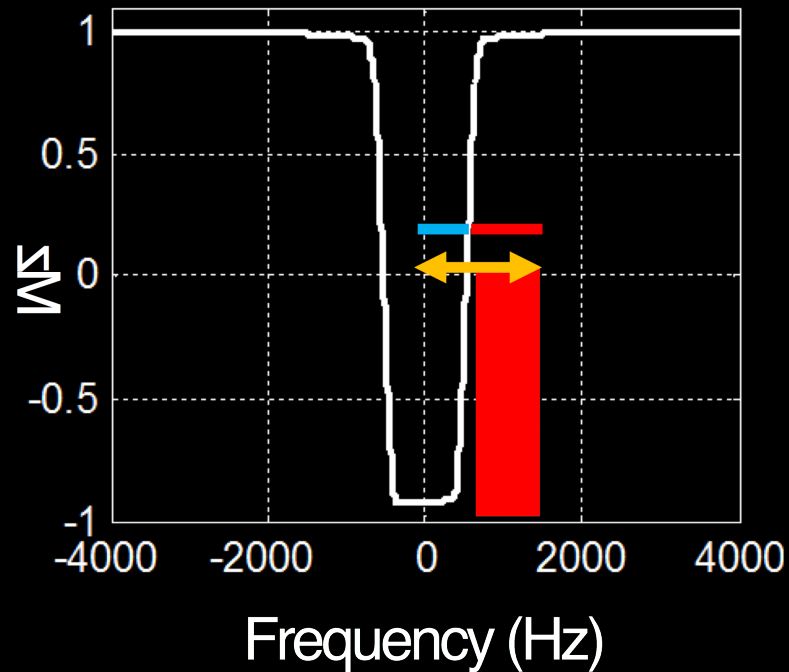


**Conventional IR
LGE Image**



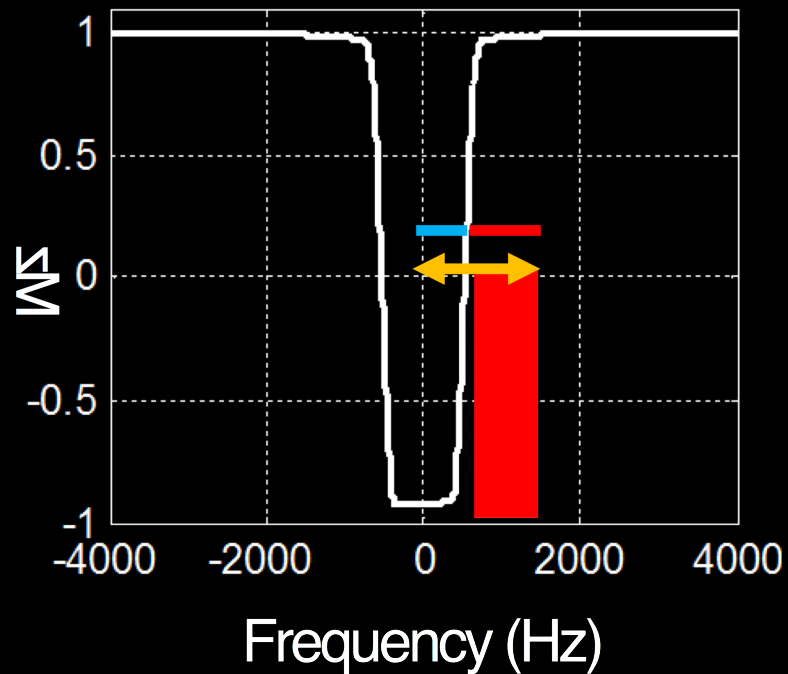
**Conventional IR
LGE Image**

Cause of Artifact

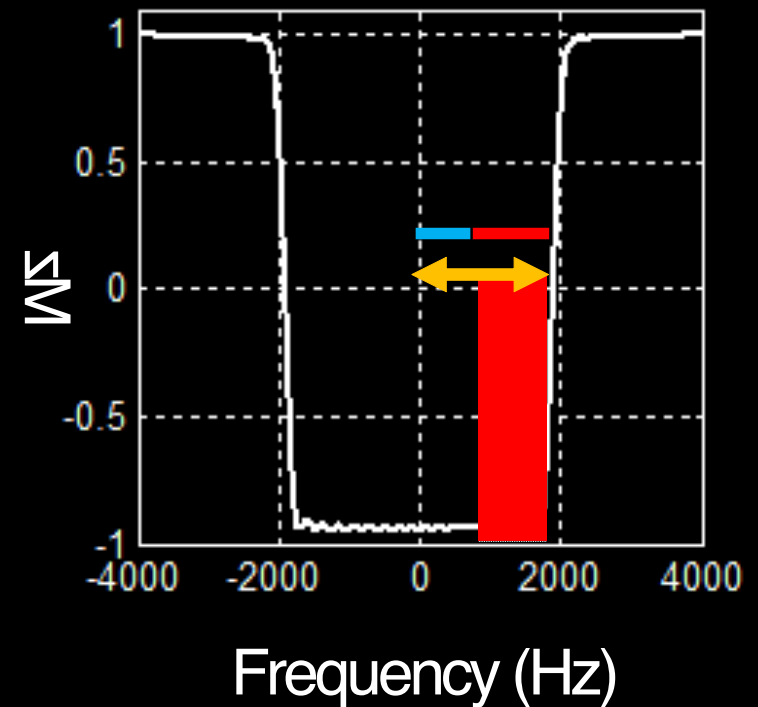


Longitudinal magnetization produced
by conventional IR pulse
BW = 1.1 kHz

Solution: Increase Bandwidth of Inversion Pulse

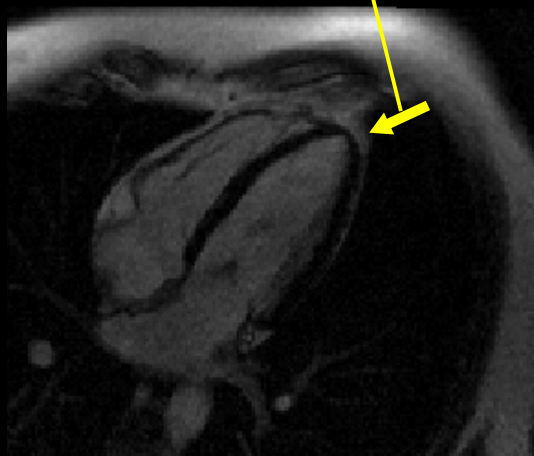


Longitudinal magnetization produced by
conventional IR pulse
BW = 1.1 kHz



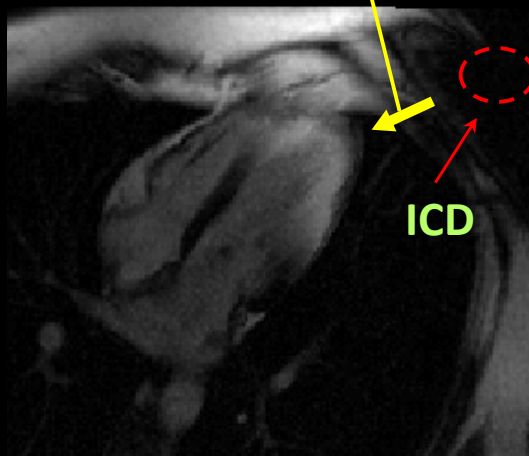
Longitudinal magnetization produced
by wideband IR pulse
BW = 3.8 kHz

No artifact (no ICD)



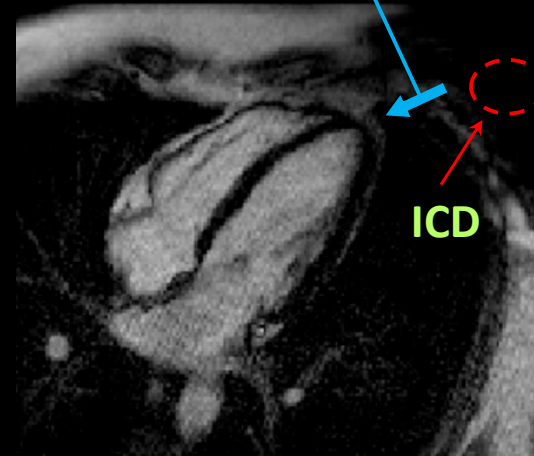
**Conventional IR
LGE Image**

Hyper-intensity artifact



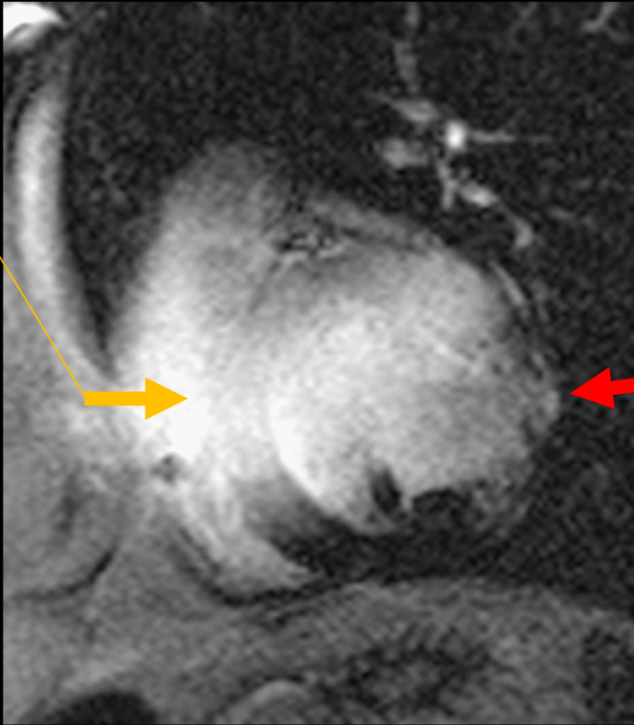
**Conventional IR
LGE Image**

Hyper-intensity artifact corrected



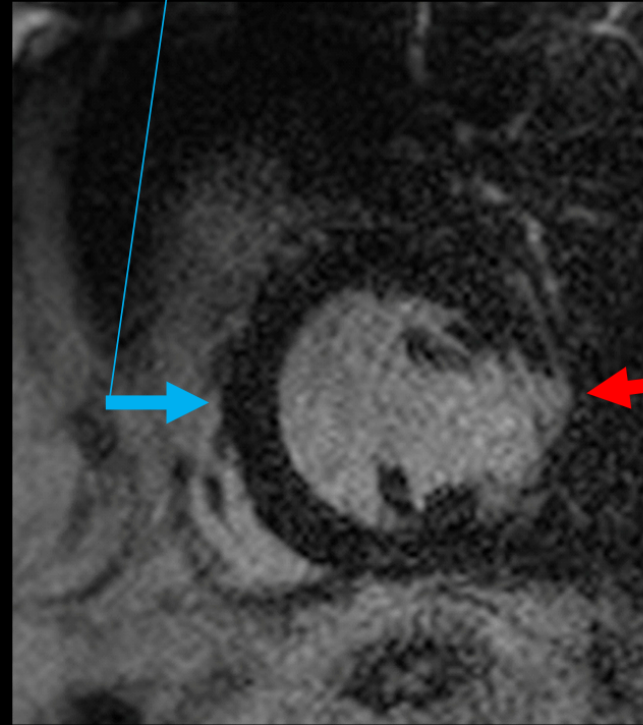
**Wideband IR
LGE Image**

Hyper-intensity artifacts



Antero-lateral scar difficult to diagnose

Artifacts eliminated



Antero-lateral scar clearly visible

Small Tip Approximation

Bloch Equation (at on-resonance)

$$\frac{d\vec{M}_{rot}}{dt} = \vec{M}_{rot} \times \gamma \vec{B}_{eff}$$

where $\vec{B}_{eff} = \begin{pmatrix} B_1(t) \\ 0 \\ \cancel{B_0} \frac{\omega}{\gamma} + G_z z \end{pmatrix}$

When we simplify the cross product,

$$\frac{d\vec{M}}{dt} = \begin{pmatrix} 0 & \omega(z) & 0 \\ -\omega(z) & 0 & \omega_1(t) \\ 0 & -\omega_1(t) & 0 \end{pmatrix} \vec{M}$$

$$\omega(z) = \gamma G_z z \quad \omega_1(t) = \gamma B_1(t)$$

Small Tip Approximation

$$\frac{d\vec{M}}{dt} = \begin{pmatrix} 0 & \omega(z) & 0 \\ -\omega(z) & 0 & \omega_1(t) \\ 0 & -\omega_1(t) & 0 \end{pmatrix} \vec{M}$$

$M_z \approx M_0$ small tip-angle approximation

$$\sin \theta \approx \theta$$

$$\cos \theta \approx 1$$

$$M_z \approx M_0 \rightarrow \text{constant}$$

$$\left. \begin{array}{l} \sin \theta \approx \theta \\ \cos \theta \approx 1 \\ M_z \approx M_0 \rightarrow \text{constant} \end{array} \right\} \frac{dM_z}{dt} = 0$$

$$\frac{dM_{xy}}{dt} = -i\gamma G_z z M_{xy} + i\gamma B_1(t) M_0$$

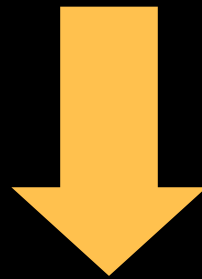
$$M_{xy} = M_x + iM_y$$

First order linear differential equation. Easily solved.

$$\frac{dM_{xy}}{dt} = -i\gamma G_z z M_{xy} + i\gamma B_1(t) M_0$$

Solving a first order linear differential equation:

$$M_{xy}(t, z) = i\gamma M_0 \int_0^t B_1(s) e^{-i\gamma G_z z \cdot (t-s)} ds$$

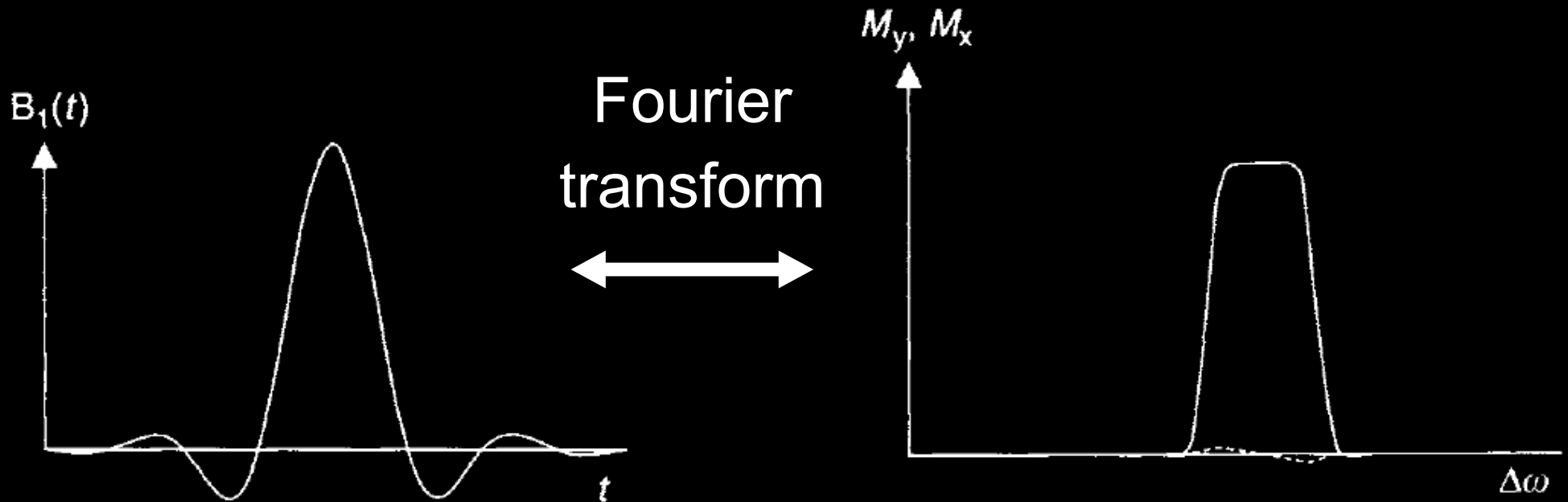


$$M_r(\tau, z) = iM_0 e^{-i\omega(z)\tau/2} \cdot \mathcal{FT}_{1D}\{\omega_1(t + \frac{\tau}{2})\} \Big|_{f=-(\gamma/2\pi)G_z z}$$

(See the note for complete derivation)

To the board ...

Small Tip Approximation

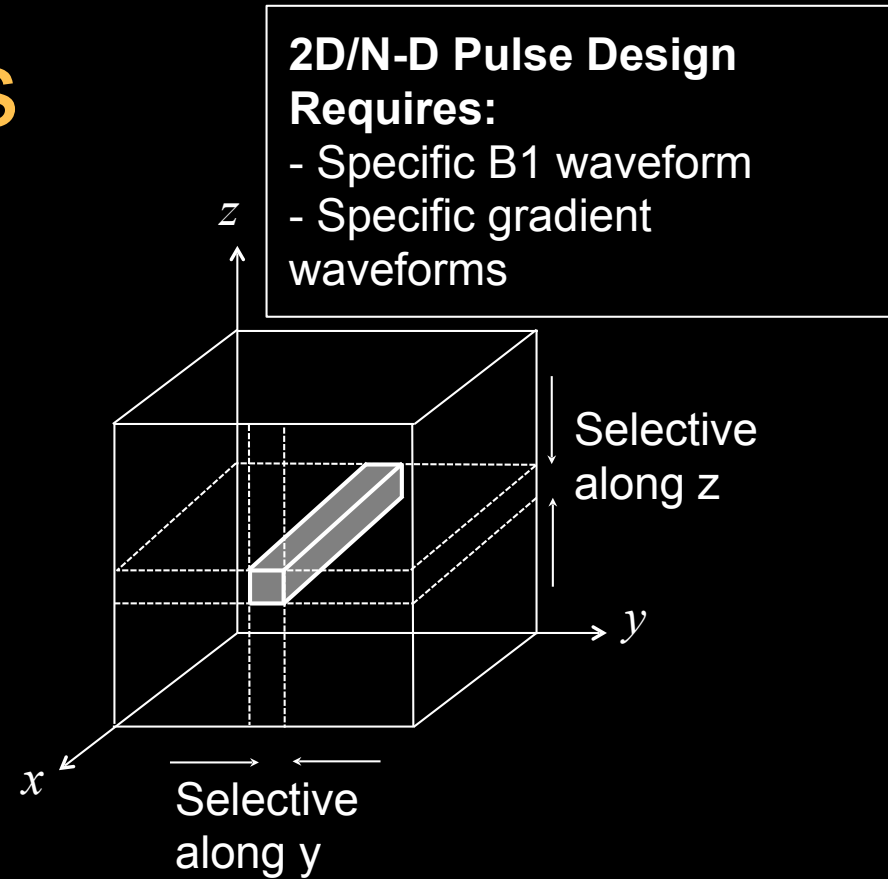
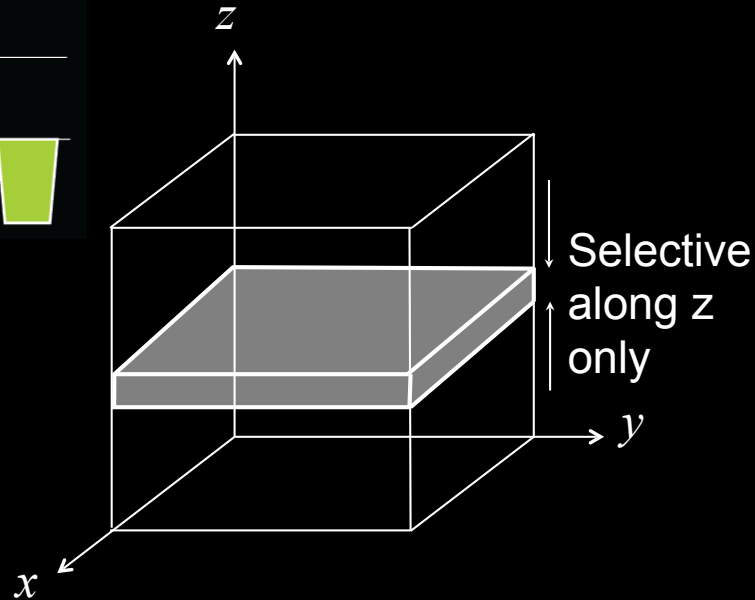


- For small tip angles, “the slice or frequency profile is well approximated by the Fourier transform of $B_1(t)$ ”
- The approximation works surprisingly well even for flip angles up to 90°

What is Multi-Dimensional Excitation?

Multi-dimensional excitation occurs when using multi-dimensional RF pulses in MRI/NMR, i.e. 2D or 3D RF pulses

1D vs. N-D RF Pulses



- 1D pulses are selective along 1 dimension, typically the slice select dimension
- 2D pulses are selective along 2 dimensions
 - So, a 2D pulse would select a long cylinder instead of a slice
 - The shape of the cross section depends on the 2D RF pulse

Thank You!

- Further reading
 - Read “Spatial-Spectral Pulses” p.153-163
- Acknowledgments
 - John Pauly’s EE469b (RF Pulse Design for MRI)
 - Shams Rashid, Ph.D.

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