Diffusion Journal Club 3: Motion-related Signal Behavior and Motion-Compensated Gradients

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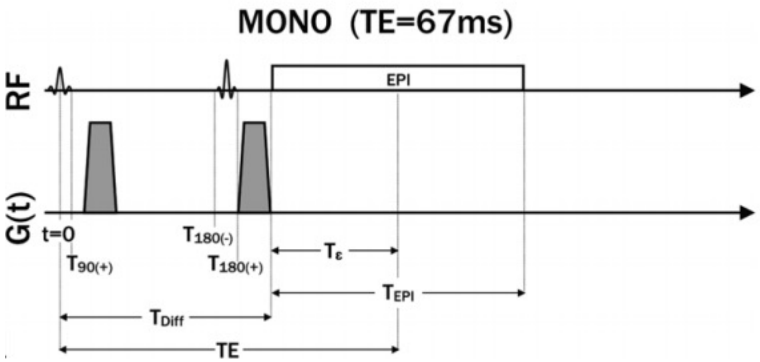
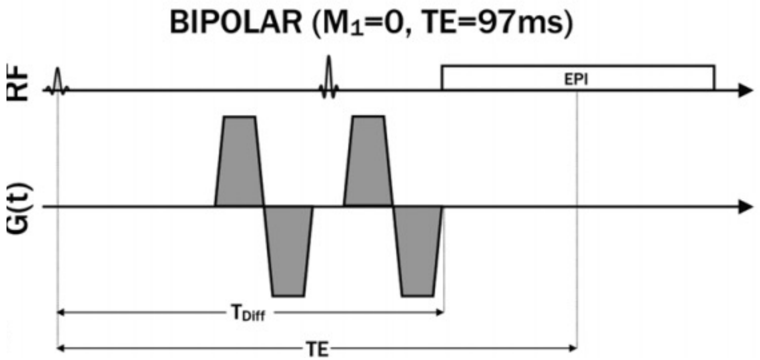
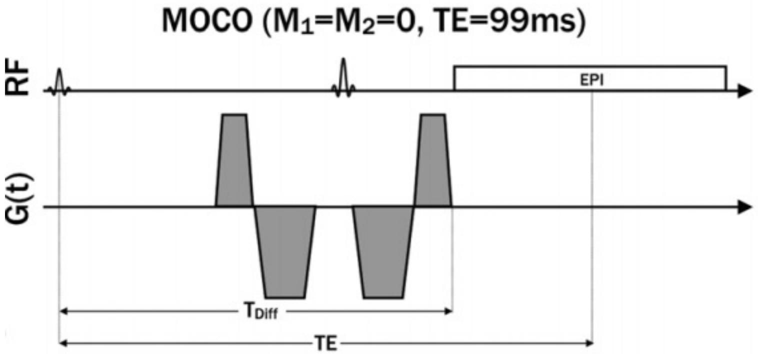
Diffusion encoding gradient

Monopolar:
Clinical convention
Sensitivity to cardiac & respiratory bulk motion --> signal loss
Cardiac & respiratory gating with limited success

Motion-compensated (MOCO):
Velocity and acceleration-compensated waveforms (M_1=M_2=0) → improve dramatically the bulk motion robustness of cardiac DWI
Long TE → more on optimization strategies later







Velocity compensated diffusion-encoding gradient waveforms (M_1=0) have been implemented in the liver and demonstrate improved ADC measurement reproducibility without respiratory or cardiac triggering

Moments of the gradients:
→ more on signal modeling

$$M_0(t) \equiv \int_0^t dt G_x(t)$$

$$M_1(t) \equiv \int_0^t dt G_x(t) t$$

$$M_2(t) \equiv \int_0^t dt G_x(t) t^2$$

Motion Simulation

- Brownian motion
- Brownian motion + Coherent, time-invariant motion
- Brownian motion + Coherent, time-variant motion
- Brownian motion + Incoherent (spread of velocities), time-invariant motion
- Brownian motion + Incoherent, time-variant motion
- Coherent, time-invariant motion
- Coherent, time-variant motion
- Incoherent, time-invariant motion
- Incoherent, time-variant motion

Signal Model from Moving Molecule

- Single spin's frequency proportional to longitudinal magnetic field strength: $$\omega(x,t) = \gamma(\Delta B_0 + G_x(t)x)$$
- For a moving molecule, position as a function of time: $$\omega(x,t) = \gamma(\Delta B_0 + G_x(t)x(t))$$
- Taylor expansion of a particle's position: $$x(t) = x_0 + vt + a\frac{t^2}{2} + H.O.T.$$
- Frequency written in terms of initial position, velocity, acceleration: $$\omega(\vec{r},t) = \gamma(\Delta B_0 + G_x(t)(x_0 + vt + a\frac{t^2}{2}))$$
- After tipping a spin at t=0, phase accrued over t is integral of frequency: $$\phi(x,t) = \gamma \int^t dt(\Delta B_0 + G_x(t)(x_0 + vt + a\frac{t^2}{2}))$$
- Separable integral: $$\phi(x,t) = \gamma\Delta B_0 \int_0^t dt + \gamma x_0 \int_0^t dtG_x(t) + \gamma v \int_0^t dtG_x(t)t + \gamma a \int_0^t dtG_x(t)\frac{t^2}{2}$$
- Moments of gradients defined: $$M_0(t) \equiv \int_0^t dtG_x(t)$$ $$M_1(t) \equiv \int_0^t dtG_x(t)t$$ $$M_2(t) \equiv \int_0^t dtG_x(t)t^2$$
- Simplified phase equation: $$\phi(x,t) = \gamma(\Delta B_0 t + x_0 M_0(t) + \gamma v M_1(t) + \gamma\frac{a}{2}M_2(t))$$

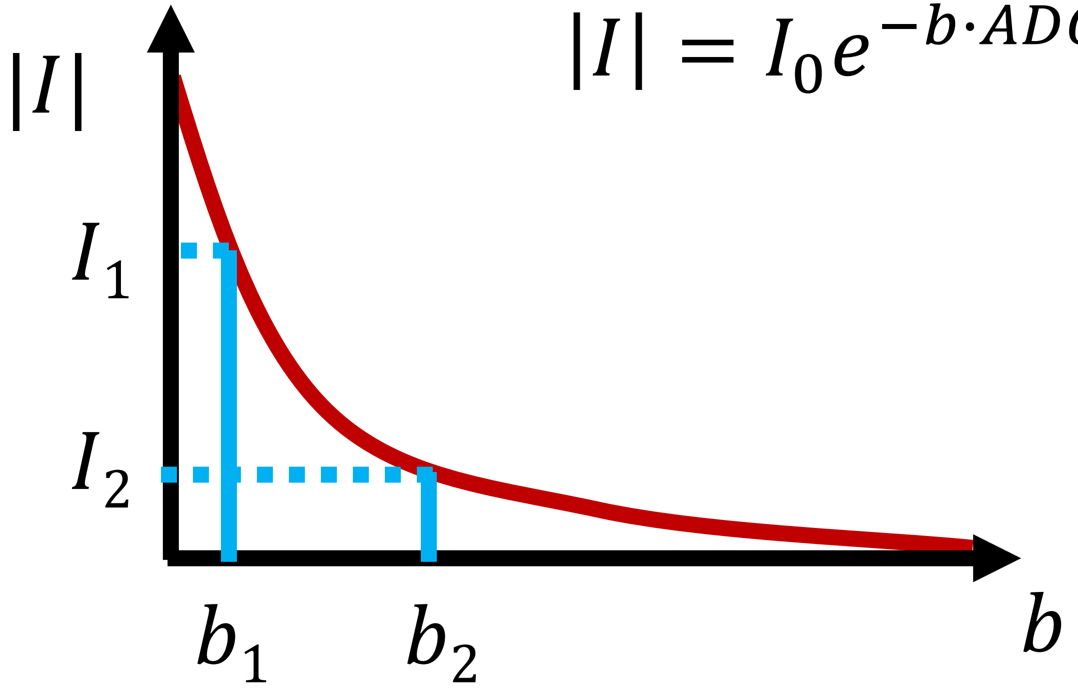
Motion-related Signal Loss

- When and why is monopolar gradient waveforms insufficient?

$$\phi(x,t) = \gamma(\cancel{\Delta B_0} t + x_0 M_0(t) + \gamma \underbrace{v}_{v(x,t)} M_1(t) + \gamma \frac{\overset{a(x,t)}{\overbrace{a}}}{2} M_2(t))$$

- Leads to bias in ADC calculation

$$|I| = I_0 e^{-b \cdot ADC}$$



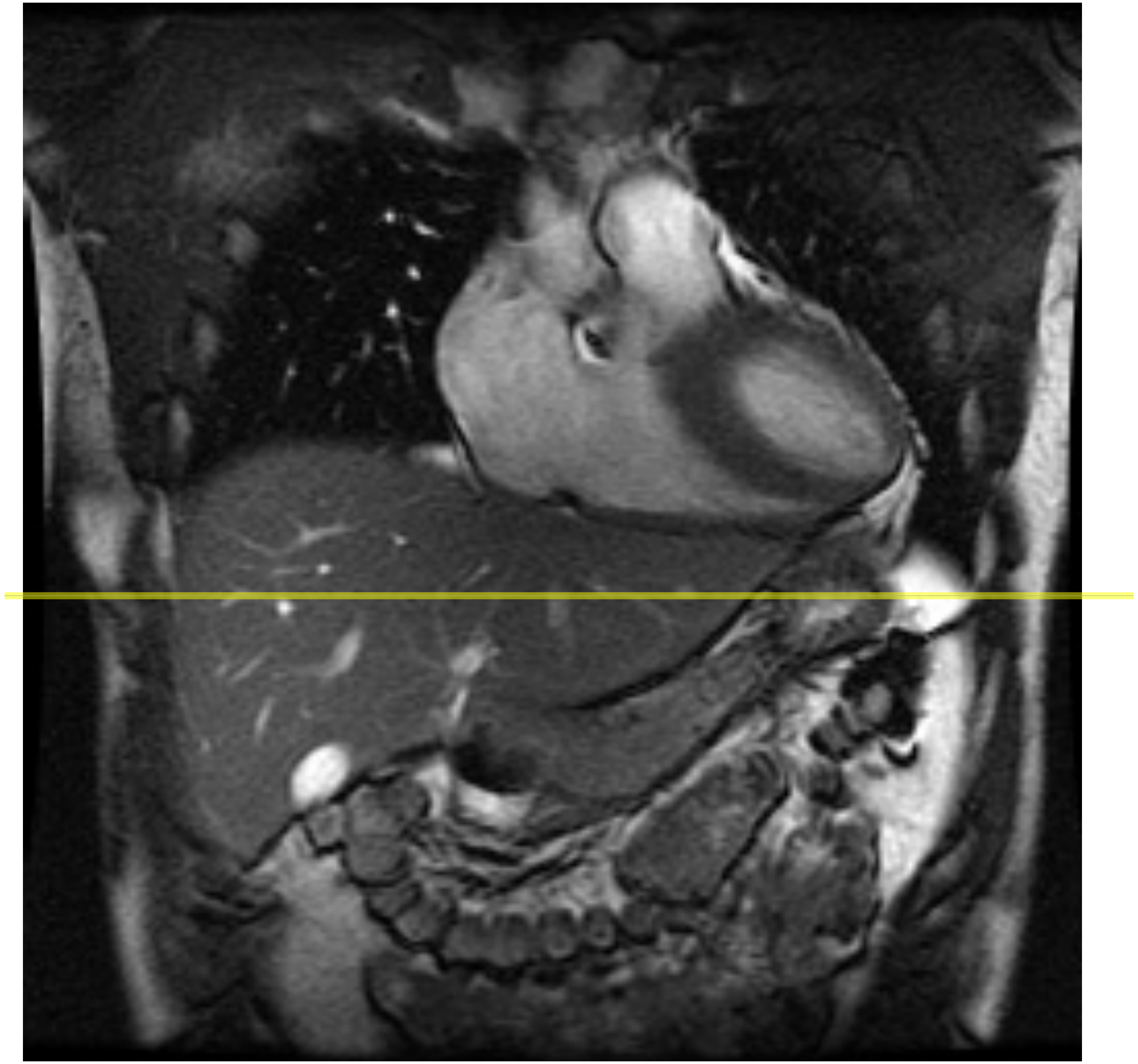
ADC using two points on the curve:

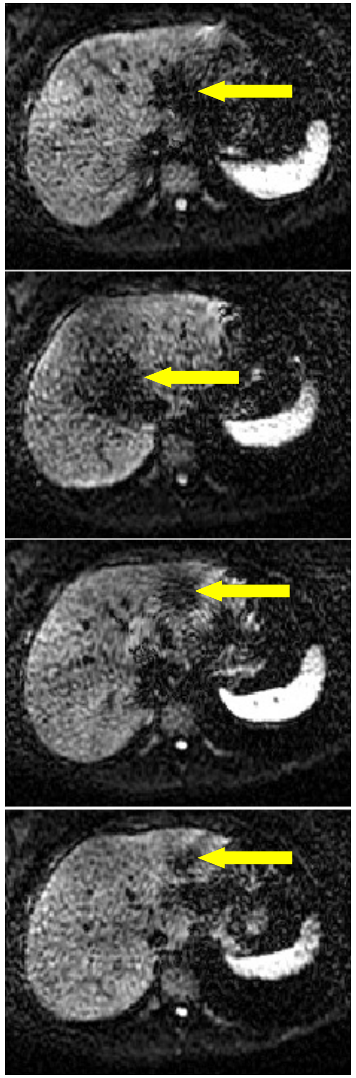
$$I_1 = image\ at\ b_1 (e.g.\ 0 \frac{s}{mm^2})$$

$$I_2 = image\ at\ b_2\ (e.g.\ 1000 \frac{s}{mm^2})$$

$$ADC = \frac{1}{b_2 - b_1} \ln \frac{I_1}{I_2}$$

Signal Voids in DWI

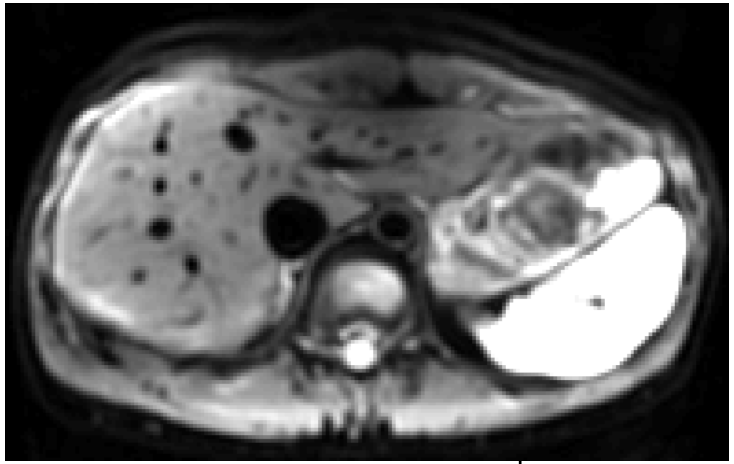




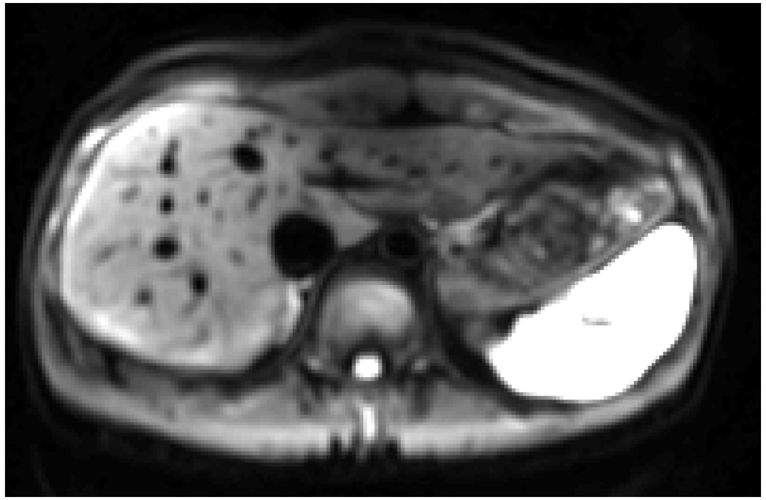
DW images at different points in cardiac cycle

Clinical Liver DWI: *Monopolar DW Waveform*

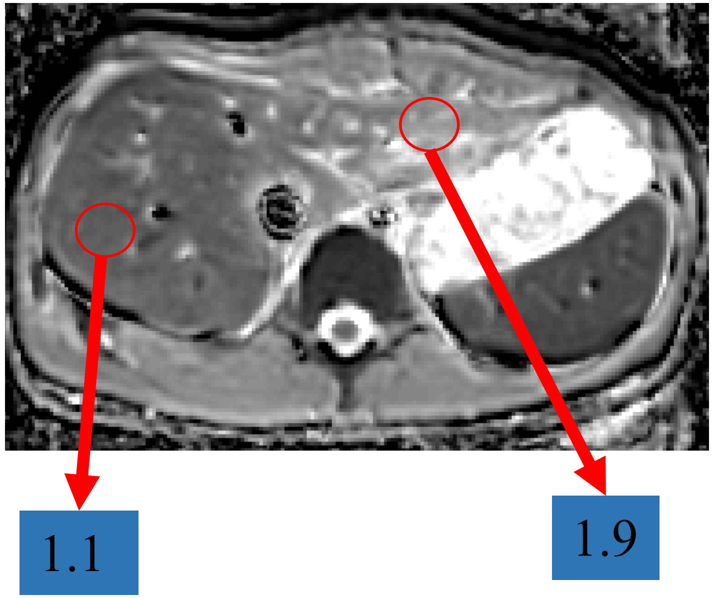
b = 50 s/mm^2



b = 500 s/mm^2



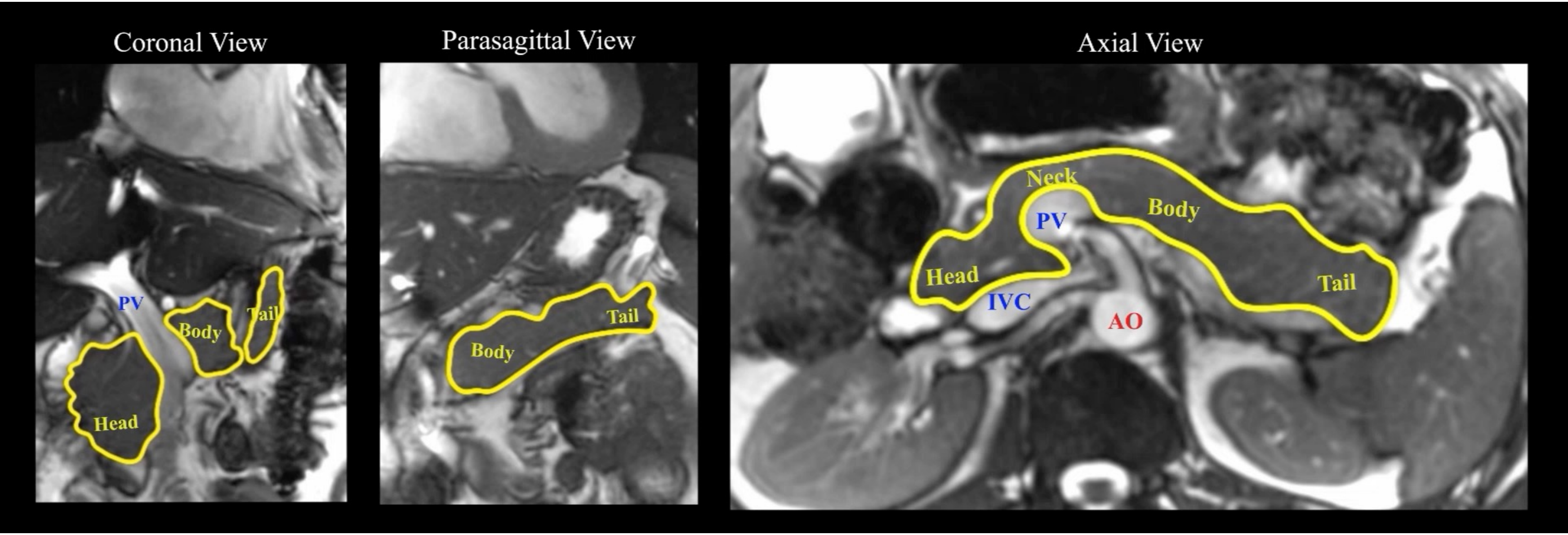
ADC map ($\times 10^{-3}$ mm^2/s)

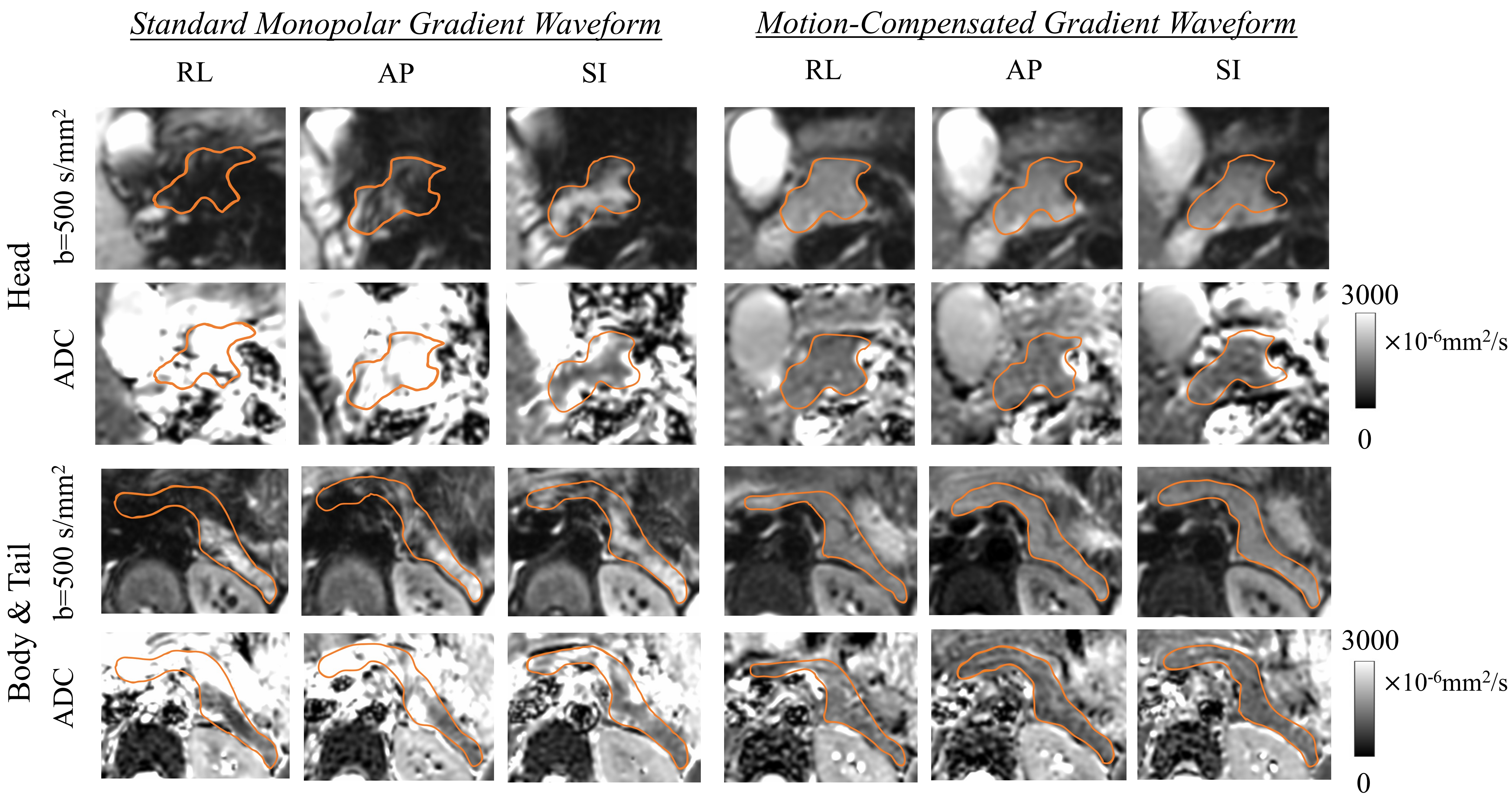


Diffusion Directions	3	
b values (s/mm^2)	50	500
# of repetitions / direction	4	8
Slice thickness	6 mm	
Fat Sat	SS excitation	
Gating	RT	

Bias in quantitative diffusion measurements

Kwee, TC., *MAGMA*, 2009. Saito, K., *World journal of radiology,* 2016.


Coronal View
PV
Body
Tail
Head
Parasagittal View
Body
Tail
Axial View
Neck
PV
Body
Head
IVC
AO
Tail

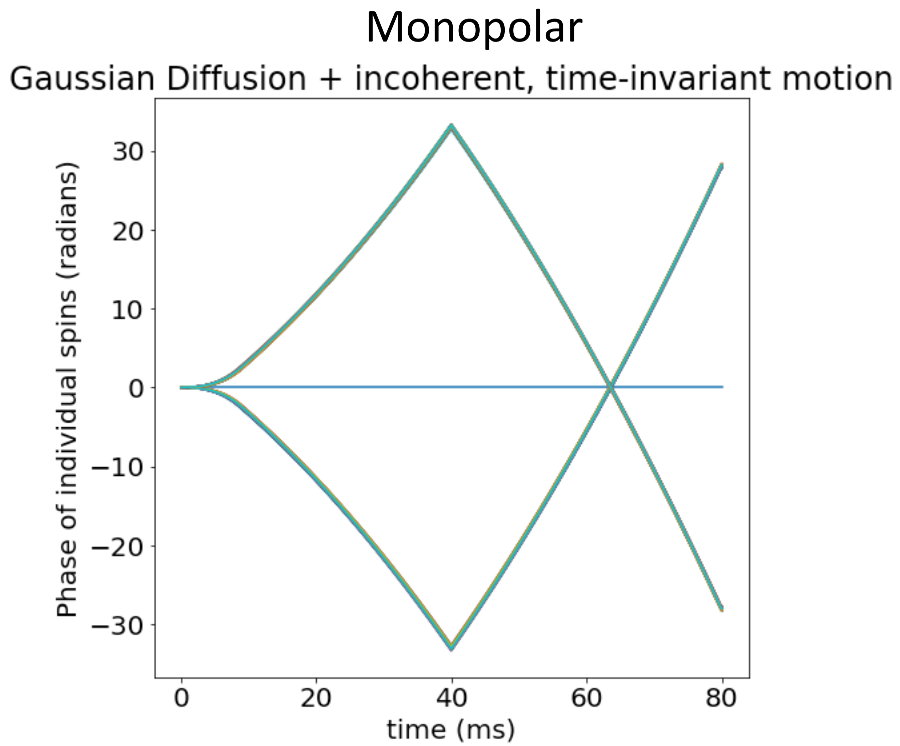


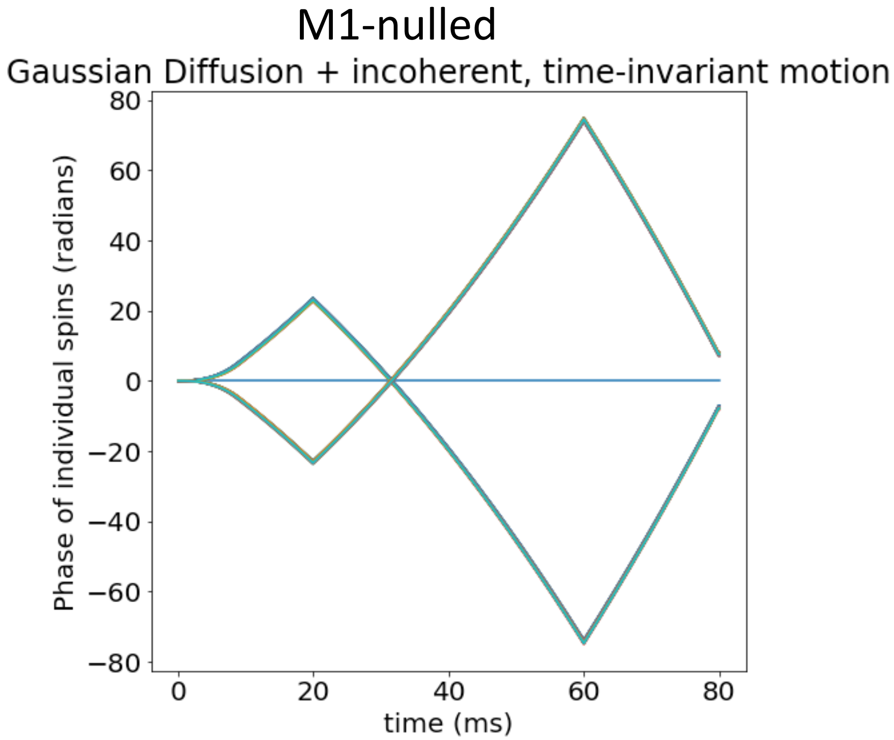
Standard Monopolar Gradient Waveform
Motion-Compensated Gradient Waveform
RL
AP
SI
RL
AP
SI
Head
b=500 s/mm2
ADC
3000
×10-6mm2/s
0
Body & Tail
b=500 s/mm2
ADC
3000
×10-6mm2/s
0

Discussions from simulations

- When and how is a monopolar gradient waveform insufficient?
- What issues can M1/M2-nulled gradients address?

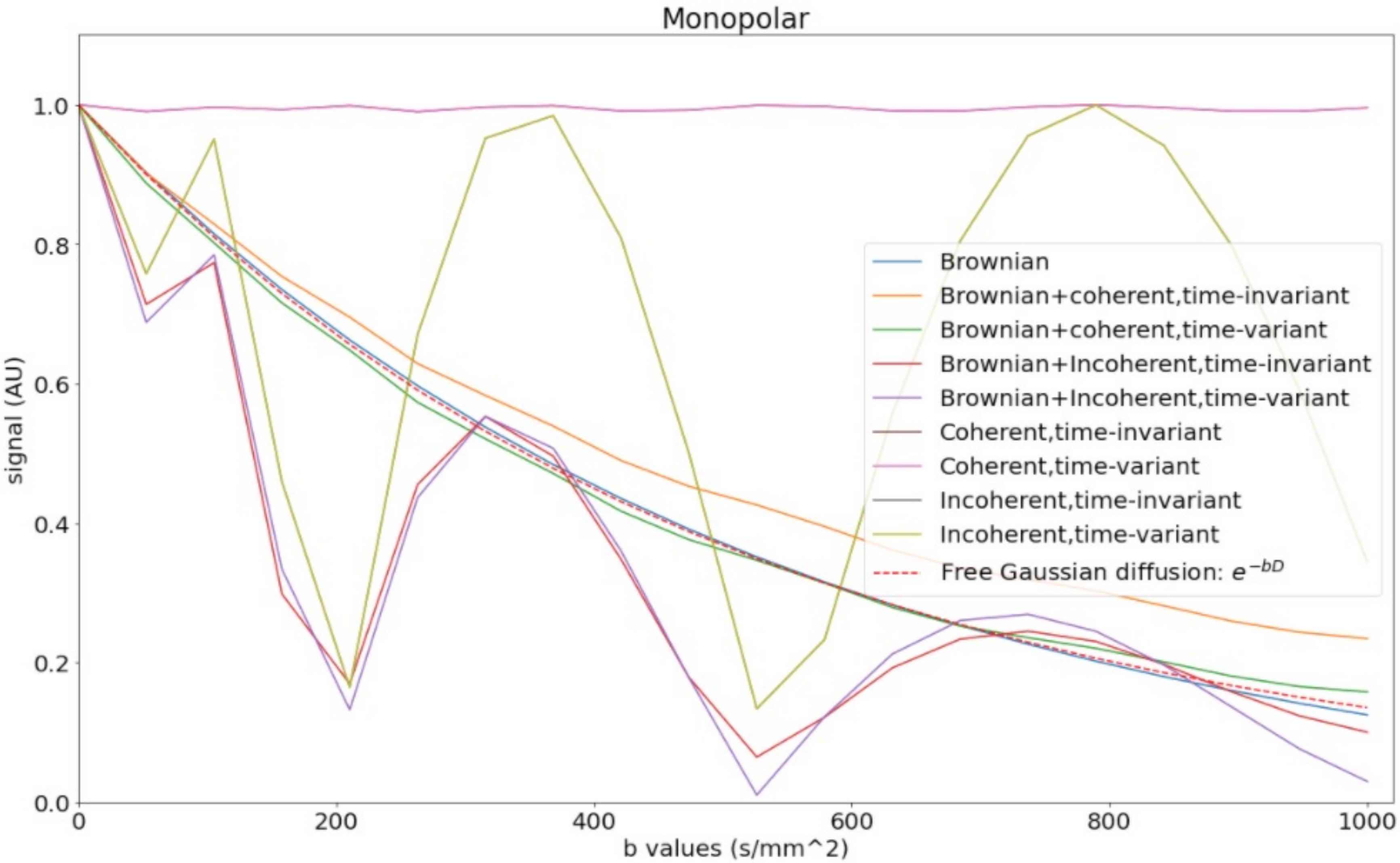
– time-invariant velocities (2), no acceleration





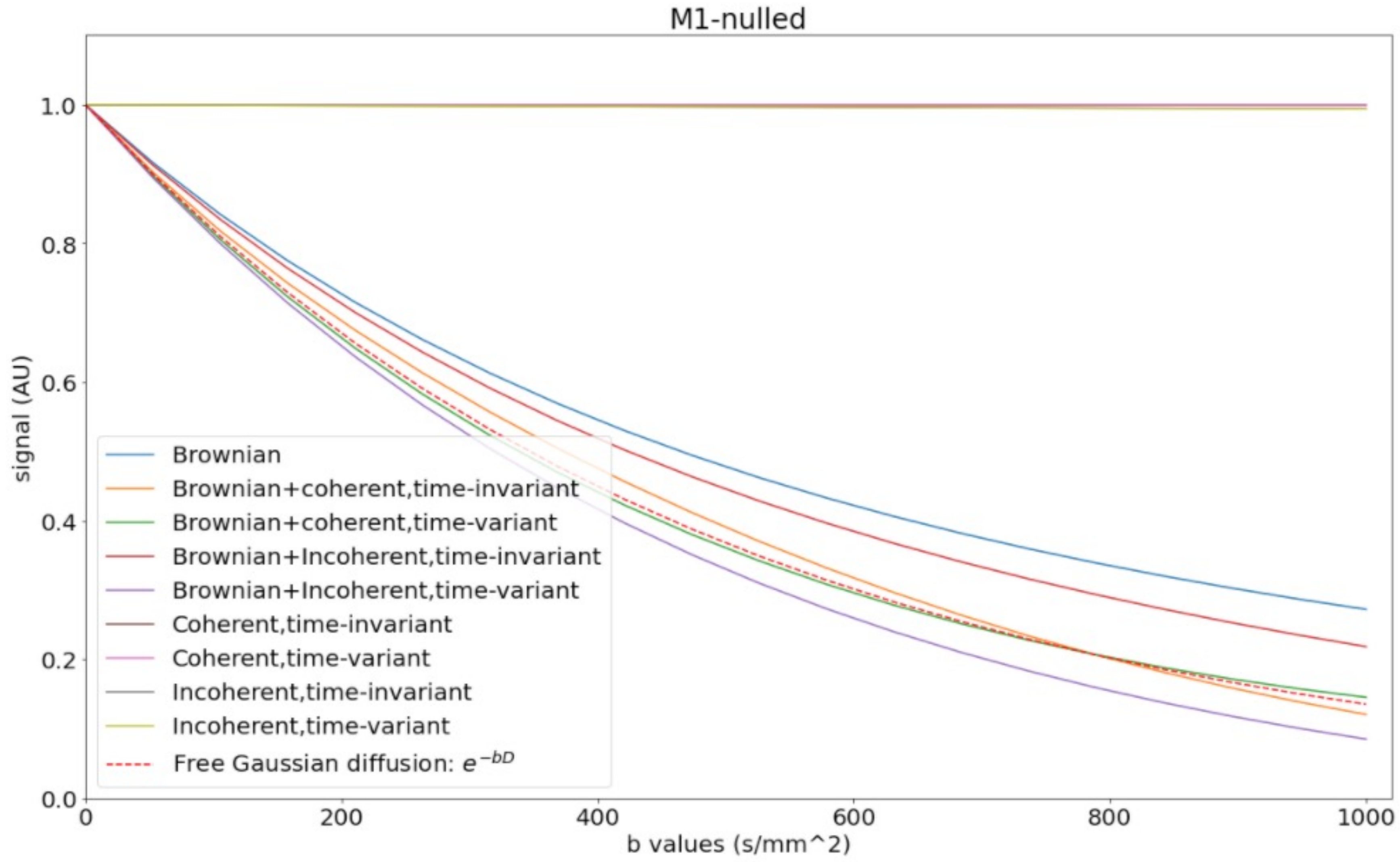
Discussions from simulations – time-invariant velocities, no acceleration

- When and why is a monopolar gradient waveform insufficient?
- When does a monopolar still do well?



Discussions from simulations – time-invariant velocities, no acceleration

- What issues can M1-nulled gradients address?

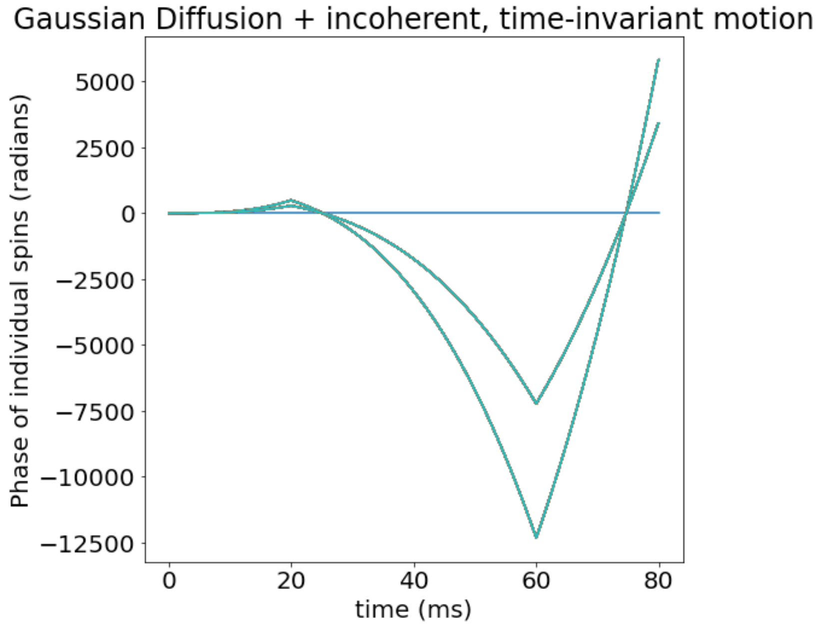


Discussions from simulations

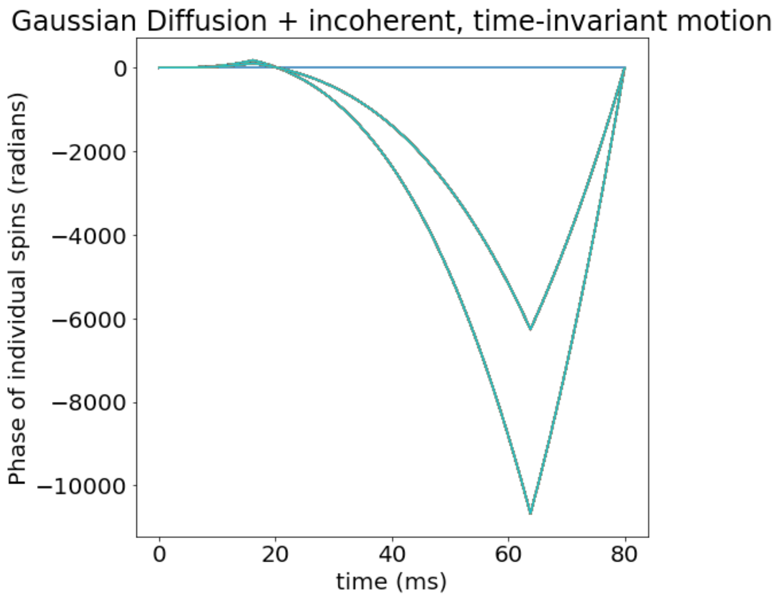
- When and how is a monopolar gradient waveform insufficient?
- What issues can M1/M2-nulled gradients address?

– time-invariant accelerations (2), no initial velocity

M1-nulled

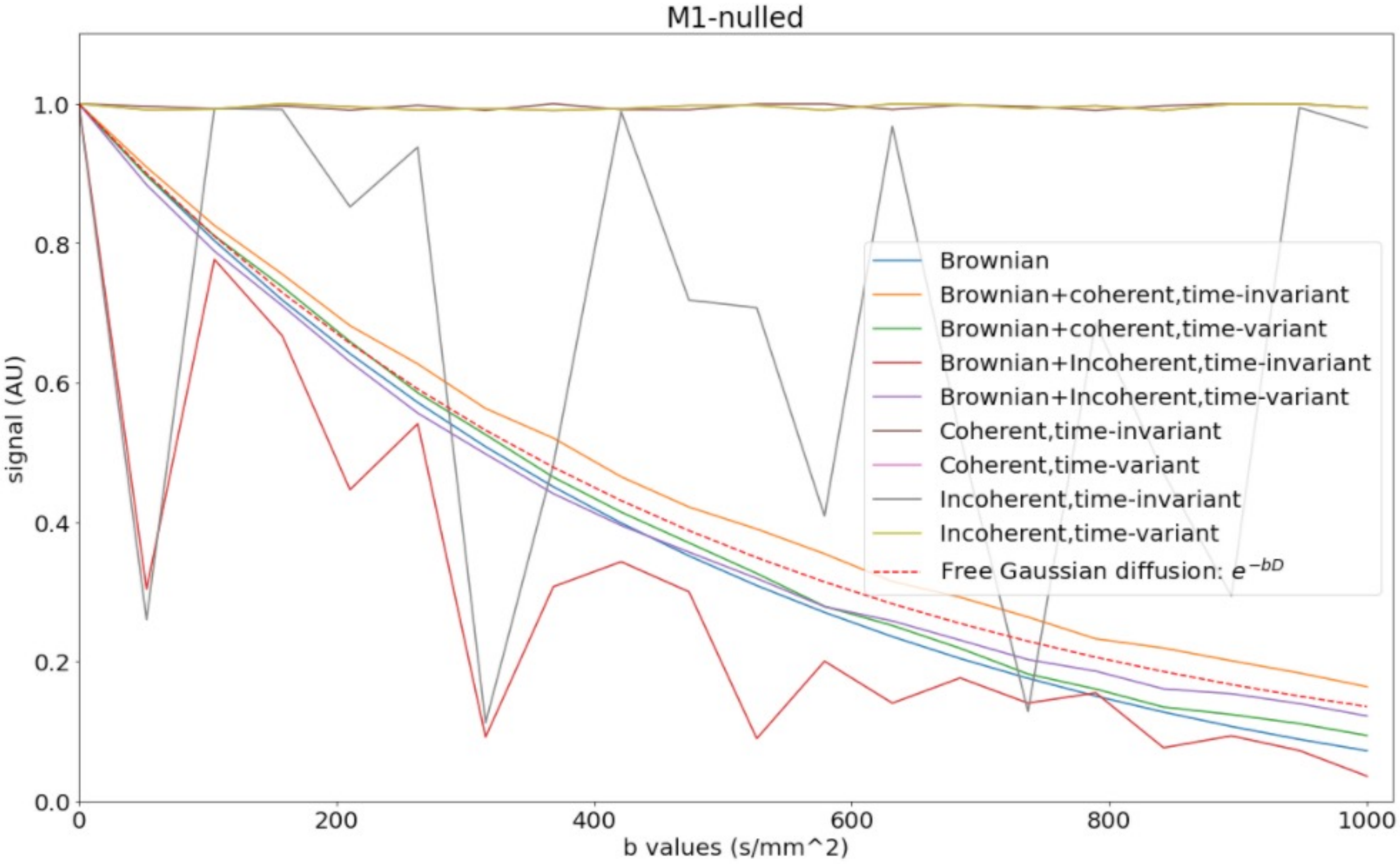


M2-nulled



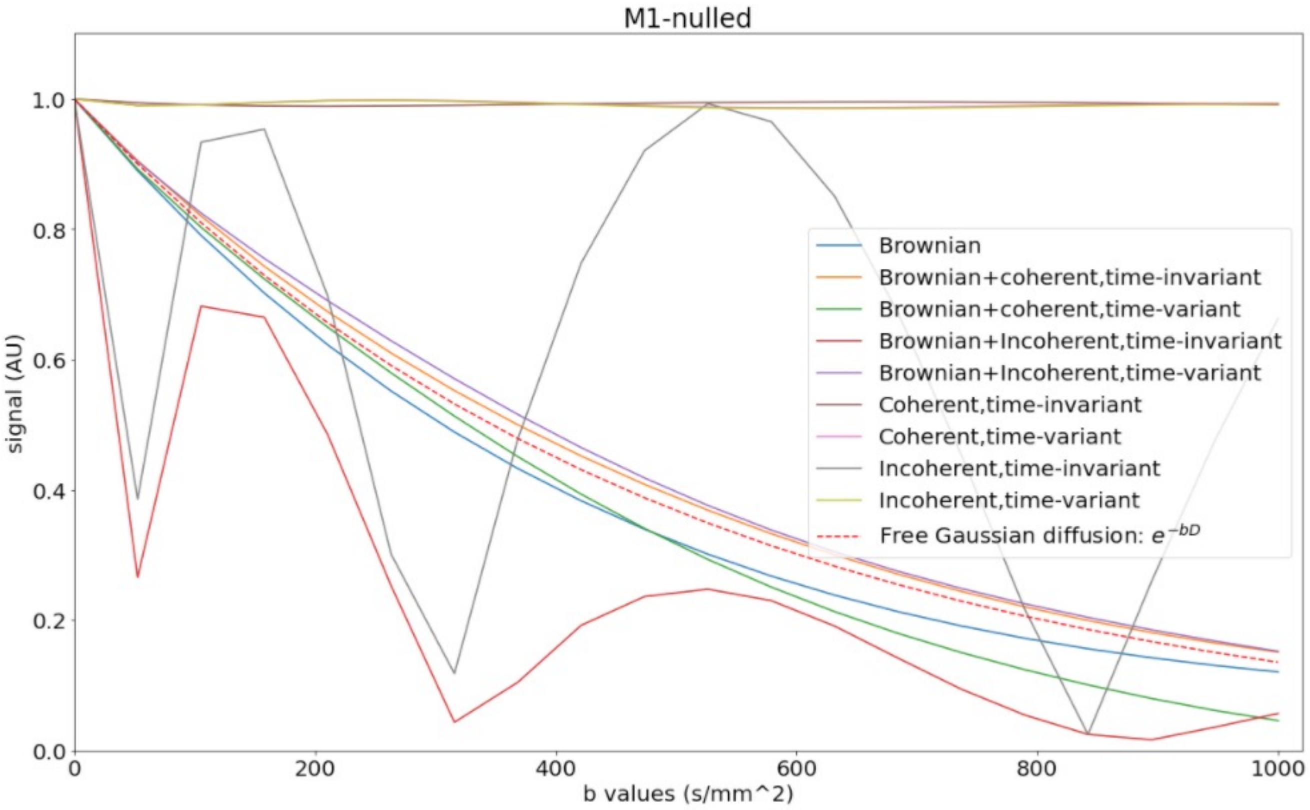
Discussions from simulations – time-invariant accelerations, no initial velocity

- What are the limitations of M1-nulled gradients address?



Discussions from simulations – time-invariant accelerations, no initial velocity

- What are the advantages of M2-nulled gradients over M1-nulled gradients?
- What issues can't M2-nulled gradients address?



Discussions from simulations

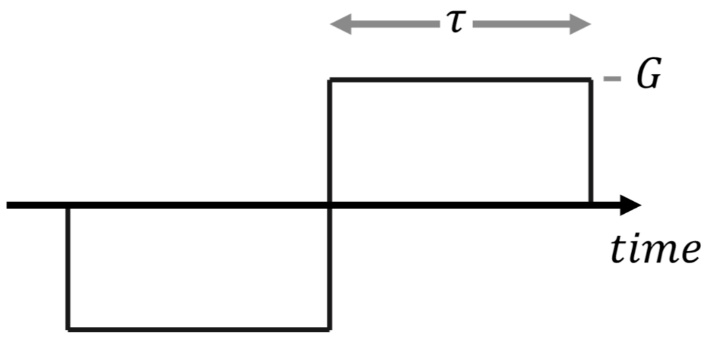
- When and how is a monopolar gradient waveform insufficient?
- What issues can M1/M2-nulled gradients address?
- What issues can't M1/M2-nulled gradients address? (time-variance)

$$\phi(x, t) = \gamma(\Delta B_0 t + x_0 M_0(t) + \gamma \underset{v(x,t)}{v} M_1(t) + \gamma \frac{\overset{a(x,t)}{a}}{2} M_2(t))$$

- Why M1/M2-nulled gradients can't refocus spins with time-variant motion?
- Isolating the effects of Brownian motion?

Motion encoding vs. Motion compensation

- Motion encoding gradients: $M_0 = 0$, $M_1 \propto G$ → phase $\propto\ v$



$$M_0(t = 2\tau) = \int_0^\tau dt - G + \int_\tau^{2\tau} dtG = -G\tau + G\tau = 0$$

$$\begin{aligned} M_1(t = 2\tau) &= \int_0^\tau dt(-Gt) + \int_\tau^{2\tau} dt(Gt) \\ &= -\frac{1}{2}Gt^2\Big|_0^\tau + \frac{1}{2}Gt^2\Big|_\tau^{2\tau} \\ &= -\frac{1}{2}G\tau^2 + \frac{1}{2}G4\tau^2 - \frac{1}{2}G\tau^2 \quad = G\tau^2 \end{aligned}$$

$$\phi = \gamma G\tau^2 v$$

- Motion compensated gradients: $M_0 = 0$, $M_1=0$, $M_2=0$…