Impact of Residual Gradient Moments on DWI

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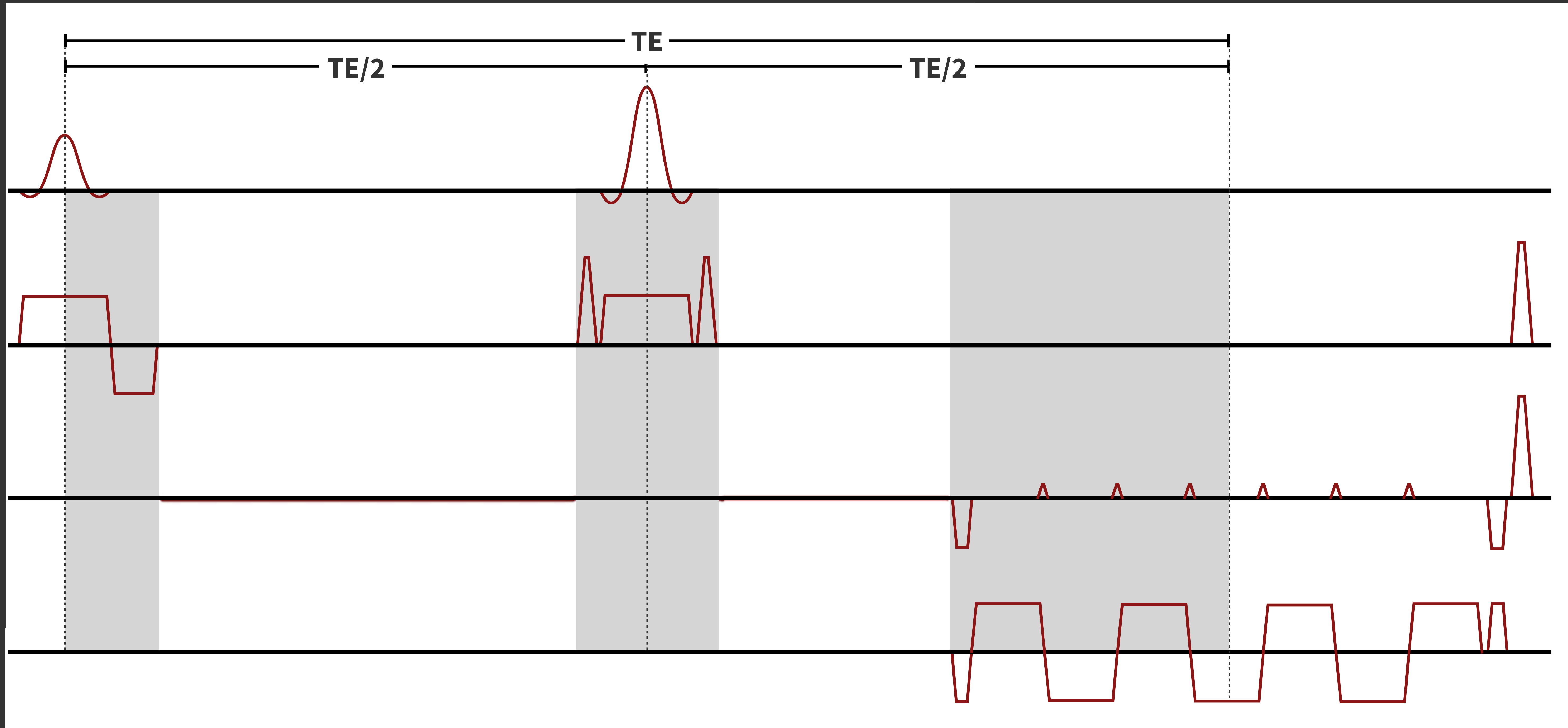
Impact: This work defines convergence criteria requirements for defining acceptable thresholds on residual gradient moments that enable on the fly optimization of diffusion encoded gradient waveforms for more accurate measurements of ADC in cardiac diffusion weighted imaging.



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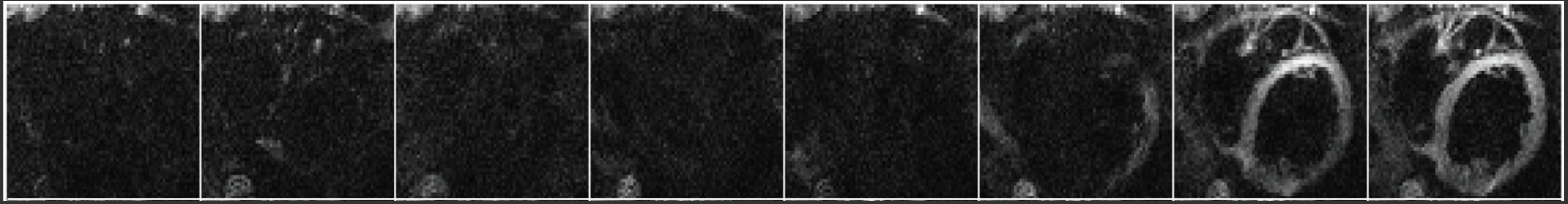
Measurements drawn from DWI provide clinical value, but sensitivity to bulk motion frequently contributes to signal losses that can confound measures of diffusion, especially in moving tissues like the heart. Bulk motion sensitivity can be mitigated by using velocity (M_1=0) or acceleration-compensated (M_1=M_2=0) gradient waveforms to null the intravoxel phase dispersion from the bulk (coherent) motion of spins while preserving the signal from incoherent diffusing spins. The intrinsic symmetry of conventional diffusion encoding strategies ensure exactly zero residual gradient moments as the waveforms are equal and opposite on either side of the refocusing pulse. However, optimization methods, which generate asymmetric gradient waveforms[1-5], are increasingly used for the design of time-optimal gradient waveforms and/or to mitigate bulk motion through the use of additional moment nulling constraints. In designing an optimization scheme, it is important to identify optimization criteria that enable fast solutions to be obtained [6]. The purpose of this work was to define acceptable limits for residual gradient moments that confer ≤5% measurement bias for ADC in the presence of bulk motion.

Introduction

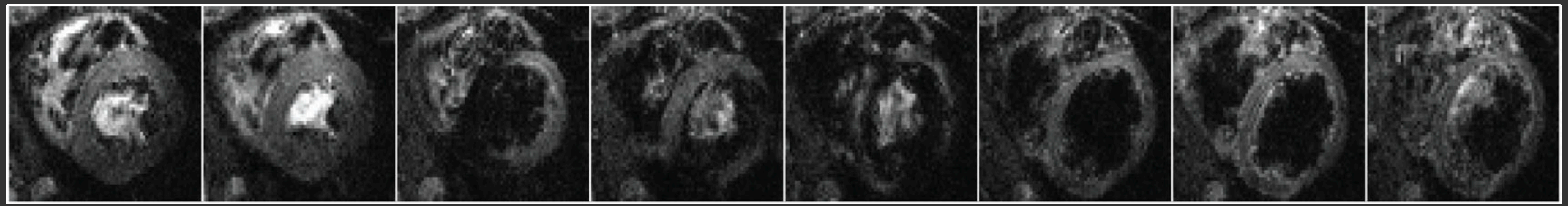
Cardiac diffusion measurements are confounded by bulk motion [1]:

Conventional M_0=0

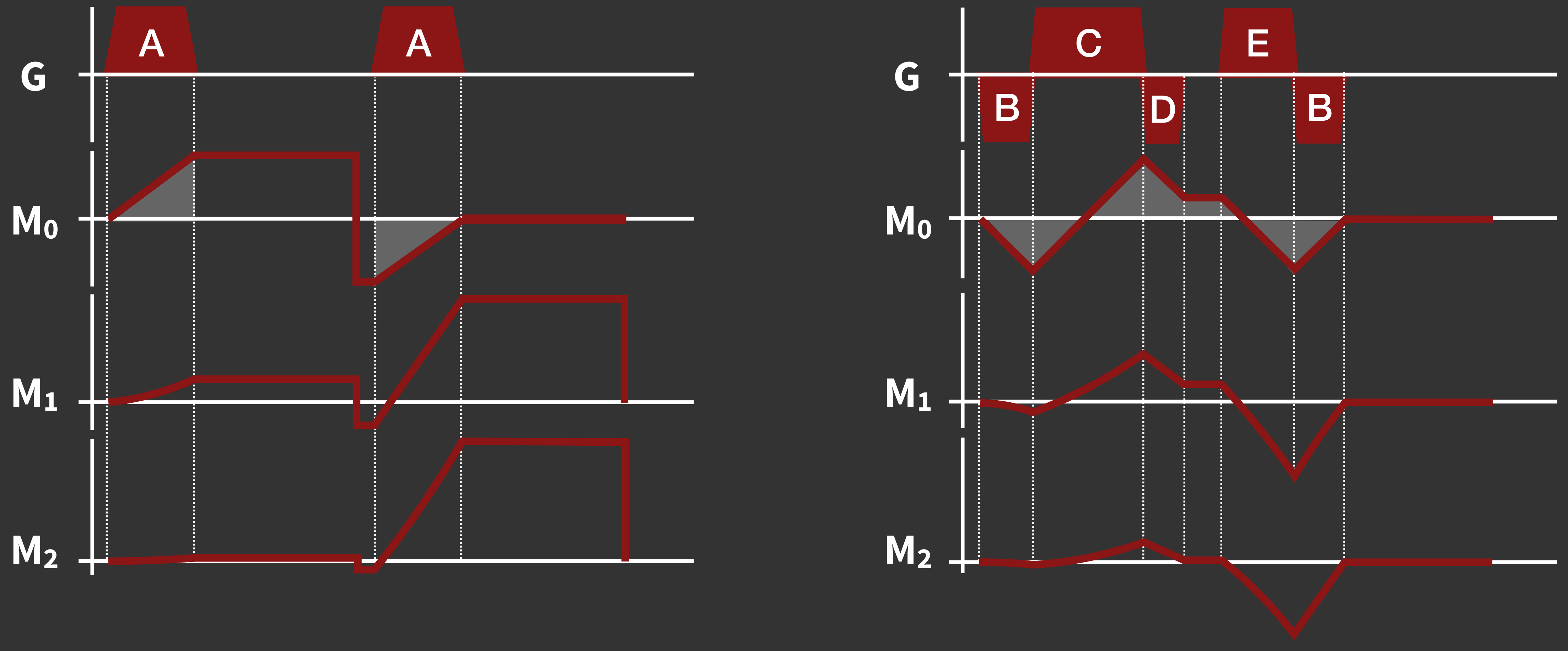


Optimization methods can offer time-optimal, motion-nulled DWI [1-5]:

M_0=M_1=M_2=0



However, these methods can yield asymmetric gradients, which are more prone to residual gradient moments and signal dephasing:



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References:

1. Aliotta et al. MRM 2017.
2. Aliotta et al. MRM 2018.
3. Yang et al. MRM 2018.
4. Sjölund et al. JMRI 2015.
5. Loecher et al. ISMRM 2018.
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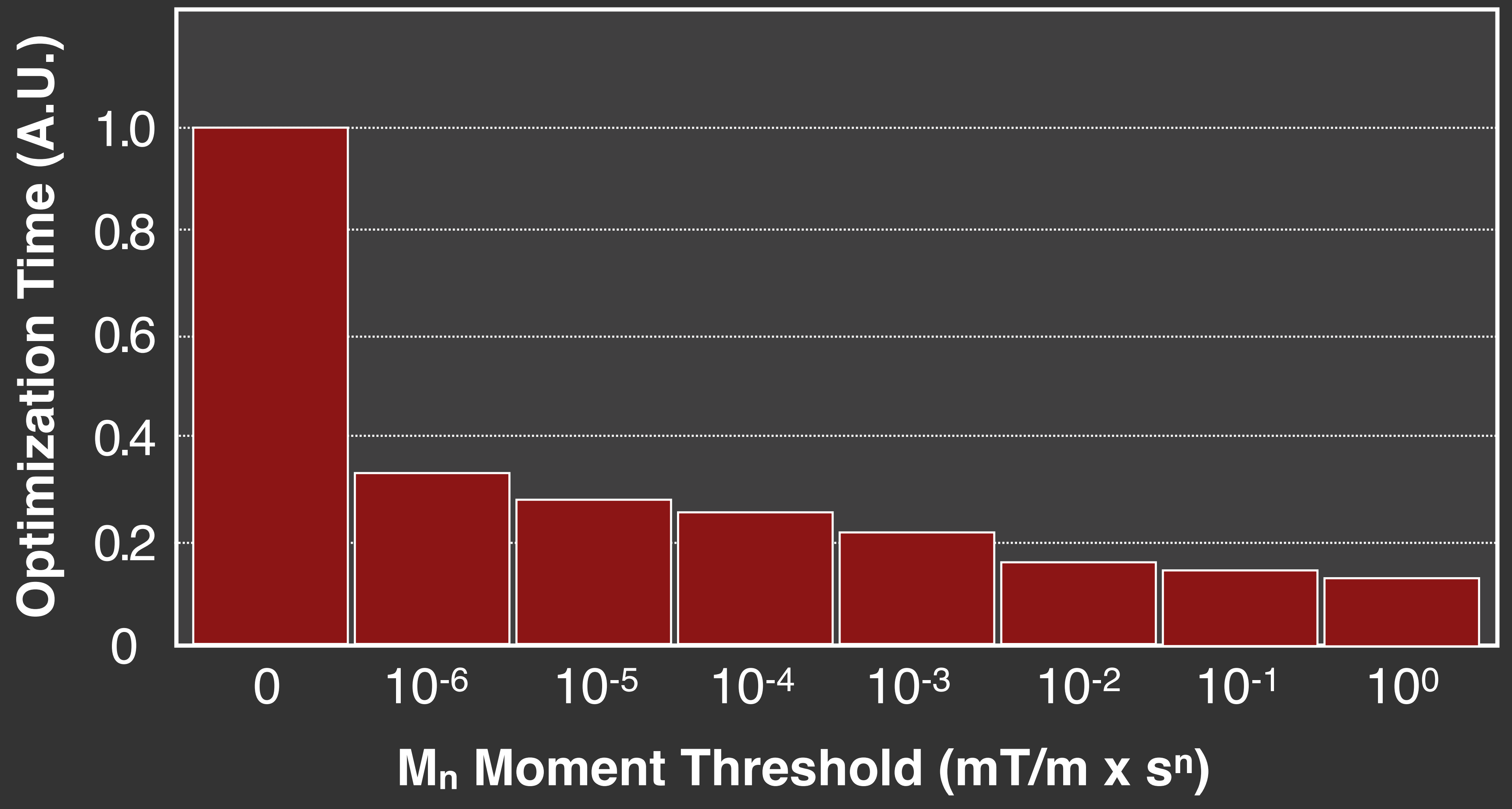
Introduction

Optimization methods require stoppage criterion for gradient moments, but their selection impacts optimization time [6]:



How do the residual moment threshold criteria impact diffusion measurement accuracy?

The purpose of this work was to define acceptable limits for residual gradient moments that confer ≤5% measurement bias for ADC in the presence of bulk motion.

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Numerical simulations were performed in Matlab to analyze the impact of residual gradient moments on intravoxel phase dispersion. The diffusion weighted signal for the n^{th} spin was calculated using **Eqns. [1-2]**. The measured ADC was calculated using **Eqn. [3]** for each of the 10,000 simulated spins per voxel with b=1000mm²/s, ADC=3x10⁻³mm²/s, and S_0=10,000, representing the cumulative signal within the voxel in the absence of diffusion encoding gradients and intravoxel phase dispersion. For all simulations, the following residual gradient moments were used: 0, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, and 10 with units of mT/m•s for M_0, mT/m•s² for M_1 and mT/m•s³ for M_2. To analyze the impact of residual M_0, ADC' was computed for different pixel sizes (1-10mm) with residual values of M_0 and M_1=M_2=0. To analyze the impact of residual M_1, ADC' was computed for simulated intravoxel velocity gradients, of varying maximum velocities (0-0.2m/s), with residual values of M_1 and M_0=M_2=0. To analyze the impact of residual M_2, ADC' was computed for simulated intravoxel acceleration gradients, of varying maximum accelerations (0-1m/s²), with residual values of M_2 and M_0=M_1=0.

METHODS

SIMULATION VARIABLES

Non-diffusion weighted signal (S_0) = 10,000 [10,000 spins]

Diffusion b-value (b) = 1,000 s/mm²
Simulated Apparent Diffusion Coefficient (ADC) = $3\text{x}10^{-3}$ mm²/s

Simulated position gradient ($\vec{r}_n$) = 1:1:10 mm
Simulated velocity gradient ($\vec{v}_n$) = 0:0.01:0.2 m/s
Simulated acceleration gradient ($\vec{a}_n$) = 0:0.05:1 m/s²

Gyromagnetic ratio (γ) = $42.577\text{x}10^{3}$ Hz/mT

Δ n^{th} moment (ΔM_n) = [0 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10] mT/m x s^n

Measured phase: $$\phi_n = \gamma(\vec{r}_n \Delta M_0 + \vec{v}_n \Delta M_1 + \vec{a}_n \Delta M_2) \quad \text{Eqn. [1]}$$

Diffusion signal: $$S_{DWI}^{n} = e^{-bADC} e^{-i\phi_n} \quad \text{Eqn. [2]}$$

Measured ADC: $$ADC' = \frac{1}{-b} \ln\left(\left| \sum_{n=1}^{10,000} \frac{S_{DWI}^{n}}{S_0} \right| \right) \quad \text{Eqn. [3]}$$

REFERENCES:
1. Aliotta et al. MRM 2017.
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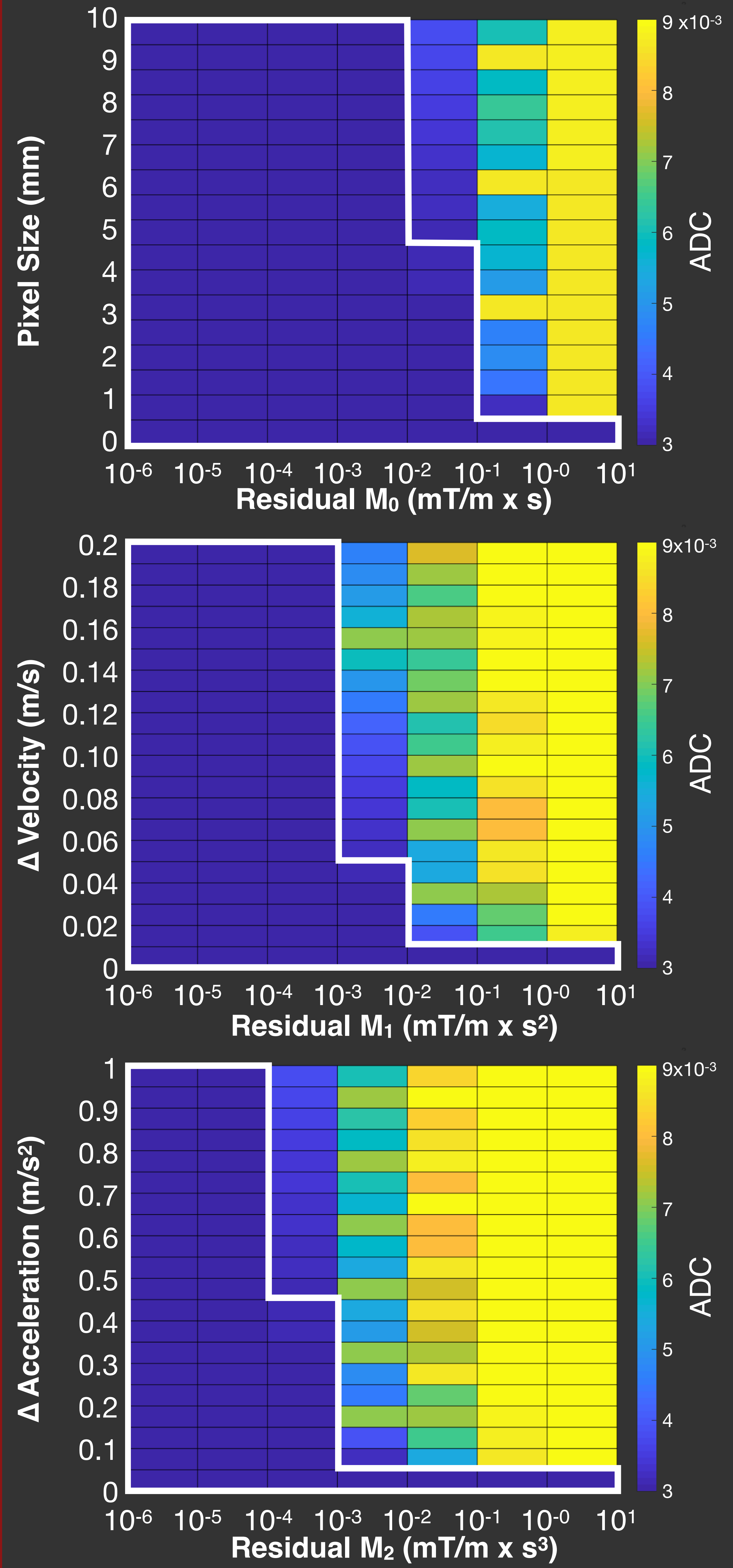
The impact of residual gradient moments on the measured ADC is analyzed through the use of numerical simulations. Figure 1 shows the result of numerical simulations highlighting the impact of intravoxel phase dispersion on measured ADC.

Figure 1: Numerical simulations showing the impact on measured ADC arising from intravoxel phase dispersion (signal loss) as a function of residual M_0 and pixel size **(A)**, residual M_1 and intravoxel velocity gradients **(B)**, and residual M_2 and intravoxel acceleration gradients **(C).** ADC' values that vary ≤5% compared to the simulated ADC ($3x10^{-3}mm^2/s$) and b-value ($1000mm^2/s$), are highlighted by the black borders (lower-left area within plots).

Results



A negligible (≤5%) increase in the measured ADC is observed when the **residual M_0** is ≤ **10^{-2}mT/m x s**.

A negligible (≤5%) increase in the measured ADC is observed when the **residual M_1** is ≤ **10^{-4}mT/m x s^2**.

A negligible (≤5%) increase in the measured ADC is observed when the **residual M_2** is ≤ **10^{-5}mT/m x s^3**.

References:

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Achieving precise gradient moment nulling is difficult. The simulations in this work show that knowledge of the pixel size and expected tissue motion can help define acceptable residual moment nulling thresholds while maintaining ADC measurements within 5%. The degree of intravoxel signal dephasing depends on the product of intravoxel velocity and acceleration gradients and any residual gradient moment(s).

Residual M_0 will always lead to an increase in the measured ADC due to intravoxel signal dephasing. A negligible (≤5%) increase in the measured ADC is observed when the residual M_0 is on the order of 10^{-2}mT/m•s for all simulated pixel sizes (0-10mm) and 10^{-1}mT/m•s for simulated pixel sizes ≤4.5mm. Hence, higher resolution imaging is less prone to bulk motion artifacts.

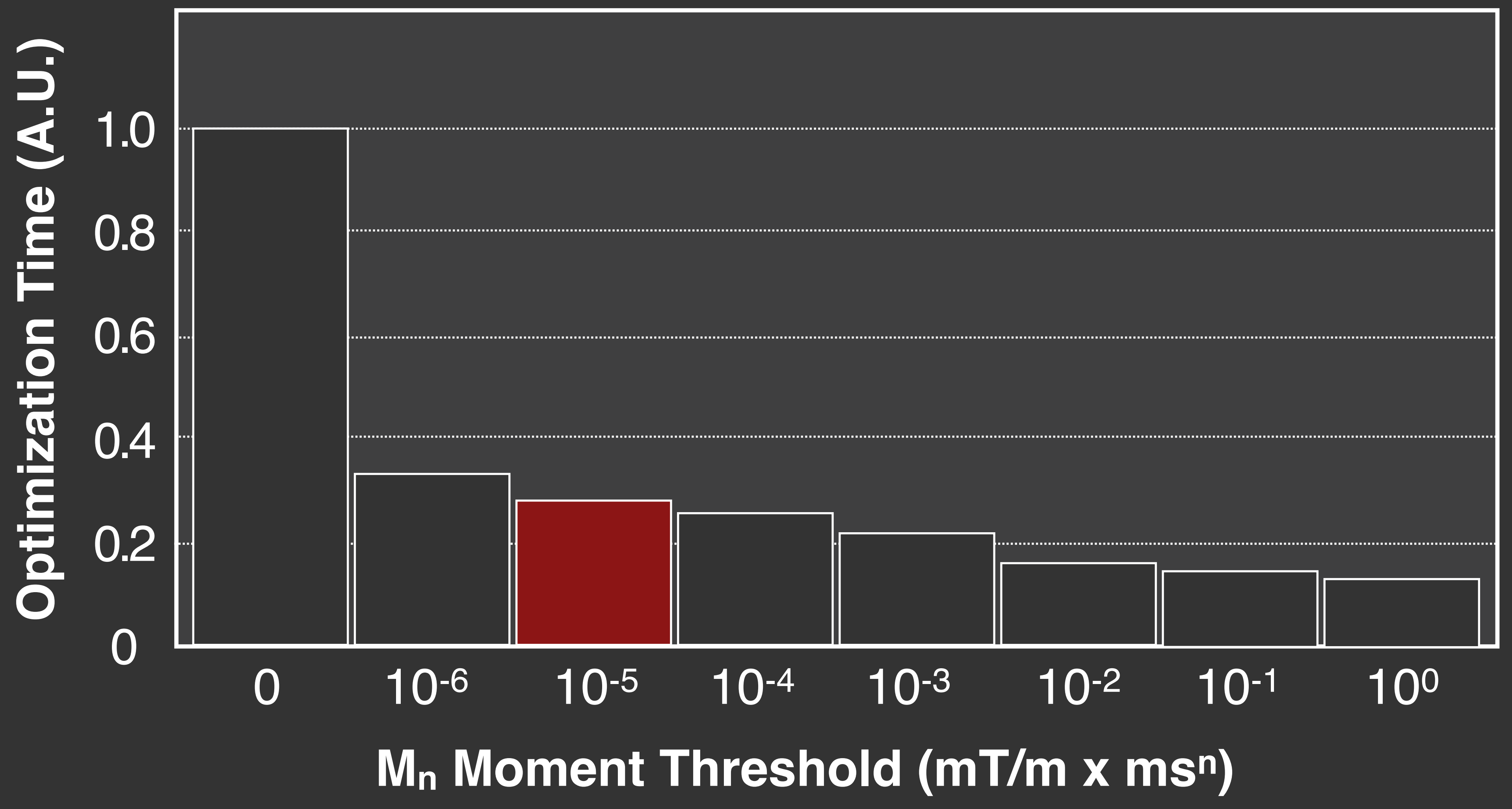
Residual M_1 and M_2 similarly lead to an increase in the measured ADC. A negligible (≤5%) increase in the measured ADC is observed when the residual M_1 is on the order of 10^{-4}mT/m•s^2 or when the residual M_2 is on the order of 10^{-5}mT/m•s^3.

Discussion

Intravoxel signal dephasing due to non-zero residual gradient moments leads to signal loss, which increases the measured ADC.

This work helps to define acceptable thresholds for residual gradient moments, which can be used to enable fast and more accurate measurements of ADC when using optimization methods for the time-optimal design of cardiac DWI sequences.

For ADC accuracy within ±5% and minimum optimization time, a ΔM_n threshold of **10^{-5} mT/m x s^n** should be used as threshold criterion for optimization methods.



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