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MR-MED: A Time-Efficient Multi-Echo DWI Sequence for Prostate Luminal Water Imaging

Albert Yen, BS[1,2,4]; Ukamaka Atueyi, MD[3]; Qingfei Luo, PhD[1,3]; Guangyu Dan, PhD[1,4]; Xiaohong Joe Zhou, PhD[1,3,4]
[1]Center for MR Research, [2]Medical Scientist Training Program, Departments of [3]Radiology and [4]Biomedical Engineering, University of Illinois Chicago

ABSTRACT

This project develops and evaluates a time-efficient MRI pulse sequence, MR-MED (multi-readout reduced field-of-view multi-spin-echo echo-planar diffusion-weighted imaging), for prostate luminal water imaging (LWI). LWI enables quantitative estimation of luminal water fraction (LWF), an imaging biomarker associated with aggressive prostate cancer, but conventional techniques require long acquisition times that limit clinical feasibility. MR-MED addresses this limitation by acquiring diffusion-weighted signals at multiple echo times following a single excitation, reducing scan time by approximately threefold while preserving spatial resolution and enabling diffusion–relaxometry modeling.

The sequence was first validated in phantom experiments with signal-to-noise ratio (SNR) analysis and subsequently evaluated in healthy volunteers at 3T. MR-MED acquisitions were compared with a conventional echo-planar imaging (EPI) sequence using similar parameters, but three times longer scan time. A custom reconstruction pipeline incorporating Marchenko–Pastur principal component analysis (MP-PCA) denoising was applied prior to nonlinear least-squares fitting to estimate five LWI parameters. MR-MED achieved sufficient SNR (>15) in approximately 4.5 minutes at b-values up to 1500 s/mm² and echo times exceeding 100 ms. In human scans, luminal water fractions ranged from 14–22%, consistent with published values, and parameter estimates of T2 and ADC were stable across volunteers. These results demonstrate that MR-MED can provide reliable quantitative measurements while substantially reducing acquisition time, improving the clinical feasibility of LWI for prostate cancer characterization.

CONTACT

[Albert Yen]
[Center for Magnetic Resonance Research]
[Medical Scientist Training Program]
[University of Illinois Chicago]
[ayen4@uic.edu]
[847-814-0537]

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INTRODUCTION

Prostate Cancer Background:

- Prostate Imaging Reporting and Data System (PI-RADS) v2.1 recommends multi-parametric MRI, which includes diffusion-weighted imaging (DWI) and T2-weighted (T2W) imaging [1].
- **DWI is more sensitive to lesions in the peripheral zone, where most tumors occur** [2].

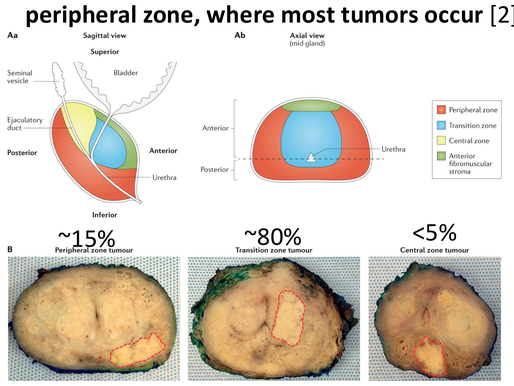

Figure 1: Prostate Tumor Prevalence in Different Zones. Adapted from Ali et al. 2022 [2].

Luminal Water Imaging (LWI):

- As cancer spreads, tumor invades the luminal space, lowering the **luminal water fraction** (LWF). *Novel imaging biomarker*
- Multi-TE DWI can assess prostate tissue composition voxel-wise by estimating compartment-specific T2 and ADC values, a technique known as **LWI** [3].

Problem: Conventional LWI relies on successive scans at different TEs, leading to long scan time.
Solution: **M**ulti-readout, **r**educed FOV (rFOV), **m**ulti-spin-echo, **E**PI-**D**WI (MR-MED) Sequence

- Multi-readout design accelerates multi-TE acquisition.
- rFOV targets the prostate with high resolution.

METHODS AND MATERIALS

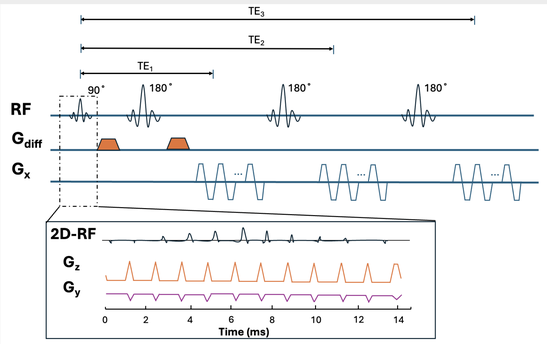

Figure 2: A diagram of the MR-MED sequence.

Experiments:

- Phantom validation followed by scans on 3 healthy volunteers (age 25, 40, 44 y.o.).
- LWF and compartment specific T2 and ADC estimated using a two-compartment model:

$$S(b,TE)/S_0 = f exp(-TE/T2_l) exp(-b \times ADC_l) + (1-f) exp(-TE/T2_{nl}) exp(-b \times ADC_{nl})$$

f = luminal fraction nl = non-luminal l = luminal

MRI:

- GE MR750 3T scanner with higher-order shimming.

Human Study:

- MR-MED: TR = 4000 ms; imaging plane = axial; matrix size = 128 × 64; FOV = 180 × 90 mm²; slice thickness = 3 mm; slice spacing = 1 mm; # slices = 18; TEs = 66.3, 85.5, and 104.7 ms; DWI with b-value$_{NEX}$ = 0_2, 200_2, 700_4, 1000_6, 1500_8 s/mm² (Figure 2).
- Conventional single-shot EPI-DWI: Identical parameters, except for TE = 65, 91.8, 122.8 ms; FOV = 18 × 18 cm²; matrix size = 128 × 128.
- **Scan time: 4:32 (MR-MED) and 13:16 (conventional).**

Phantom study (spherical phantom containing $NiCl_2$):

- MR-MED: Same as human study, except for slice thickness = 4 mm and DWI with b-value$_{NEX}$ = 0_1, 200_1, 700_2, 1000_3, and 1500_4 s/mm² (Figure 2).
- Conventional single-shot EPI-DWI: Identical parameters, except for TE = 65, 91.8, 122.8 ms; FOV = 18 × 18 cm²; matrix size = 128 × 128.
- **Scan time: 2:18 (MR-MED) and 6:40 (conventional).**

RESULTS

- **Achieved 3-fold acceleration** in imaging time in both phantom (2:18 vs. 6:40) and human (4:32 vs. 13:16) studies (Figure 3).
- MR-MED obtained adequate SNR (>=20) across all TE and b-value combinations (Figure 4; Table 1).
- Mean SNR Ratio ($SNR_{MR\text{-}MED}/SNR_{Conventional}$): ~0.7, consistent with theoretical value based on acquisition parameters (Table 1).
- MR-MED yielded LWF estimates (14-22%) more consistent with literature than the conventional sequence (Figure 5).
- MR-MED produced lower LWF and non-luminal T2 and ADC compared to the conventional sequence (Table 2).

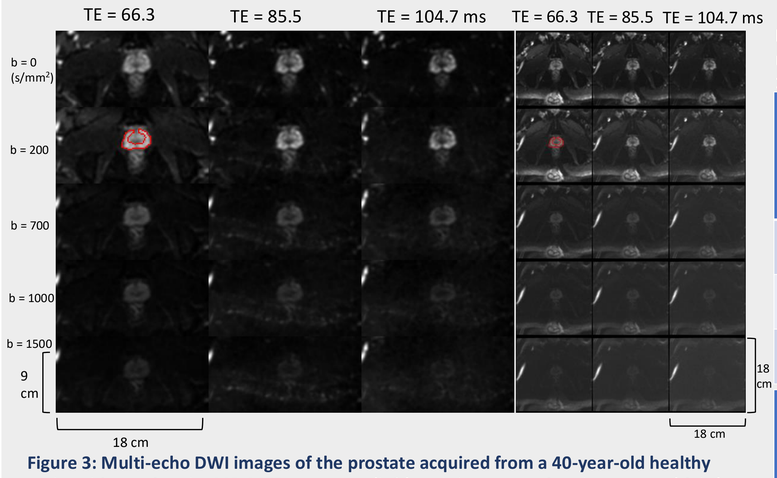

Figure 3: Multi-echo DWI images of the prostate acquired from a 40-year-old healthy male subject using the MR-MED sequence (left) and the conventional sequence (right). A region of interest (ROI) is drawn on the images with b = 200 s/mm² and TE = 66.3 ms.

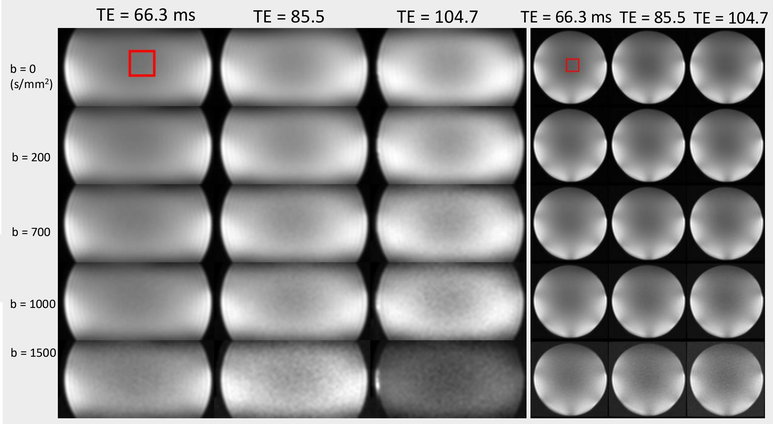

Figure 3: Multi-echo DWI of a spherical phantom acquired with the MR-MED sequence (left) and the conventional sequence (right). A region of interest (ROI), outlined in red on the image with b = 0 s/mm² and TE = 66.3 ms, was used for SNR calculations.

MR-MED SNR	b = 0	b = 200	b = 700	b = 1000	b = 1500 s/mm²
TE = 66.3 ms	388.0	298.6	183.4	104.1	36.0
TE = 85.5 ms	233.1	195.8	97.6	68.2	31.7
TE = 104.7 ms	198.2	113.6	62.6	38.4	21.2
SNR Ratio	**b = 0**	**b = 200**	**b = 700**	**b = 1000**	**b = 1500 s/mm²**
TE = 66.3 ms	0.84	0.85	0.92	0.81	0.86
TE = 85.5 ms	0.60	0.59	0.62	0.71	0.70
TE = 104.7 ms	0.74	0.52	0.53	0.61	0.66

Table 1: SNR of the MR-MED sequence across all TEs and b-values in the phantom study (top) and SNR ratio between MR-MED and the conventional sequence at corresponding TE and b-values (bottom).

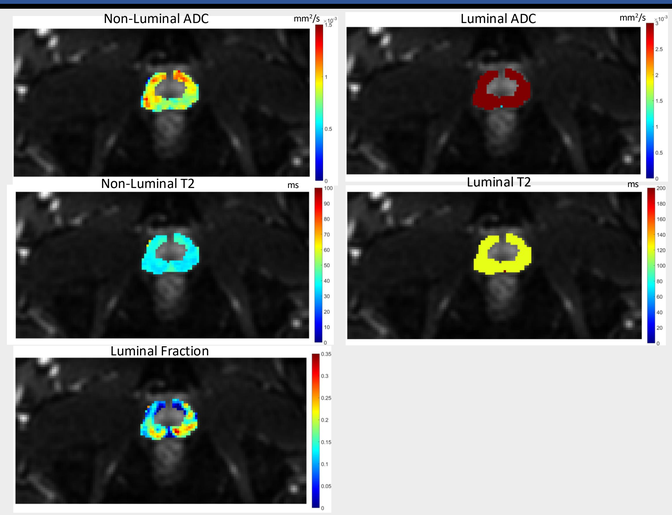

Figure 5: A set of representative parameter maps of luminal fraction, luminal and non-luminal ADC and T2 calculated from the two-compartment model, using the 15 images acquired with 5 *b*-values and 3 TEs.

Age (Years)	Luminal Fraction	Luminal ADC (mm²/s)	Non-Luminal ADC (mm²/s)	Luminal T2 (ms)	Non-Luminal T2 (ms)	Residual
40	0.143 ± 0.062	0.003 ± 0.00051	8.63e-4 ± 1.15e-4	120 ± 24	38 ± 9	0.0374 ± 0.0059
25	0.142 ± 0.031	0.0029 ± 0.00050	8.14e-4 ± 1.52e-4	140 ± 31	42 ± 7	0.0421 ± 0.0083
44	0.227 ± 0.059	0.003 ± 0.00064	9.36e-4 ± 2.06e-4	121 ± 26	38 ± 8	0.0265 ± 0.0068
Age (Years)	**Luminal Fraction**	**Luminal ADC (mm²/s)**	**Non-Luminal ADC (mm²/s)**	**Luminal T2 (ms)**	**Non-Luminal T2 (ms)**	**Residual**
40	0.462 ± 0.057	0.0029 ± 0.00035	3.16e-4 ± 4.15e-5	179 ± 25	79 ± 10	0.0310 ± 0.0043
25	0.450 ± 0.056	0.0029 ± 0.00035	4.19e-4 ± 5.67e-5	193 ± 30	69 ± 9	0.0398 ± 0.0056
44	0.456 ± 0.071	0.003 ± 0.00046	6.77e-4 ± 1.05e-4	257 ± 48	69 ± 11	0.0197 ± 0.0034

Table 2: Quantitative comparison of compartment-specific parameters across three healthy volunteers estimated from MR-MED (top) and the conventional sequence (bottom).

DISCUSSION

- MR-MED extends prior multi-readout rFOV methods [4] by incorporating multiple 180° refocusing pulses, enabling **efficient assessment of T2–ADC coupling** for prostate LWI.
- Differences in LWF between MR-MED and the conventional sequences may be related to reduced motion sensitivity.
- **Elevated artifacts and reduced SNR were expected but acceptable.**
  - The ~30% SNR reduction agreed with theoretical predictions for rFOV imaging.
  - Mild fold-over artifacts did not compromise prostate visualization, but they can be mitigated with saturation bands in future studies.

CONCLUSIONS

- MR-MED enables efficient prostate luminal water imaging with a 3-fold scan time reduction (13:16 → 4:32) while preserving spatial resolution.
- MR-MED achieves reliable estimation of LWF and compartment-specific T2 and ADC, despite modest SNR reductions.
- Future work will extend the method to 3D-imaging with more TEs and validate performance in prostate cancer patients.

Acknowledgement

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