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Higher-Resolution Prostate Diffusion MRI with Minimized Echo Time using Eddy Current Nulled Convex Optimized Diffusion Encoding (ENCODE)

Zhaohuan Zhang[1,2], Kevin Moulin[1], Eric Aliotta[1], Sepideh Shakeri[1], Sohrab A. Mirak[1], Daniel B. Ennis[1,2], and Holden H. Wu[1,2]

[1]Department of Radiological Sciences, University of California, Los Angeles, Los Angeles, CA, United States, [2]Department of Bioengineering, University of California, Los Angeles, Los Angeles, CA, United States

Synopsis

Higher-resolution prostate DWI has the potential to improve prostate cancer diagnosis, but suffers from additional SNR reduction due to increased TE at longer EPI readouts for current diffusion encoding schemes. In this work, we evaluated the newly proposed Eddy Current Nulled Convex Optimized Diffusion Encoding to achieve eddy-current-free diffusion encoding with minimized TE for prostate diffusion MRI using standard and higher-resolution protocols. The ENCODE higher-resolution protocol achieves higher scores for image sharpness and contrast compared to standard-resolution prostate DWI.

Introduction

Diffusion-weighted MRI (DWI) is a key component of prostate multi-parametric MRI. Monopolar spin echo (MONO) is the standard DWI encoding scheme, but suffers from eddy current induced distortion artifacts. Twice refocused spin echo (TRSE) DWI effectively reduces eddy current artifacts, but increases TE and reduces SNR compared to MONO. Higher-resolution prostate DWI has potential to improve prostate cancer diagnosis[1], but suffers from additional SNR reduction due to increased TE at longer EPI readouts for current encoding schemes (MONO or TRSE). Recently, Eddy Current Nulled Convex Optimized Diffusion Encoding (ENCODE) has been developed to null eddy current effects and minimize TE.[2] The **objective** of this study was to evaluate ENCODE versus MONO and TRSE for prostate DWI in terms of eddy current artifacts, SNR, ADC, and diagnostic image quality (sharpness and contrast) at standard- and higher-resolution imaging protocols.

Methods

Prostate DWI using ENCODE/MONO/TRSE were evaluated for: 1.Standard-resolution protocols with 1.6x1.6mm^2 nominal resolution (R_N) and partial Fourier factor (PF) = 6/8,[3] and 2.Higher-resolution protocols with modified R_N (up to 1.0x1.0mm^2) and PF (6/8 or off). Parameters are in **Figure 1**. Effective resolution (R_E) of each protocol was estimated by R_E=R_N * blurr(PF), where blurr(PF=6/8) =1.55.[4]

Theoretical Comparison: ENCODE, TRSE and MONO waveforms were generated to compare their TE. Assuming normal prostate $T_{2,norm}$ = 120ms and ADC_{norm} = 1200*10^{-6}mm2/s, prostate cancer (PCa) $T_{2,PCa}$ = 70ms and ADC_{PCa} = 800*10^{-6}mm^2/s,[5,6] SE-DWI signals were compared using $S(TE,b)=M_0*\exp(-TE/T_2)*\exp(-b*ADC)*R_N$.

Phantom Imaging: A standardized diffusion phantom was imaged at 3T (Prisma, Siemens, G_{Max}=76mT/m) using prostate DWI protocols (**Figure 1b**). To evaluate eddy-current induced distortion artifacts, voxel-wise coefficient of variation (CoV) was calculated across diffusivity maps of each diffusion direction and compared.

Prostate Imaging: In an IRB-approved and biosafety-approved study, one ex-vivo prostate specimen and 10 healthy subjects (age 27±3 years) were imaged using identical protocols as phantom study. ***Ex-vivo Prostate Imaging***: **SNR analysis**: Prostate DWI at b=800s/mm^2 were acquired 7 times to calculate SNR maps for each sequence. **ADC analysis**: Linear correlation of ADC from each sequence were investigated using mean ADC from 12 regions within the prostate. ***In-vivo Prostate Imaging***: **SNR analysis**: SNR maps were computed from 7 repetitions and mean SNR of the whole prostate were compared among sequences. **ADC analysis**: Mean ADC from the prostate transition zone (TZ) and peripheral zone (PZ) were measured and compared among sequences. **Image Quality Analysis**: Two radiologists scored the ENCODE and TRSE DWI/ADC (blinded and randomized) in terms of image sharpness (IS) and contrast (CA) on a 5-point Likert scale (1:worst,5:best) for standard- and higher-resolution protocols. **Statistical Analysis:** Differences among ENCODE/TRSE/MONO prostate DWI were tested using one way analysis of variance; $P<0.05$ was considered significant.

Results

Theoretical Comparison: ENCODE achieved substantially lower TE than TRSE, especially for higher-resolution protocols (up to 35ms shorter) (**Figure 1**), which resulted in 25%-40% higher expected prostate signal versus TRSE.

Phantom Imaging: ENCODE achieved comparable eddy current nulling performance as TRSE in prostate DWI protocols, while eddy current induced artifacts were evident on MONO (**Figure 2**).

Prostate Imaging: **ADC**: Ex-vivo imaging shows ENCODE ADC within prostate were consistent with TRSE/MONO across all protocols using linear regression (**Figure 3**). Standard-resolution in-vivo results show that ENCODE ADC in the prostate PZ and TZ were similar to MONO and TRSE (**Figure 4**). For higher-resolution in-vivo imaging, ENCODE and MONO ADC were consistent with each other, while TRSE ADC had increased variation. **SNR**: By minimizing TE, ENCODE achieved 20%-60% higher SNR than TRSE in ex-vivo (**Figure 3b**) and in-vivo prostate DWI (**Figure 4c**), with the most pronounced gain for higher-resolution protocols. **Image Quality**: For in-vivo imaging, the ENCODE higher-resolution protocol

(1.6x1.6mm^2, PF=off) had the highest scores for both IS and CA: $IS_{\mathbf{ENCODE,High}}$=4.5±0.5, $IS_{\mathbf{ENCODE,standard}}$=3.0±0.6, $IS_{\mathbf{TRSE,standard}}$=2.2±0.4, $IS_{\mathbf{TRSE,High}}$=1.7±0.6; $CA_{\mathbf{ENCODE,High}}$=4.3±0.7, $CA_{\mathbf{ENCODE,standard}}$=3.5±0.6, $CA_{\mathbf{TRSE,standard}}$=2.7±0.4, $CA_{\mathbf{TRSE,High}}$=1.3±0.4. Representative images are shown in **Figure 5**.

Discussion

ENCODE prostate DWI achieves comparable eddy current nulling performance as TRSE, while substantially decreasing TE and significantly increasing prostate tissue SNR. The advantages in decreasing TE and increasing SNR are most pronounced for the higher-resolution protocols. Prostate ADC quantification using ENCODE is consistent with MONO for both standard- and higher-resolution protocols, while TRSE ADC was found to have increased variation at higher resolution, mostly likely due to the SNR loss caused by elongated TE. The ENCODE higher-resolution protocol (1.6x1.6mm^2, PF=off) achieved higher scores for image sharpness and contrast compared to standard-resolution prostate DWI, and could potentially improve prostate cancer diagnosis.

Conclusion

ENCODE generates eddy-current-free diffusion encoding with minimized TE for prostate DWI at standard and higher-resolution protocols. The improvement in image quality using higher-resolution ENCODE prostate DWI can potentially improve clinical prostate cancer diagnosis.

Acknowledgements

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References

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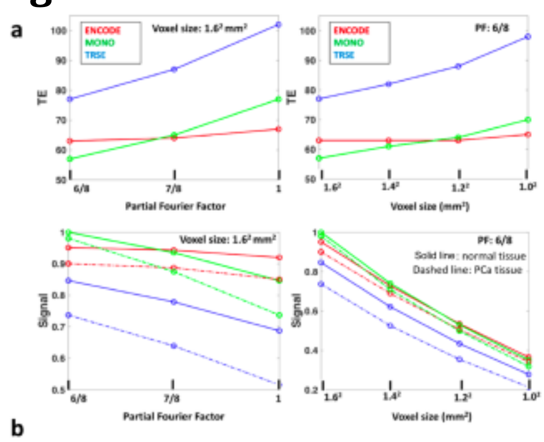
Figures

a



b

Protocol	FOV (mm²)	Nominal Resolution (mm²)	Partial Fourier Factor	Effective Resolution (mm²)	B values (s/mm2), Directions	Echo Time: TE (ms)			ΔTE (ms)		Other:
						ENCODE	MONO	TRSE	ENCODE - TRSE	ENCODE - MONO	
Standard	260*216	1.6 x 1.6	6/8	1.6 x (1.6*1.55)	0,100,400,800 3 Scan Trace	63	57	77	-14	6	GRAPPA:2 7 Averages 20 Slices Slice Thickness: 3.6mm
Higher Resolution		1.6 x 1.6	off	1.6 x 1.6		67	77	102	-35	-10	
		1.0 x 1.0	6/8	1.0 x (1.0*1.55)		65	70	98	-33	-5	

Figure.1 a) Theoretical comparisons of TE and prostate tissue signal for ENCODE/MONO/TRSE prostate SE-EPI DWI protocols over a range of resolution and partial Fourier factors. For expected prostate signal: S_{ENCODE} was up to 25% higher than S_{TRSE} and 8% higher than S_{MONO} in normal tissue, and S_{ENCODE} was up to 40% higher than S_{TRSE} and 15% higher than S_{MONO} in PCa tissue.**b)** Standard-resolution and higher-resolution prostate SE-EPI DWI protocol parameters for experimental evaluation. Scan time was 5min 23s for all sequences.

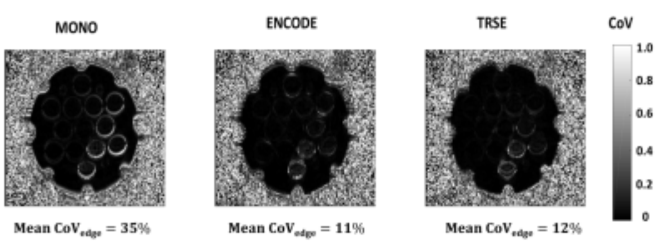


Figure.2 Evaluation of eddy current artifacts in a standardized diffusion phantom (High Precision Devices) using the MONO/ENCODE/TRSE standard-resolution prostate DWI protocols. Eddy currents lead to bright rings around the edges of the tubes in the diffusion phantom on the

MONO coefficient of variation (CoV) map, while effectively suppressed in ENCODE and TRSE.

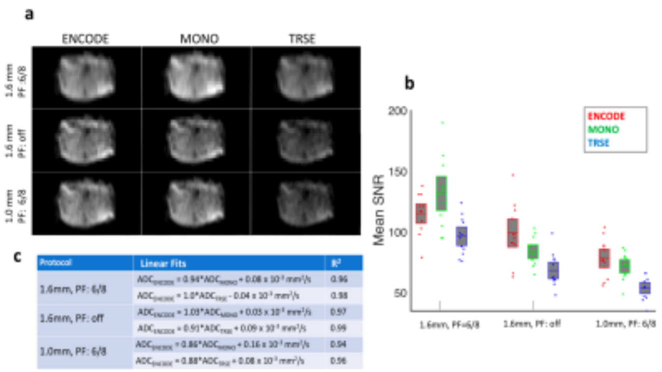


Figure.3 a) Ex-vivo prostate DWI (b=800s/mm^2) with each encoding scheme at standard (1.6x1.6mm^2,PF=6/8) and higher-resolution protocols (1.6x1.6mm^2,PF=off; 1.0x1.0mm^2, PF=6/8) under same window level. **b)** Measured SNR of each sequence in prostate. For standard-resolution imaging, ENCODE mean SNR was 19% higher than TRSE, and 13% lower than MONO (p<0.005). For higher-resolution imaging, ENCODE mean SNR was 45% higher than TRSE and 18% higher than MONO for 1.6x1.6mm^2 and PF=off (p<0.001), and 45% higher than TRSE and 9% higher than MONO for 1.0x1.0mm^2 and PF=6/8 (p<0.001) **c)** Linear correlation of ENCODE ADC estimates to MONO and TRSE shows high degree of agreement.

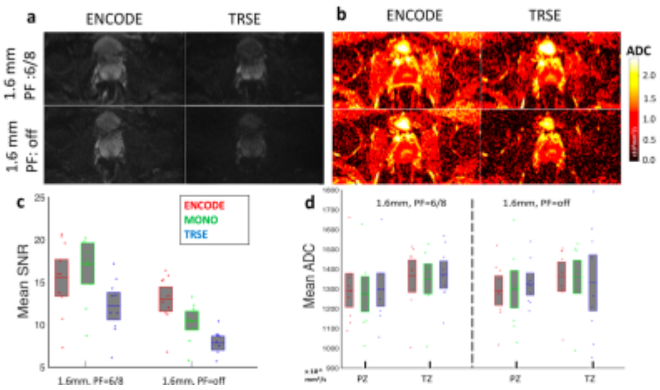


Figure.4 a) In-vivo ENCODE DWI (b=800s/mm^2) compared to TRSE for standard-resolution (1.6x1.6mm^2, PF=6/8) and higher-resolution protocols (1.6x1.6mm^2,PF=off). **b)** ADC maps. **c)** Mean SNR comparisons of each sequence from 10 subjects. Standard-resolution in-vivo results show ENCODE mean SNR was 27% higher than TRSE and 10% lower than MONO (p<0.05). For higher-resolution in-vivo imaging, ENCODE mean SNR was 63% higher than TRSE and 24% higher than MONO (p<0.001) **d)** Mean ADC estimates in the prostate peripheral zone (PZ) and transition zone (TZ) of each sequence for standard-resolution and higher-resolution protocols are in good agreement, except for the increased variation using higher-resolution TRSE.

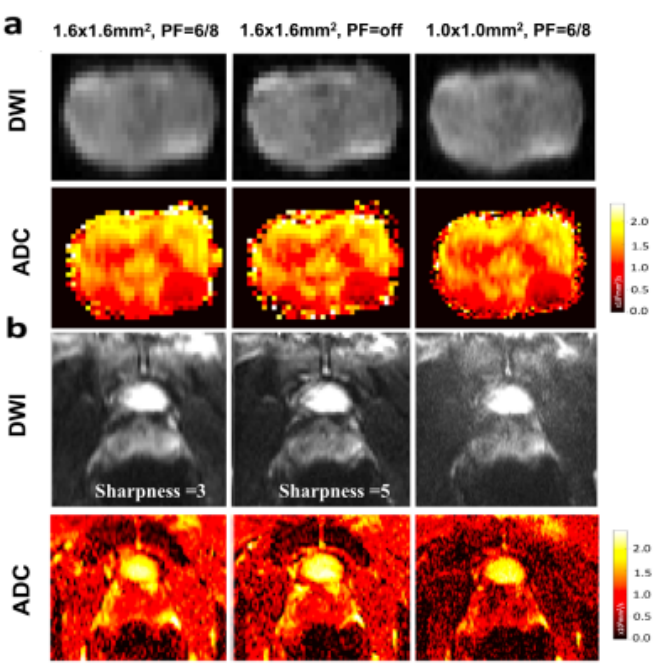


Figure.5 a) Ex-vivo prostate ENCODE DWI using standard- and higher-resolution protocols (top). Corresponding ADC maps (bottom). **b)** In-vivo prostate ENCODE DWI using standard- and higher-resolution protocols (top). Corresponding ADC maps (bottom). The sharpness scores are labeled in the images and both have contrast score of 4. The higher-resolution ENCODE DWI protocol (1.6x1.6mm^2, PF=off) achieved the highest image quality scores for sharpness and contrast.