Effect of Noise Floor Suppression on Diffusion Kurtosis for Prostate Brachytherapy

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Objective

Diffusion-weighted magnetic resonance imaging (DW-MRI) and recently diffusion kurtosis imaging (DKI) can be used to characterise prostate tumours and improve the treatment. However, DKI is sensitive to the effects of signal noise due to strong diffusion weightings and higher order modelling of the diffusion weighted signal. The purpose of the study is to evaluate DKI data and the reliability of kurtosis estimates in the existence of noise floor suppression using different sequences and scanners for DW-MRI using gel phantoms with the aim of applying to prostate brachytherapy.

Materials and Methods

Six plain agar gel phantoms and five agar gel phantoms containing various amounts of glass microspheres were prepared at Cancer Research Wales Laboratories in Velindre Cancer Centre with a volume of 100 cm^3. All of the gel phantoms were made to arrange MRI parameters to be consistent with those found in healthy and diseased prostate tissue. Glass microspheres (gm) were added into agar gels to obtain remarkable kurtosis values. Preparation method was summarized in our previous study in detail[1].

Several DW-MRI protocols were tested on the two clinical systems (Optima MR450w 1.5T, GE Medical Systems, Waukesha, WI and Magnetom Skyra 3T, Siemens Healthcare, Erlangen, Germany) by applying 9 different diffusion weighting "b-values" between 0 and 4000 s/mm^2 in intervals of 500 are summarized in *Table 1*. Analysis of DKI was performed on a pixel-by-pixel basis in-house software (MATLAB).

Table 1. Imaging Protocols for the DKI Scans

	GE 1.5T	Siemens 3T	Siemens 3T	Siemens 3T
Sequence type	*SS SE EPI* Single-shot spin-echo echo planar imaging	*SS SE EPI* Single-shot spin-echo echo planar imaging	*SE ST* modified Stejskal-Tanner spin-echo	*SE ST* modified Stejskal-Tanner spin-echo
FOV (mm) Field of View	100	100	100	64
Matrix size	256 x 256	64 x 64	64 x 64	64 x 32
Slice thickness (mm)	20	10	20	10
TR/TE (ms) Repetition time/Echo time	5000/130	5000/130	3000/120	3000/120
Bandwidth (Hz/px)	1000	1000	130	130
N_A Number of averages	8	8	1	1
b-values (s/mm²)	9 b-values	9 b-values	9 b-values	9 b-values
T_A ***(min)*** Acquisition time	6.45	6.07	27.81	11.97
Coil	Birdcage	Spine, loop	Spine, loop	Spine, loop

DWI scans of the phantoms were performed using a single-shot spin-echo echo-planar (SE-EPI) sequence and a version of the Stejskal-Tanner spin echo diffusion (ST-SE) sequence, which does not use single short EPI readout.

Monoexponentional and Kurtosis models[2] were used to obtain diffusion coefficients of the gel phantoms by using the equation below;

$$S(b)=S_0.e^{-ADC.b} \qquad S(b)=S_0\, e^{(-D.b\,+\,1/6.b^2.D^2.K)}$$

where S(b) is the signal intensity depending on the b-factor and S_0 is the signal without applying a diffusion weighting gradient (b=0 s/mm^2). ADC and D are the diffusion coefficients and K is the dimensionless kurtosis expressing the degree of deviation from Gaussian behavior.

Results and Discussion

ADC values of plain agar gel phantoms were defined with the ones with microspheres for b_{max}= 1500 s/mm^2 respectively by using all scanning protocols. The ADC values (*Table 2*) are comparable with the ones indicated in the literature[3]. A wide variation between the ADC values of the gel phantoms with the microspheres show that the gels are appropriate to represent healthy and diseased tissues for the prostate[4].

Table.2. ADC values of agar gel phantoms at b_{max} = 1500 s/mm^2 for each protocol

Agar Gel Phantom	1.5T SS SE EPI	3T SS SE EPI	3T SE ST (FOV 100)	3T SE ST (FOV 64)
1.0%	2008 ± 46	2201 ± 15	2183 ± 9	2081 ± 13
1.5%	1899 ± 39	2156 ± 9	2130 ± 25	2150 ± 18
2.0%	1947 ± 72	2127 ± 12	2134 ± 16	2174 ± 28
2.5%	1817 ± 48	2078 ± 13	2120 ± 19	2106 ± 22
3.0%	1802 ± 61	2042 ± 13	2076 ± 18	2089 ± 27
3.5%	1820 ± 98	2007 ± 18	2058 ± 44	2002 ± 30
2.0% + 0.1g gm	1815 ± 77	2037 ± 23	2066 ± 23	2106 ± 44
2.0% + 0.3g gm	1812 ± 84	1966 ± 34	1944 ± 68	2050 ± 35
2.0% + 1.0g gm	1408 ± 106	1462 ± 57	1484 ± 70	1407 ± 56
2.0% + 2.0g gm	767 ± 222	907 ± 226	929 ± 263	876 ± 192
2.0% + 3.0g gm	449 ± 191	852 ± 312	769 ± 276	684 ± 233

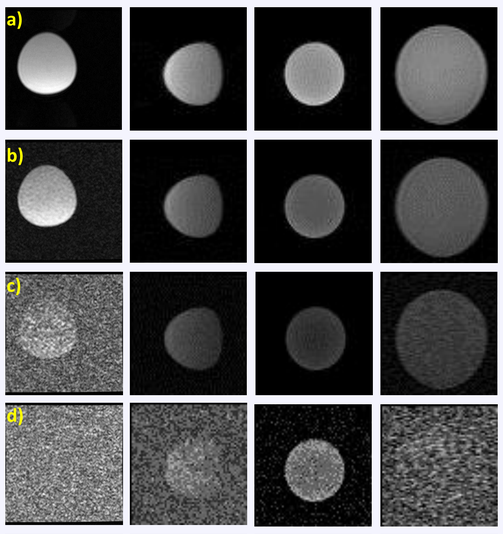

Fig.1. a) b=0, b) b=1000, c) b=2000, d) b=3000, e) b=4000 s/mm^2 images of SS SE EPI at 1.5T, SS SE EPI at 3T, SE ST at 3T (FOV=100mm), and SE ST at 3T (FOV=64mm), respectively.

Noise floors of each method are shown in *Fig.1* and *Fig.2* for the same sample, plain 2.0% agar gel phantom. In general perspective, modified SE ST sequence shows lower noise floor level than SS SE EPI sequence for all of the gel phantoms.

It is also clearly seen that the image with FOV=100 mm using modified SE ST sequence shows the best image quality than all the others. While plain gels were found to have low kurtosis values, it can be increased significantly by adding gm due to the increase of the barrier concentration.

Furthermore, the maximum K value was obtained as 0.55 ± 0.17 mm^2/s which can represent the healthy prostate tissue based on some of the clinical research[5]. However, K values are still too low to mimic canserous tissue. Although the higher values were obtained by other protocols, it should be known that they do not represent the correct values due to the noise floor contribution.

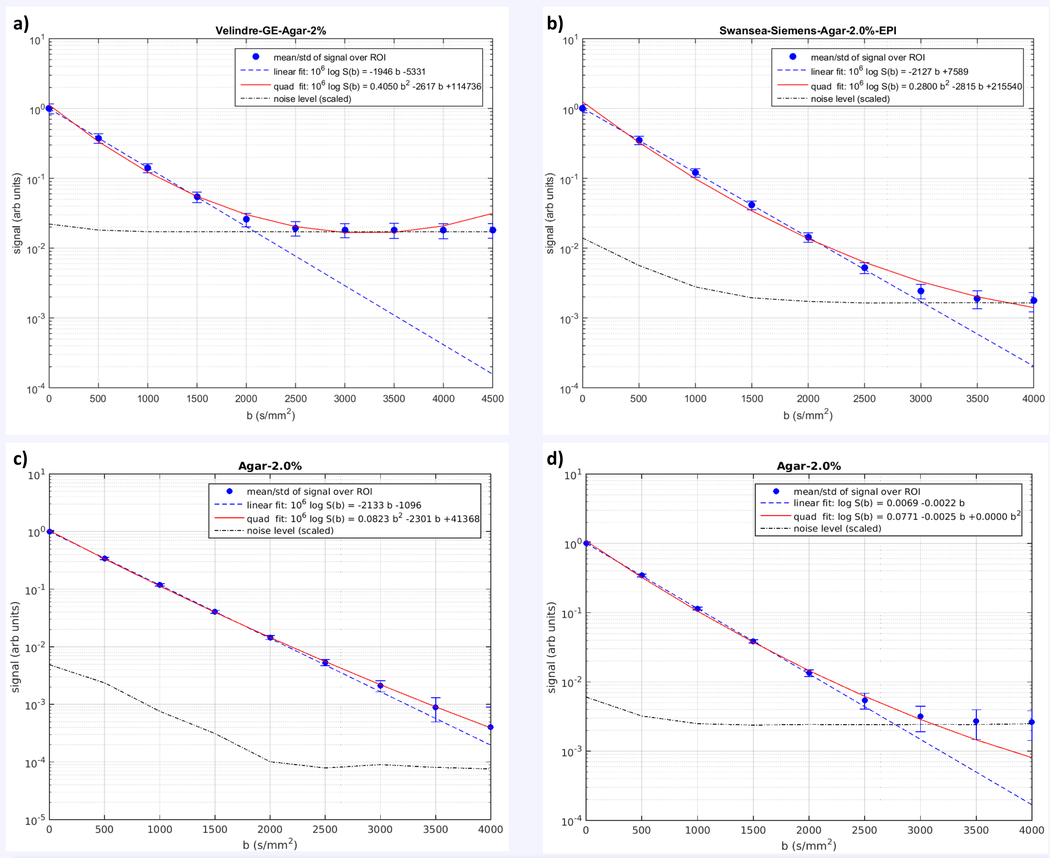

Fig.2. a) SS SE EPI at 1.5T, b) SS SE EPI at 3T, c) SE ST at 3T (FOV=100 mm), and d) SE ST at 3T (FOV=64 mm)

Multiple slices can be composed in the same time without loss of higher b-value contrast for the SE sequence. With a repetition time of T_R = 3000 ms, it could be possible to squeeze in 15-20 slices before it is needed to increase the scan time even for the long echo times required for the large gradients, while for the EPI sequence the length of the echo train and the need for multiple averages limit the number of slices that can be acquired concurrently.

The crux of the study is to emphasize though is that we did not optimize the acquisition time as the latter is irrelevant if there is no contrast at high-enough b-values to detect kurtosis.

Conclusion

We presented the effect of noise floor fitting using gel phantoms for the assessment of isotropic diffusion kurtosis to investigate its potential in the characterization of prostate cancer treated by brachytherapy. We have shown that the rectified noise floor, which exists in standard magnitude data, increases the systematic error of the ADCs. To minimize the impact of noise floor in DKI, high SNR at high b-values are needed. Although conventional readout is unfavourable compared to EPI in terms of acquisition times for single slice imaging, significant gains can be made for multi-slice imaging by interleaving the slices. EPI requires multiple averages and lastly getting results fast is useless if they are not accurate.

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Physics track: Images and analyses

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