

Influence of image noise and microcapillary perfusion (IVIM) on diffusional kurtosis measurements in the body

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Target audience: MR physicists, (radiologists)

Purpose: Diffusional kurtosis imaging (DKI) can be used to assess the extent of non-Gaussian water diffusion in biological tissue, which reflects properties of tissue microstructure.¹ DKI is based on the non-monoexponential signal attenuation at high b-values ($b_{\max} \approx 2000$ s/mm²). However, non-monoexponential signal attenuation influencing the DKI analysis can also occur due to very low signals at the noise level—particularly, in body applications, where relatively short T_2 relaxation times and high diffusion coefficients compromise the obtainable signal-to-noise ratio (SNR).

Microcapillary tissue perfusion is an additional cause of non-monoexponential signal attenuation present at very low b-values ($0 < b < 200$ s/mm²), described by intravoxel-incoherent-motion (IVIM) MRI.^{2,3} In DKI of the brain, the IVIM influence is generally neglected because of the low cerebral blood volume.¹ However, the influence of IVIM effects on DKI measurements can be relevant, e. g., in abdominal or pelvic applications. The purpose of this study was to analyze the influence of noise and IVIM on DKI measurements in data from pelvic MRI.

Methods: Pelvic MRI was performed on a 1.5-Tesla whole-body MRI system in 4 patients with oncologic disease outside the prostate. The diffusion coefficient, D , and the diffusional kurtosis, K , of healthy appearing prostate tissue (in 2 regions: center of gland and periphery) were obtained by a DKI measurement with $b_{\max} = 2000$ s/mm² (isotropic diffusion weighting, scan duration: 7:06 min). D and K were determined from b-values **0**, 500, 1000, 1500, 2000 s/mm² (a) without and (b) with fitting of the noise level, N , (based on power-image data assuming Rician noise⁴) and (c) from b-values **200**, 500, 1000, 1500, 2000 s/mm² with fitting of the noise level, N , and, thus, minimizing the influence of IVIM effects on the analysis.

To reduce the number of free fit parameters, we used the signal attenuation $S(b)/S(b_{\min})$ and did not fit the initial signal S_0 .⁵ This requires the adequate inclusion of the minimum b-value into the squared (kurtosis) term of the exponential: $S(b)/S(b_{\min}) = \exp[-D \cdot (b-b_{\min}) + D^2 \cdot (b-b_{\min})^2 \cdot K/6 + D^2 \cdot b_{\min} \cdot (b-b_{\min}) \cdot K/3]$.

Based on the in-vivo results, the influence of noise and IVIM on DKI was then numerically simulated for fixed D and K and a broad range of SNR ($5 < \text{SNR}_{b=0} < \infty$) and IVIM parameters, f (perfusion fraction) and D^* (pseudo-diffusion) using published reference values:^{6,7} $0 < f < 0.25$, $2 \mu\text{m}^2/\text{ms} < D^* < 14 \mu\text{m}^2/\text{ms}$. The simulated (squared) signal, $S_{\text{sim}}(b)^2$, including noise, IVIM, and kurtosis contributions is:

$$S_{\text{sim}}(b)^2 = S_0^2 [(1-f) \cdot \exp(-bD + (bD)^2 \cdot K/6) + f \exp(-b \cdot (D+D^*))]^2 + N^2.$$

We determined D and K from simulated values $S_{\text{sim}}(b)$ using a non-linear least-squares fit to a DKI model without IVIM contribution corresponding to measurements (a), (b), and (c) above. The relative deviation of the determined values, D and K , from the original values was calculated.

Results: Measured prostate diffusivity was between 1.5 and 2.2 $\mu\text{m}^2/\text{ms}$. The measured mean values of K are listed in Table 1. K is systematically increased by about 90 % if noise and IVIM influences are not taken into account (row a). IVIM effects alone result in an increase of K between 4 and 17 % (row b). The influence of noise and IVIM effects on the diffusivity, D , was substantially lower with deviations between 0 and 6 %. The simulated relative deviation of K due to noise and IVIM influence is shown in Fig. 1. With increasing noise level (Fig. 1A), the determined kurtosis, K , is strongly biased towards higher values (by up to 100 %). For a noise-free simulation of IVIM effects and $b_{\min}=0$ (Fig. 1B), a considerable increase of K (of 10 to 15 %) was found. An improved estimation of K was obtained for $b_{\min}=200$ s/mm² (Fig. 1C).

Table 1: Experimentally determined diffusional kurtosis of human prostate tissue in vivo

$n = 4$	Prostate periphery		Prostate center	
	Kurtosis K (S.D.)	Deviation from (c)	Kurtosis K (S.D.)	Deviation from (c)
(a) $b_{\min}=0$	0.76 (0.09)	+95.2 %	0.91 (0.13)	+87.9 %
(b) $b_{\min}=0$ with noise fit	0.46 (0.18)	+17.3 %	0.50 (0.28)	+4.4 %
(c) $b_{\min}=200$ s/mm ²	0.39 (0.16)		0.48 (0.36)	

Discussion: Our results in vivo (in particular those in row b) agree reasonably with recently published data⁸, which may be affected to a certain degree by IVIM and/or noise effects. Generally, more b-values (than 6 as used in this study) are desirable for a detailed analysis of different influences on the signal attenuation; however, a further increased scan duration is frequently not tolerable in DKI protocols.

Conclusions: IVIM effects and, in particular, image noise can considerably influence the kurtosis determined in DKI outside the brain leading to a parameter bias of about +10 % and +90 %, respectively. Using a noise-aware fit and a minimum b-value of 200 s/mm² reduces this bias substantially.

References: 1. Jensen JH et al. NMR Biomed. 2011;24:452. 2. Le Bihan D et al. Radiology 1988;168:497. 3. Koh D et al. AJR 2011;196: 1351. 4. Miller AJ et al. Magn Reson Imaging 1993;11:1051. 5. Schneider M et al. Proc ISMRM 2012;20:2029. 6. Döpfert J et al. Magn Reson Imaging 2011;29:1053. 7. Riches SF et al. NMR Biomed 2009;22:318. 8. Rosenkrantz AB et al. Radiology 2012;264:126.

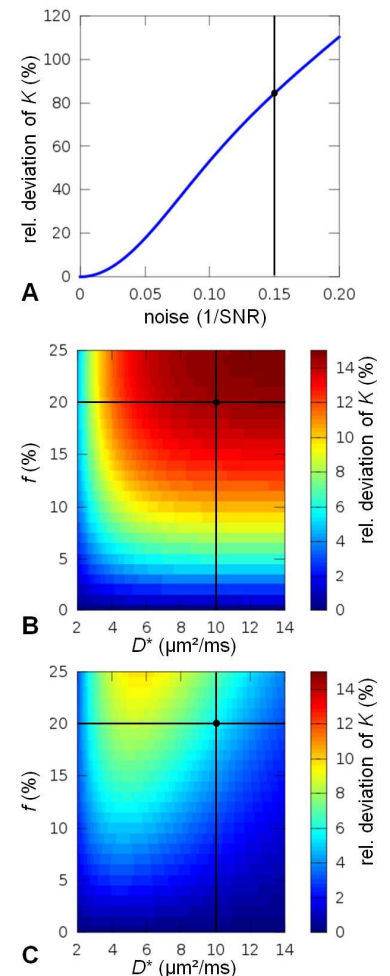


Fig. 1: Relative deviation of kurtosis K depending on: (A) the SNR (at $b=0$), (B) IVIM parameters f , D^* with $b_{\min}=0$ and (C) f , D^* with $b_{\min}=200$ s/mm². Black lines (with circle) indicate typical prostate parameters.