Relaxation Time Effects in Intra Voxel Incoherent Motion Imaging

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Introduction:

Recently, parameters extracted from the intra voxel incoherent motion (IVIM) theory [1] have been reported to be of use to differentiate abdominal lesions from healthy tissue [2,3]. The IVIM theory predicts an additional component to the monoexponential signal decay measured with diffusion weighted imaging (DWI) due to perfusion. However, in the original IVIM approach, relaxation effects are neglected. This may apply when the relaxation time of tissue and blood are similar. But, when these relaxation times diverge, e.g. in the abdomen, the extracted perfusion related parameters may exhibit a dependency on measurement parameters such as TE and TR. To this end the signal was measured as a function of b-value in the pancreas under varying echo times and a modified equation, incorporating relaxation effects, was introduced. Parameters derived from this equation were compared to the original IVIM equation.

Materials and Methods:

DWI-data of six healthy volunteers was acquired using three echo times (TE=50, 70 and 100 ms) at 1.5 Tesla (Magnetom Avanto, Siemens Healthcare, Erlangen). Axial DWI was performed using a single-shot echo-planar imaging (SE-EPI) pulse sequence in expirational breath-hold: TR=2800 ms, matrix size=100x78 with a 3.5 mm resolution, 14 slices, thickness/gap=5/0.25 mm, GRAPPA with acceleration factor 2, spectral fat saturation, 2 averages and a bandwidth of 3000 Hz/pixel. Diffusion weighting was accomplished with a twice-refocused spin echo diffusion preparation using eight different b-values ranging from 0-300 s/mm^2. The acquisition was separated into seven blocks (b_0, b_{25}), (b_0, b_{50})…(b_0, b_{300}), each block was acquired in a single breath-hold (TA=31 s) to avoid motion artifacts, total measurement time six minutes. The DWI images in different expirational breath-holds were co-registered with a linear rigid transformation and the Downhill Simplex method. The signals averaged over the individual groups were fitted to the biexponential IVIM-equation according to [1] (yielding the perfusion fraction f, the diffusion constant D and the pseudo diffusion coefficient D*) and to the modified relaxation compensated equation 1. For analysis of the data from individual subjects, only two parameters were fitted, D* was fixed to 59.4 µm²/s. This value was inferred from the experiments where signal of the individual groups were averaged and then fitted. A stable three parameter fit for individual data would require a higher SNR than available with our experimental setup [4]. To test for statistically significant differences in the single subject IVIM-parameters that were determined with varying echo times, a Friedman test was used.

Results:

Figure 1 shows diffusion weighted images acquired with two different echo times. Figure 2 shows the average signal intensities of the six subjects in the pancreas. The signal is plotted as a function of the applied b-value for TE=50 ms, TE=70 ms and TE=100 ms. With increasing TE, a faster signal decay at low b-values (b=25 s/mm²) is observed. This can be attributed to a faster transversal relaxation of the tissue signal which increases the signal fraction of the vascular compartment. A three parameter fit derived from the averaged data using the IVIM equation yields: f=11.4±0.7 %, 20.2±1.6 %, 24.2±1.0 %; D=1.59±0.05 µm²/ms,1.43±0.11 µm²/ms, 1.33±0.07 µm²/ms; D*=148±158 µm²/ms, 78±31 µm²/ms, 123±53 µm²/ms, for TE=50, 70, 100 ms, respectively. The mean values of individual two parameter fits at different echo times are shown in table 1. The perfusion fraction f increases significantly with increasing echo time (P=0.0025), whereas the relaxation time compensated perfusion fraction f ' showed no significant dependence on TE (P=0.31). The relaxation time compensation has no influence on the diffusion coefficient. D and D' are not significantly different under varying TE.

Discussion:

Our results demonstrate that perfusion fraction is indeed dependent on echo time. Since the relaxation time of blood differs considerably from pancreatic tissue and the exchange time of water protons in the capillaries (0.5 s [5]) is five times higher than the maximal TE, it can be assumed that the blood signal is the main contributing factor causing the non-monoexponential signal decay. The echo time dependence of f is most important for tissues whose transversal relaxation time is considerably shorter than that of blood. This effect can be expected to be significant for IVIM-imaging of organs with short T_2 times like pancreas, liver and muscles (46 ms, 46 ms, 27 ms at 1.5 T respectively [6]) and may be reduced in the brain (T_2=72 ms and 95 ms at 1.5 T for gray and white matter [7]). To permit a useful comparison of results of different studies, it is essential that echo times are properly reported or better still, that the relaxation time compensated IVIM equation should be applied.

References:

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$$\frac{S}{S_0}=\frac{(1-f')\cdot\left(1-\exp\left(-\frac{TR}{T_{1\,tiss}}\right)\right)\cdot\exp\left(-\frac{TE}{T_{2\,tiss}}-bD'\right)+f'\cdot\left(\left(1-\exp\left(-\frac{TR}{T_{1\,bl}}\right)\right)\cdot\exp\left(-\frac{TE}{T_{2\,bl}}-b(D'+D'^{*})\right)\right)}{(1-f')\cdot\exp\left(-\frac{TE}{T_{2\,tiss}}\right)\cdot\left(1-\exp\left(-\frac{TR}{T_{1\,tiss}}\right)\right)+f'\cdot\exp\left(-\frac{TE}{T_{2\,bl}}\right)\cdot\left(1-\exp\left(-\frac{TR}{T_{1\,bl}}\right)\right)}$$

Eq. 1: Modified relaxation compensated IVIM equation. T_{1tiss}, T_{2tiss} and T_{1bl}, T_{2bl} are the longitudinal and transversal relaxation times of pancreatic tissue and blood respectively, yielding the relaxation time compensated IVIM parameters D'^{*}, D' and f '.

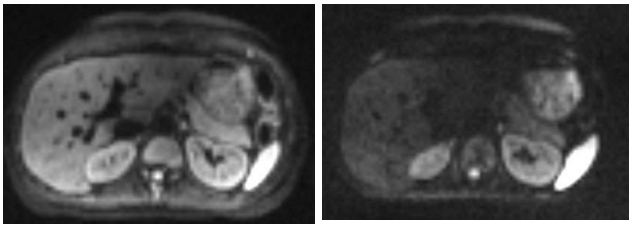

Fig. 1: Diffusion weighted (b=300 s/mm²) echo planar image of an abdominal slice obtained with: TE=50 ms (left) and TE=100 ms (right)

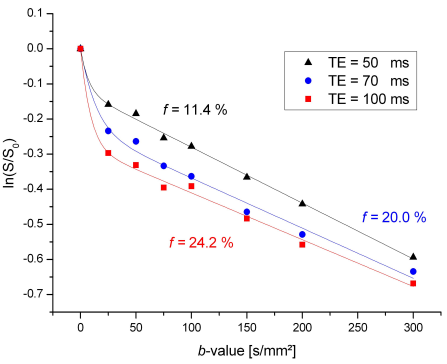

Fig. 2: Signal measured in the pancreas. The signal decays faster at low b-values at longer echo times indicating an increased perfusion fraction. This can be explained by a shorter transversal relaxation time of the tissue signal

	f [%]	f ' [%]	D [µm²/ms]	D' [µm²/ms]
TE=50 ms	13.3±4.0 (8.3-17.9)	6.7±2.3 (4.0-9.3)	1.44±0.20 (1.17-1.67)	1.44±0.20 (1.17-1.67)
TE=70 ms	20.2±5.8 (13.6-26.7)	7.8±2.6 (4.4-10.7)	1.49±0.50 (1.02 -2.30)	1.49±0.50 (1.02 -2.30)
TE=100 ms	26.3±5.0 (20.4-31.9)	6.1±1.5 (4.5-7.8)	1.19±0.34 (0.70-1.51)	1.19±0.34 (0.70-1.51)
P	0.0025	0.31	0.17	0.17

Tab. 1: Mean values of the calculated IVIM parameters at different echo times using the standard IVIM equation and the modified equation including relaxation effects. The maximum range is shown in parenthesis. The perfusion fraction f increases significantly with increasing echo time, whereas the modified perfusion fraction f ' shows no significant difference.