Characterizing the diffusion properties of blood

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Target audience: Researchers interested in the intravoxel incoherent motion (IVIM) model or in the properties of blood in diffusion MRI.

Purpose: To characterize the dependence of the apparent diffusion coefficient (ADC) of human blood samples on diffusion time (T), echo time (TE) and diffusion gradient profile.

Introduction: Recent findings[1] have shown the utility of using both bipolar and flow-compensated diffusion gradients for IVIM measurements in liver and pancreas. Model parameters like D* and the characteristic timescale and velocity of the incoherent motion are accessible by application of such gradients for different T. Since the flow-compensated signal in the examined organs does not exhibit the strong biexponential decay known from bipolar gradients, the diffusion coefficient of blood D_b becomes a non-negligible parameter in the IVIM model. Diffusion time and gradient profile dependent values for D_b are not available in the literature and thus the aim of this work was to measure this reference data.

Methods: The phantom used to measure the diffusion coefficient of blood samples is shown in Fig.1. It allows one to keep the temperature constant and to rotate the sample to prevent sedimentation of blood cells, which is known to significantly alter the lineshape within 3 min[2]. Blood drawn from five healthy volunteers was examined at 37°C. A blood picture was provided for each sample. Diffusion times from 40 to 100 ms which are typical for IVIM measurements were chosen and blood ADCs were measured using both bipolar and flow-compensated diffusion gradients. Acquisition parameters were TR = 2,5 s, TE = 120 ms, BW = 2000 Hz/Pixel, matrix 100 x 78, GRAPPA 2, 5 slices of 5 mm thickness, in plane resolution 2,5 x 2,5 mm, 3 diffusion gradient directions, 1,5 T Magnetom Symphony (Siemens Healthcare, Erlangen, Germany). Diffusion weighting was achieved using the b-values 0, 50 and 150 s/mm^2. Different echo times from 60 to 140 ms were applied in a subsequent study. Total duration of each protocol step was below 3 min to allow for frequent rotation of the sample. Details on the pulse sequence can be found in[1]. Data evaluation was based on regions of interest, mean signal intensities were averaged over all 3 diffusion gradient directions and 5 slices and ADCs were calculated using all b-values.

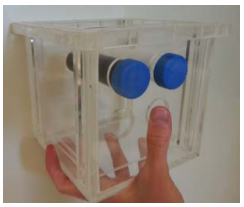

Fig.1: Water tank with rotatable sample tubes.

Results: Measured ADCs are plotted against effective diffusion times (T_{eff}) in Fig.2. The term 'effective' describes the time to the first refocusing of magnetisations due to the diffusion gradients, which is approx. one third of the total duration of the diffusion experiment for the flow-compensated profile whereas the effective time equals T in the bipolar case (see Fig.3). ADCs decrease with increasing T_{eff} for the flow-compensated measurements. At longer times above 40 ms, which are covered by the experiments with bipolar gradients, ADC values are smaller and no trend is visible. A slight increase in measured ADCs was observed for increasing echo times (data not shown). Tab.1 shows the ADCs averaged over all measurements with different T for both gradient profiles compared to the volunteer's haematocrit. Except for the last volunteer, ADCs increase with decreasing haematocrit.

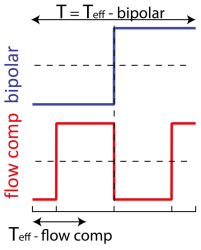

Fig.3: Gradient profiles

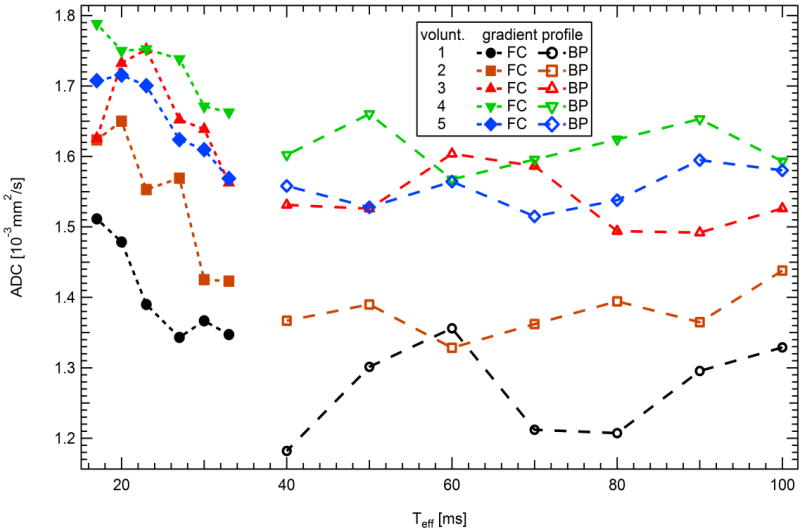

Fig.2: ADCs measured for different samples and diffusion times. A clear trend is only visible in the flow-compensated case.

volunteer	haematocrit	$ADC_{bipolar}$ $\left[10^{-3}\ \frac{mm^2}{s}\right]$	$ADC_{flow\ comp}$ $\left[10^{-3}\ \frac{mm^2}{s}\right]$
1	0.439	1.27 ± 0.07	1.41 ± 0.07
2	0.426	1.38 ± 0.03	1.54 ± 0.10
3	0.418	1.54 ± 0.04	1.66 ± 0.07
4	0.389	1.61 ± 0.03	1.73 ± 0.05
5	0.384	1.55 ± 0.03	1.65 ± 0.06

Tab.1: ADCs averaged over all diffusion times for both gradient profiles compared to haematocrit of blood samples.

Discussion: Water diffusion in blood is restricted by the red blood cells' membranes. The observed dependence of the ADC can thus be understood as the diffusion process approaching the long-term limit[3] with increasing T. The signal variations visible in the bipolar case might, however, overshadow a continuing decrease. Increasing ADCs for longer echo times could be explained by smaller T_2 decay times inside red blood cells and by less restricted diffusion in plasma[4]. Both mentioned effects are however small compared to differences in the measured ADC between individual blood samples.

Conclusion: The measured blood ADCs vary strongly between individual volunteers and also show a dependence on T and TE. The accuracy of IVIM measurements might be improved by considering individually measured values of D_b.

References: [1] Wetscherek *et al.* MRM 2014, DOI 10.1002/mrm.25410; [2] Spees *et al.* MRM 2001, 45:533-542; [3] Grebenkov *et al.* Rev. Mod. Phys. 2007, 79:1077-1137; [4] Stanisz *et al.* MRM 1998, 39:223-233