Identification of over-estimated diffusion coefficients obtained with very high b-values in diffusion MRS

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Introduction: Diffusion magnetic resonance spectroscopy (MRS) allows for studying the environment of specific metabolites, including the cellular ultra structure in which the metabolites are embedded. Intramyocellular lipids (IMCL) are metabolically highly active and related to insulin resistance and to the endemic metabolic syndrome [1]. Therefore, the diffusion properties of IMCL droplets are of great interest because they might influence function and availability of IMCL [2]. Due to the extremely slow diffusion of lipids, and IMCL in particular, diffusion measurements of IMCL in vivo require very high b-values making the measurements prone to artifacts. Among these are eddy currents, which are arising from rapid switching of currents in gradient coils and lead to a reduction of the signal intensity. Since this artifact can lead to an overestimation of the diffusion coefficient (ADC) of IMCL, we propose a method to identify misadjustments of diffusion gradient pairs. We have also tested the effect of a gradient cycling scheme [3] to improve diffusion measurements.

Methods: Measurements were performed on two 3T systems: TRIO and VERIO (Siemens Medical, Erlangen, Germany) using the spine and body matrix coils. A lard phantom (~ 1 kg) was measured at room temperature (~ 23°C) and placed in the isocenter of the magnets and also in a location approx. 15 cm offcenter, mimicking the position of the VOI in muscle measurements [2]. A modified STEAM sequence allowed for a complete inversion of all gradients in an interleaved manner. In addition, the amplitude of the 2nd diffusion gradient pulse could be adjusted in 0.001 mT/m steps. A sweep from -0.015 to 0.015 mT/m was sampled. For all measurements were TR = 1500 ms, TE = 125 ms, TM = 50 ms, diff. gradient strength G = 17 and 30 mT/m per axis, diff. pulse duration $\delta = 40$ ms and effective diffusion time $\Delta = 112.2$ ms. These settings corresponded to b-values of $3x10^4$ and $1x10^4$ s/mm^2 respectively.

Results: Due to the presence of eddy currents, the signal maxima are not observed with numerically balanced diffusion gradients (0 mT/m on the x-axis), but are shifted towards left or right depending on the polarity of the gradients (Fig. 1). With use of numerically balanced diffusion gradients – as shown in Fig.1, the signal amplitude is reduced in this example by 3.7% with the 17 mT/m-gradients and 10% with the 30 mT/m-gradients, confirming that eddy current effects would lead to a considerable over-estimation of the ADC. Table 1 summarizes this gradient misbalance (shift of the signal maxima on the x-axis) for the two MR systems, for isocenter vs. offcenter positions, and positive vs. inverted gradients. Table 2 illustrates that neither gradient cycling [3], nor the introduction of a 15 ms gap between the 1st diffusion gradient and the 2nd RF-pulse completely removes the eddy-current related artifact. Tables 1 and 2 also illustrate that (1) eddy currents are not necessarily symmetrical (inversion of gradients does not always lead to an inversion of the eddy current), (2) eddy current do not scale with the strength of the diffusion gradients, and moreover (3) eddy currents may but don't have to be more prominent offcenter (depending on the pre-emphasis adjustment by the manufacturer).

Discussion: Eddy currents present in MRS diffusion measurements add to the gradient amplitudes which can lead to improper rephasing of the signal and consequently to a signal reduction and thus to an overestimation of the ADC. Metabolites with very slow diffusion, such as IMCL, are particularly prone to such effects. As a proof-of-principle, a pulse sequence allowing modification of the 2nd diffusion gradient amplitude in small increments shows how the influence of eddy currents, their correction schemes or related hardware imperfections, can be assessed. While the amplitude of correction gradients are relatively small (typically 0.002 mT/m – being in the order of shim gradient amplitudes), the effects on the signal amplitude with numerically balanced diffusion gradients is considerable, from modest 1% up to prohibitive 10 %. The potential addition/subtraction of shim-effects further complicates the situation and may be responsible for the non-linearity of the effect.

References: [1] Boesch C. et al. NMR Biomed 19:968 (2006) [2] Brandejsky V. et al. MRM Epub ahead of print (2011) [3] Lin C. et al. JMRI 4:823 (1994)

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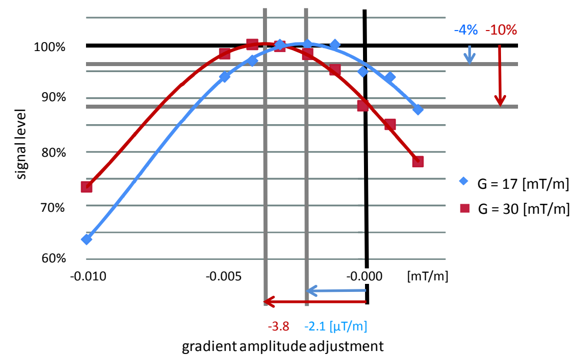

Fig. 1: The effect of eddy currents on balanced diffusion gradients. Due to the currents, the maxima are shifted to the left and the signal amplitude is reduced by 4% and 10% depending on the diffusion gradient amplitude. Lines represent fit of a 4th order polynomial of the data.

TRIO		isocenter		offcenter	
gradient amp. [mT/m]		G=17	G=30	G=17	G=30
Negative	*shift [µT/m]*	-2.1	-3.8	-0.5	-1.4
	decrease [%]	3.7	10	1.16	2.4
Positive	*shift [µT/m]*	1.4	0.5	0.6	0.1
	decrease [%]	2.5	1.26	1.1	0.8
VERIO		isocenter		offcenter	
gradient amp. [mT/m]		G=17	G=30	G=17	G=30
Negative	*shift [µT/m]*	-1.3	30	11	1.3
	decrease [%]	2.4	9.7	53 *	2.6
Positive	*shift [µT/m]*	-1.4	-1.9	10	4.7
	decrease [%]	2.4	3	45 *	17.4

Table 1: Summary of the lard phantom measurements. Signal shift on the x-axis and relative signal decrease are shown for the two systems. Negative/Positive indicates whether the gradients have been in standard direction or inverted. * Due to strong eddy currents, the sweep range was too short to obtain reliable fits.

TRIO		isocenter		offcenter	
gradient amp. [mT/m]		G=17	G=30	G=17	G=30
Corrected	*shift [µT/m]*	-0.3	-1.6	0.1	-0.9
	decrease [%]	1.1	2.3	0.2	1.7
Corrected	*shift [µT/m]*	-0.2	-1.5	0.1	-1.4
+ Gap	*decrease [%]*	0.7	3.3	0.4	3.4
VERIO		isocenter		offcenter	
gradient amp. [mT/m]		G=17	G=30	G=17	G=30
Corrected	*shift [µT/m]*	-1.3	-2.4	-10	-7.5
	decrease [%]	2.2	4.6	50 *	14
Corrected	*shift [µT/m]*	0.5	0.9	4	0.5
+ Gap	*decrease [%]*	1	0.75	38 *	1.1

Table 2: The effect of correction algorithm from [3] and of a gap introduced before the 2nd RF pulse of the STEAM sequence on the resulting signal amplitude and maxima shift. * Due to strong eddy currents, the sweep range was too short to obtain reliable fits.