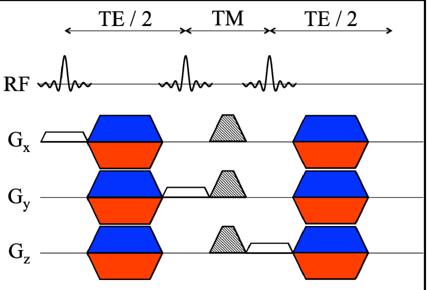
Eddy current correction in diffusion-weighted STEAM MRS in the presence of water and fat peaks

Stefan Ruschke[1], Thomas Baum[1], Hendrik Kooijman[2], Marcus Settles[1], Axel Haase[3], Ernst J. Rummeny[1], and Dimitrios C. Karampinos[1]
[1]*Department of Diagnostic and Interventional Radiology, Technische Universität München, Munich, Germany,* [2]*Philips Healthcare, Hamburg, Germany,*
[3]*Zentralinstitut für Medizintechnik, Technische Universität München, Garching, Germany*

<u>Target audience</u>: Basic scientists working in MRS of fat in skeletal muscle and body organs

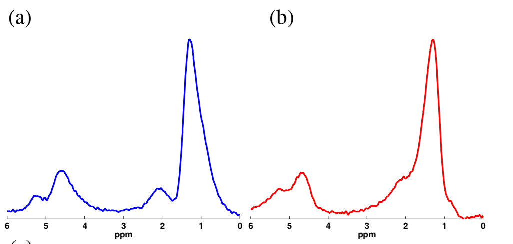
<u>Purpose</u>: Diffusion-weighted (DW) single-voxel MRS has been proposed as a method to study the diffusion properties of adipose tissue [1], to distinguish intramyocellular lipids (IMCLs) from extramyocellular lipids (EMCLs) in skeletal muscle [2,3] and to measure the diffusion properties of the water peak in organs containing fat (e.g. bone marrow, breast, fatty liver) [4]. A common problem encountered in a DW-MRS experiment is the effect of uncompensated eddy currents, originating from the applied strong diffusion-weighted gradients. Eddy current effects can distort the line shapes of the water and fat peaks in the phased real spectrum and affect peak area quantification. Multiple approaches have been previously proposed for correcting eddy current effects in non-DW single-voxel MRS. The most frequently used correction techniques rely on using the phase information from a reference signal, based on the dominant peak of a reference spectrum or based on an isolated single-resonance peak in the measured spectrum [5]. However, the above techniques could not be necessarily applied in DW spectra containing both water and fat peaks and not having a reliable single-resonance peak that could be used as a reference. A first example of such spectra would be bone marrow, where water and fat peaks are broad and overlap. A second example would be skeletal muscle spectra, where the strength of the water peak is highly dependent on the employed b-value and most fat peaks include multiple resonances. An alternative approach, previously proposed for eddy current correction in non-DW MRS, would be the acquisition (instead of two averages) of two MR spectra acquired with opposite diffusion gradient polarities [6]. Therefore, purpose of the present work is to investigate the performance of the eddy current correction approach using opposite diffusion gradient polarities in DW-MRS of tissues where both water and fat peaks are present.

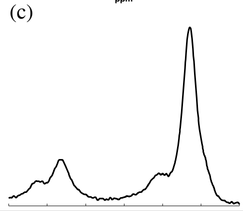


<u>Fig. 1</u>: DW-STEAM MRS sequence: diffusion-weighting gradients were alternating between positive (blue) and negative (red) polarity.

<u>Methods:</u> <u>DW-STEAM sequence:</u> The employed DW-STEAM MRS sequence (Fig. 1) is based on a standard STEAM MRS sequence with additional paired gradients after the first and third RF pulse to induce diffusion weighting. The paired diffusion gradients are switched to opposite polarity for half of the acquired averages. The diffusion gradient strengths are scaled in order to compensate for the area of the slice selective gradients, causing small deviations in the b-value and diffusion gradient orientation between the two polarities. These deviations are expected to have a stronger effect on the water peak than the fat peaks, given the much higher diffusion coefficient of water compared to fat.

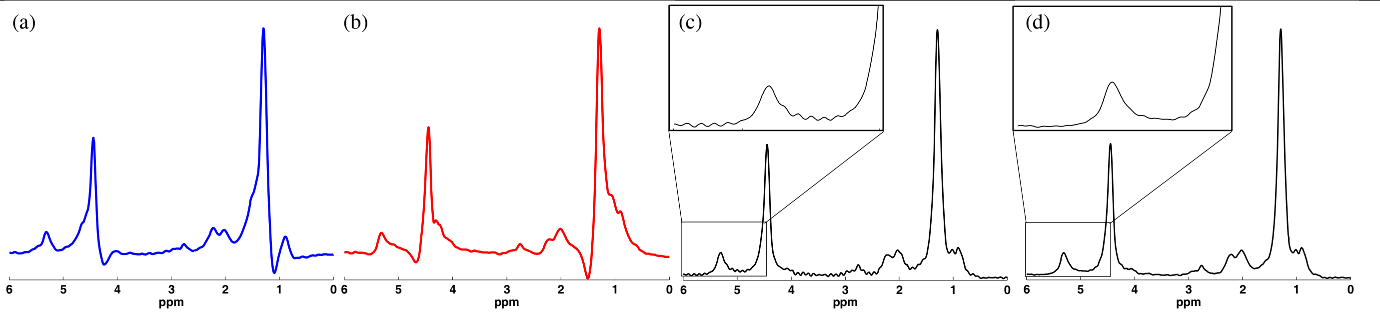
<u>FID signal combination approach:</u> If S(t) is the FID signal in the absence of eddy currents and $\varphi_e(t)$ is the eddy current-induced phase term, then the measured FID with the positive and negative diffusion gradient polarity would be $S_+(t) = S(t)\exp(j\varphi_e(t))$ and $S_-(t) = S(t)\exp(-j\varphi_e(t))$ respectively. A band-pass filter is first applied to eliminate peak contributions in the spectral region between 3.5 and 6 ppm (including the water peak), resulting in the filtered FID signals $S_{f+}(t)$ and $S_{f-}(t)$. The eddy current phase term is then derived using the expression $\exp(j\varphi_e(t))=\mathrm{sqrt}(S_{f+}(t)\ /\ S_{f-}(t))$ and is applied to correct for the eddy current term on $S_+(t)$ and $S_-(t)$. Finally, the corrected FID data from the two polarities are averaged to derive the desired FID signal S(t).





<u>Fig. 2</u>: DW-STEAM MR spectra acquired in the bone marrow: (a) with positive polarity, (b) negative polarity and (c) after the proposed eddy current correction approach.

<u>*In vivo* measurements:</u> The L5 vertebral body (VOI: 16x16x16 mm) and the calf muscle (VOI: 12x12x14 mm) of a healthy volunteer were scanned on a 3T Philips Ingenia scanner. In both regions, a DW-STEAM single-voxel MRS sequence was employed with parameters TR=3000 ms, TE=40 ms, TM=16 ms, BW=3000 Hz, 4096 samples, 64 averages, b-value=~2200 s/mm^2.



<u>Fig. 3</u>: DW-STEAM MR spectra acquired in the skeletal muscle: (a) with positive polarity, (b) negative polarity, (c) after the proposed eddy current correction approach without band-pass filtering and (d) after the proposed eddy current correction approach using a band-pass (excluding the region from 3.5 to 6 ppm).

<u>Results</u>: Fig. 2ab and 3ab show the asymmetric line shapes induced by eddy current effects in DW-MRS of bone marrow and skeletal muscle, respectively. In the bone marrow, the water peak has a similar height (difference in height of 2.8%) in the two acquisitions with positive and negative polarity, while in the skeletal muscle, the water peak has different heights (difference in height of 8.4%). Not applying the band-pass filtering (Fig. 3c) on the skeletal muscle spectrum induces oscillations across the entire spectrum originating from the difference in the water peak heights between the two polarities. After adopting the proposed approach that filters-out the water peak the eddy current effects are removed in both tissues (Fig. 2c and 3d).

<u>Discussion & Conclusion</u>: The present results show that a DW-MRS experiment combining an acquisition with alternating diffusion gradient polarities and the proposed FID signal combination approach can significantly reduce eddy current effects. A DW-MRS scan usually involves the acquisition of multiple averages. Therefore, the implementation of the two alternating diffusion gradient polarities should not increase the total scan time. The spectral region between 3.5 and 6 ppm contains the water peak and should be excluded in the referencing of the eddy current phase term to avoid potential differences in the height of the water peak for the two applied diffusion gradient polarities.

<u>References</u>: [1] Lehnert et al., J Magn Reson Imaging. 2004 Jan;22(1):39-46. [2] Brandejsky et al., Magn Reson Med. 2012 Feb;67(2):310-6. [3] Xiao et al., Magn Reson Med. 2011 Oct;66(4):937-44. [4] Taviani et al., Proc Intl Soc Mag Reson Med 21, 2013. [5] De Graaf et al., Magn Reson Med. 1990 Mar;13(3):343-57. [6] Lin et al., J Magn Reson Imaging. 1994;4(6):823-7.

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