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Effects of eddy currents on selective spectral editing experiments at 3T

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Abstract

PURPOSE—To investigate frequency-offset effects in edited MRS experiments arising from B_0 eddy currents.

MATERIALS AND METHODS—Macromolecule-suppressed (MM-suppressed) GABA-edited experiments were performed at 3 Tesla. Saturation-offset series of MEGA-PRESS experiments were performed in phantoms, in order to investigate different aspects of the relationship between the effective editing frequencies and eddy current associated with gradient pulses in the sequence. Difference integrals were quantified for each series, and the offset dependence of the integrals was analyzed to quantify the difference in frequency (Δf) between the actual vs. nominal expected saturation frequency.

RESULTS—Saturation-offset N-acetyl-aspartate-phantom experiments show that Δf varied with voxel orientation, ranging from 10.4 Hz (unrotated) to 6.4 Hz 45-degree rotation about caudal-cranial axis) and 0.4 Hz 45-degree rotation about left-right axis), indicating that gradient-related B_0 eddy currents vary with crusher-gradient orientation. Fixing the crusher-gradient coordinate-frame substantially reduced the orientation dependence of Δf (to ~ 2 Hz). Water-suppression crusher gradients also introduced a frequency offset, with $\Delta f = 0.6$ Hz ('excitation' water

suppression), compared to 10.2 Hz (no water suppression). *In-vivo* spectra showed a negative edited 'GABA' signal, suggesting f on the order of 10 Hz; with fixed crusher-gradient coordinate-frame, the expected positive edited 'GABA' signal was observed.

CONCLUSION—Eddy currents associated with pulsed field gradients may have a considerable impact on highly frequency-selective spectral-editing experiments, such as MM-suppressed GABA editing at 3T. Careful selection of crusher gradient orientation may ameliorate these effects.

Keywords

Edited MRS; Offset; GABA; Macromolecules; Eddy currents; MEGA-PRESS

INTRODUCTION

The use of spectral editing in *in-vivo* proton magnetic resonance spectroscopy substantially reduces overlap between signals, and increases the accuracy and specificity with which lower concentration compounds can be quantified (1, 2). Most editing methods rely on frequency-selective pulses to modulate the evolution of specific spin-systems of interest. Among these, J-difference editing has been applied to detect a number of metabolites including γ -aminobutyric acid (GABA), glutathione (GSH), lactate, and N-acetyl aspartyl glutamate (NAAG) (1, 3–6).

Editing is usually performed at the maximum-achievable frequency selectivity, which is related to the duration of the editing pulses. The maximum length of the editing pulse is usually limited by the echo time (TE) needed for optimal editing, and the durations of the localizing radiofrequency and field gradient pulses. Editing pulses as long as 45 ms have been reported in some applications (7, 8), corresponding to a bandwidth of 39 Hz. Additionally, symmetrical editing schemes can be employed to boost the selectivity of editing and suppress co-edited signals, most notably unwanted macromolecular (MM) signals in GABA editing (9–11). Increasing the selectivity of the editing pulse reduces the likelihood of co-editing of unwanted compounds, but also increases the sensitivity of the experiment to editing efficiency changes associated with B_0 field drift, resonance frequency (F_0) mis-calibration, or other effects (12, 13).

Pulsed field gradients are important pulse sequence elements, responsible for slice selection and coherence transfer pathway selection, including 'crushing' of unwanted coherences for water suppression and spatial localization. However, despite advances in technology, pulsed field gradients are known to induce eddy currents in conductive components of the magnet structure, which cause transient shifts in the B_0 field (14–16). Eddy currents have a number of potential impacts on MRS experiments, including altering the line shapes of detected signals, which can be corrected post-hoc (17). A less frequently considered effect of eddy currents is their impact on the performance of RF pulses. The majority of MR experiments use relatively non-selective RF pulses, so that this effect can be safely ignored; however, highly selective spectral-editing experiments are uniquely and highly sensitive to such field shifts.

This manuscript was originally motivated by a study using macromolecule-suppressed MEGA-PRESS (9, 10) spectral editing of GABA in an elderly patient population. The unexpected observation of a nulled or net-negative edited GABA signal was consistent across subjects and brain regions. This manuscript investigates the effects of uncorrected eddy currents (resulting from pulsed field gradients) on the performance of selective J-difference editing experiments, and their dependence on voxel orientation and gradient amplitudes are described. A procedure for minimizing eddy-current-related transient B_0 field shifts by use of a fixed gradient orientation is described, and its performance to ensure correct selective editing is investigated.

MATERIALS AND METHODS

All experiments were performed on a Philips 3T 'Achieva' MR scanner (Philips Healthcare LLC, Best, The Netherlands). The body coil was used for transmit, and a 32-channel phased-array volume head coil for receive. All GABA-edited experiments were performed using a MEGA-PRESS sequence (Figure 1A) with the following parameters: TR/TE = 2000/80 ms; 20-ms sinc-Gaussian editing pulses (FWHM bandwidth 53 Hz) as described previously (10). In this implementation of MEGA-PRESS, the editing pulses are applied 1.2 ms after 1.47 ms long crusher gradients (31 mT/m gradient strength, 0.31 ms ramp time, i.e. 100 mT/m/ms slew rate) applied along 2 axes (Figure 1A). The orientations of the crusher gradients vary depending on the rotation of the slice selection gradients.

In-vivo MEGA-PRESS Acquisition Without Fixed Crusher-gradient Coordinate-frame

As part of a clinical study in an elderly patient cohort, one 65-year-old male subject gave informed consent to participate in the study after local IRB approval. Water-suppressed GABA measurements were made in the inferior frontal gyrus and primary sensory motor areas ($3 \times 3 \times 3 \text{ cm}^3$ voxel size, 320 averages, 11 minutes total scan time), in two sessions performed ten days apart. Editing pulses were applied at offsets, relative to the resonance frequency of water ($F_0 = 4.68 \text{ ppm}$ *in-vivo* as determined during pre-scan calibration), of -2.78 ppm (-355 Hz) in the 'ON' experiment, and -3.18 ppm (-406 Hz) in the 'OFF' experiment. These offsets correspond to chemical shifts of 1.9 and 1.5 ppm, i.e. symmetrical about 1.7 ppm (i.e. the presumed frequency of the coupled MM resonance), so as to suppress MM contributions to the difference spectrum (Figure 1B). Data were processed using the 'Gannet' program (18), including 3 Hz exponential line broadening, and frequency-and-phase correction of individual transients using the time-domain spectral registration method (19). Such post-processing correction addresses subtraction artefacts (20), but does not account for signal changes due to editing pulse offsets.

Determination Of Frequency Offsets Due To Eddy-current Effects In The MEGA-PRESS Sequence

Measurements were performed on a $3 \times 3 \times 3 \text{ cm}^3$ voxel in a 1-liter phosphate-buffered saline phantom containing 12.5 mM NAA. The *in-vivo* MM-suppressed editing scheme described above corresponds to pulses applied at $\pm 0.2 \text{ ppm}$ ($\pm 25.5 \text{ Hz}$) relative to a symmetry-point offset of $(1.7-4.68) \text{ ppm} = -2.98 \text{ ppm}$ (-380.5 Hz). In order to characterize the frequency offset-dependence of this editing scheme, a series of experiments were

performed using the MEGA-PRESS sequence, in which this symmetry-point offset was varied, and the intensity of the NAA signal (reduced due to the saturating effects of the editing pulses) at 2.01 ppm in the difference spectrum was measured. In the absence of eddy currents, the NAA signal in the (ON – OFF) difference spectrum will be zero (i.e. of equal magnitude in both ON and OFF experiments) at a symmetry point offset of -2.77 ppm (-353.7 Hz), corresponding to the difference between the chemical shift of NAA, 2.01 ppm, and the chemical shift of water, 4.78 ppm (measured in the phantom at room temperature).

The deviation of the nominal symmetry-point of the MEGA-PRESS experiment from this expected zero-crossing is defined here as δf . Correct editing would occur if the zero-crossing appears at $\delta f = 0$ Hz, and deviations from this value can therefore be viewed as a measure of the eddy-current-associated change in B_0 ($\delta f = \gamma \delta B_0$) during application of the editing pulses. For each offset measurement series, the integral of the NAA signal in the MEGA-PRESS difference spectrum was plotted against δf . The exact frequency of the zero-crossing was determined from a 4th order Fourier series fit to the data points.

To assess eddy-current-induced B_0 shifts, MEGA-PRESS ON/OFF pairs were acquired with varying δf . Unless otherwise noted, all experiments shared a common δf range from -0.33 ppm (-42.2 Hz) to $+0.47$ ppm ($+60$ Hz), corresponding to symmetry-point offsets relative to the water frequency from -3.10 ppm (-395.9 Hz) to -2.30 ppm (-293.7 Hz), in steps of 0.05 ppm (6.4 Hz). In each case, ON and OFF editing pulses were applied at ± 0.2 ppm (± 25.5 Hz) relative to the symmetry-point.

Dependence Of Eddy-current Effects On Crusher-gradient Amplitude

In order to confirm that the transient B_0 shifts relate to the crusher gradients, offset series were acquired from an unrotated (i.e. aligned with the scanner axes) voxel as described above for three different crusher gradient amplitude settings: (i) full crusher gradient amplitude (31 mT/m); (ii) three-quarter amplitude (23.25 mT/m); (iii) half crusher gradient amplitude (15.5 mT/m). The crusher-gradient pulse pairs were separated by 10.6 ms.

Dependence Of Eddy-current Associated Frequency Offsets On Crusher-gradient Orientation

In order to investigate the dependence of eddy currents on crusher gradient orientation, offset series were acquired in the NAA phantom as described above for three different voxel rotation settings (as noted above, the crusher gradients are programmed to follow the same directions as the slice selection gradients, in the version of MEGA-PRESS used). The 3 orientations were: (i) no voxel rotation; (ii) 45-degree rotation about the caudal-cranial axis (i.e. rotating in the axial plane); and (iii) 45-degree rotation about the left-right axis (i.e. rotating in the sagittal plane).

Fixing The Crusher-gradient Coordinate-frame

An option was then implemented in the MEGA-PRESS sequence which allowed the crusher gradient coordinate frame to be fixed, regardless of the voxel orientation. The angle at which the crusher gradient coordinate frame was fixed corresponded to a 45-degree rotation about

the left-right axis. MEGA-PRESS frequency-offset series were acquired as described above from an unrotated voxel with and without the crusher gradient coordinate frame being fixed.

To assess whether use of the fixed coordinate-frame crusher gradients removes orientation-dependence of editing, offset series were acquired as described above with fixed crusher-gradient coordinate-frame, and the following voxel rotations: (i) 22.5° and (ii) 45° about the left-right axis; (iii) 22.5° and (iv) 45° about the anterior-posterior axis; (v) 22.5° and (vi) 45° about the caudal-cranial axis.

Dependence Of Eddy-current Associated Frequency Offsets On Presence Of Water Suppression

In order to investigate whether the use of water suppression (and its associated crusher gradients) also impacts the offset of the editing pulses, saturation-offset series were performed with, and without, the Philips ‘excitation’ water suppression module (Figure 1C). The crusher-gradient coordinate-frame was fixed. With water suppression, MEGA-PRESS offset series were acquired as described above. Since quantifying the NAA reporter signal is challenging in the presence of an unsuppressed water signal, saturation pulses were applied around the water signal in this series. Thus, without water suppression, MEGA-PRESS saturation experiments were performed in which the editing pulses were applied at offsets (from the water signal) of -0.45 ppm (-57.5 Hz) to $+0.55$ ppm ($+70.2$ Hz) in steps of 0.05 ppm (6.4 Hz). The water signal from the ON spectrum was integrated in each experiment. Although the water signal is used in the series without water suppression, and the NAA signal in the series with water suppression, the deviation of the editing pulse center frequency from the ideal (-353.7 Hz for NAA, 0 Hz for water) can be assessed in each case and directly compared.

Further, MEGA-PRESS offset series were acquired as described above from an unrotated voxel with fixed crusher-gradient coordinate-frame and varied water-suppression gradients of the Philips ‘Excitation’ module (cf. Fig. 1C): (i) full gradient amplitude (G_1 : 12 mT/m and -12 mT/m; G_2 : 10 mT/m, G_3 : 10 mT/m); (ii) $\frac{3}{4}$ gradient amplitude (G_1 : 9 mT/m and -9 mT/m; G_2 : 7.5 mT/m, G_3 : 7.5 mT/m); (iii) $\frac{1}{2}$ gradient amplitude (G_1 : 6 mT/m and -6 mT/m; G_2 : 5 mT/m, G_3 : 5 mT/m); (iv) $\frac{1}{4}$ gradient amplitude (G_1 : 3 mT/m and -3 mT/m; G_2 : 2.5 mT/m, G_3 : 2.5 mT/m).

MEGA-PRESS Of GABA With And Without Fixed Crusher-gradient Coordinate-frame

GABA-edited MEGA-PRESS data were acquired from a GABA phantom with and without fixing the crusher-gradient coordinate-frame. The ON, OFF and difference spectra of the 3-ppm GABA multiplet were compared to simulated MEGA-PRESS spectra with (i) the symmetry-point of the MEGA-PRESS sequence at 1.7 ppm; and (ii) the symmetry-point offset by 10 Hz.

In order to investigate whether fixing the crusher-gradient coordinate-frame restores the expected positive edited GABA peak in the *in-vivo* spectrum, GABA-edited MEGA-PRESS data were acquired with and without fixing the crusher-gradient coordinate-frame from an unrotated voxel in the midline parietal region in three healthy male subjects (mean age 30 ± 3.4 y) after providing written informed consent. Acquisition and post-processing details

were identical to the *in-vivo* acquisition described above, except for the use of the fixed crusher-gradient coordinate-frame.

RESULTS

In-vivo MEGA-PRESS Acquisition Without Fixed Crusher-gradient Coordinate-frame

Four *in-vivo* MM-suppressed GABA-edited MEGA-PRESS difference spectra from one subject (2 brain regions, 2 time points) are shown in Figure 2. In all four spectra, the edited 'GABA' peak at 3 ppm appears negative, while the remaining peaks in the spectrum show their expected polarity, i.e. Glx at 3.75 ppm is positive and NAA at 2.01 ppm is negative. NAA, creatine and choline singlets in the editing sum spectrum (not shown) are measured at their expected chemical shifts (2.01 ppm, 3.02 ppm, and 3.20 ppm, respectively), indicating that this does not arise from a mis-calibration of F_0 , but rather appears to be due to a transient shift of the magnetic field during the application of the editing pulses.

Phantom Measurement Of Frequency Offset

The notion of a transient field shift was further supported by data from the NAA phantom (Figure 3A). Two curves are plotted; the expected editing efficiency function (in the absence of eddy currents, black line) and the offset-shifted function that fits the experimental data points (gray). In the case of correct editing, the zero-crossing should appear at $f = 0$ Hz (corresponding to an offset from water of -353.7 Hz, i.e. a chemical shift offset of -2.77 ppm between the water signal at 4.78 ppm and the NAA signal at 2.01 ppm (21)). However, the observed zero-crossing occurs at $f = 11.5$ Hz, i.e. the actual symmetry-point of the MEGA-PRESS sequence occurs 0.09 ppm closer to the water signal than the nominal one.

Crusher-gradient-amplitude-dependence Of Offset

The observed frequency offset varied with crusher gradient amplitude (Figure 3B). The observed zero-crossing appears at $f = 10.0$ Hz for the full gradient amplitude of 31 mT/m (light gray), $f = 7.4$ Hz for the $\frac{3}{4}$ gradient amplitude of 23.25 mT/m (dark gray), and $f = 0.4$ Hz for the half gradient amplitude of 15.5 mT/m (black). These series differ only by the crusher gradient amplitude; the voxel rotation and gradient coordinate frames were kept constant.

Voxel-rotation Dependence Of Offset

The NAA difference integral plotted against f is shown in Figure 4A for three voxel orientations, clearly demonstrating that the editing efficiency curve is shifted in each case. Zero-crossings occur at $f = 10.4$ Hz for the unrotated voxel (light gray), $f = 6.4$ for the axially rotated voxel (dark gray), and $f = 0.4$ Hz for the sagittally rotated voxel (black). Experimentally, these series only differ by the coordinate frames in which slice-selective and crusher gradients are defined.

Fixing The Coordinate Frame of PRESS Crusher Gradients

The NAA difference integrals are plotted against f in Figure 4B, for fixed crusher gradient coordinate frame (black), and the crusher gradient coordinate frame determined by voxel

orientation (gray). Zero-crossings occur at $f = 0.1$ Hz for the fixed coordinate frame, and at $f = 11.5$ Hz for the coordinate frame determined by voxel orientation. Fixing the crusher gradient coordinate frame substantially reduced the previously observed incorrect offset of the editing pulse frequency.

The NAA difference integral is plotted against f in Figure 4C for voxel rotations about the left-right axis (black), the anterior-posterior axis (dark gray), and the caudal-cranial axis (light gray). Solid lines indicate a 45° rotation; dotted lines represent a 22.5° rotation. Zero-crossings appeared at $f = 0.1$ Hz (RL45); $f = 0.3$ Hz (RL22.5); $f = 0.2$ Hz (AP45); $f = -0.5$ Hz (AP22.5); $f = 2.0$ Hz (FH45); and $f = -0.7$ Hz (FH22.5), respectively.

Dependence On Water Suppression

The saturation-offset series for NAA and water are shown in Figure 5A, acquired with and without water suppression, respectively. In case of correct editing, the minima of both signal envelopes should occur at $f = 0$ Hz, corresponding to -353.7 Hz from water for the NAA saturation series, and to 0 Hz from water for the water saturation series.

The minimum of the NAA saturation series fit (upper panel) appears at $f = 1.0$ Hz. However, the minimum of the water saturation series (lower panel) appears at $f = 10.2$ Hz.

The NAA difference integral is plotted against f in Figure 5B for water-suppression gradients with full amplitude (black), $\frac{3}{4}$ amplitude (dark gray), $\frac{1}{2}$ amplitude (medium gray), and $\frac{1}{4}$ amplitude. Zero-crossings for the editing efficiency curves appeared at $f = 0.4$ Hz, $f = 2.0$ Hz, $f = 3.3$ Hz and $f = 5.7$ Hz, respectively.

Given the dependence of editing pulse f on gradient factors, these results suggest that the additional crusher gradients employed for water suppression also alter the effective editing pulse offset.

MEGA-PRESS Of GABA With And Without Fixed Crusher-gradient Coordinate-frame

Simulated (black) and phantom (green) spectra of the 3-ppm GABA multiplet are shown in Figure 6A. The right column indicates that the lineshapes of the GABA signal acquired from the phantom with fixed crusher-gradient coordinate-frame are consistent with the intended editing behavior (i.e. correct frequency offset of the MEGA-PRESS symmetry-point). The left column shows that the lineshapes of the GABA signal acquired from the phantom without the crusher-gradient coordinate-frame are consistent with a 10-Hz symmetry-point offset, resulting in decreased edited GABA signal in the difference spectrum.

The edited spectra from the three *in-vivo* acquisitions with (red) and without (black) fixed crusher gradient coordinate frame are shown separately for each subject in Figure 6B. Consistently, no edited signal appears at 3 ppm for acquisitions without the fixed crusher gradient coordinate frame, while the spectra with the fixed frame feature a clear positive 'GABA' peak at 3 ppm. This suggests that eddy-current induced B_0 effects on the order of 10 Hz, which otherwise negatively impact the precision needed for highly selective editing, can be compensated for by fixing the crusher gradient coordinate frame.

DISCUSSION

Frequency-selective spectral-editing substantially increases the scope of proton MRS, beyond measurements of only the few most concentrated metabolites. The method relies on being able to apply editing pulses at a specific radiofrequency that corresponds to a given chemical shift of the molecule to be edited. This paper shows that eddy-current effects, while relatively small and transient, can have significant effects on the performance of spectral editing experiments that use very selective pulses, particularly those which use the symmetrical editing scheme, as typically used for MM-suppressed GABA measurements. This manuscript also demonstrates that the effects can be minimized by finding (and fixing, independent of slice selection orientation) crusher gradient orientations which have the least eddy current effects on the sequence.

The initial observation of a negative signal in MM-suppressed GABA-edited spectra was surprising. This effect was consistently seen in an elderly study cohort (although data is presented from one exemplary subject here for brevity). It has previously been reported that MM-suppressed editing is highly susceptible to mis-calibrations in the F_0 water frequency (12, 13). However, it was clear that in the case of these data, F_0 itself was not mis-calibrated, as evidenced by the correct resonance frequencies observed for the major metabolite signals during data acquisition. Therefore, we hypothesized that the resonance frequencies of the spins of interest changed during the experiment due to transient perturbations of the B_0 field due to eddy currents, so that editing pulse frequencies did not correspond as intended to chemical shift offsets.

Phantom experiments confirmed this transient field shift during the editing pulses, and established that the magnitude of the effect depended on the amplitude of the crusher gradients, as well as on the voxel orientation, which also defines the crusher gradient orientation. Given that the radiofrequency pulses do not change when the gradient amplitude is modulated or the voxel is rotated, this unambiguously established that the effect is related to the gradient pulses. In the implementation of MEGA-PRESS used, all pulse sequence gradients are planned in the coordinate frame of the voxel, and both slice-selection gradients and crusher gradients change as the voxel is rotated. This is also true for the crusher gradients associated with the water-suppression module, explaining the finding that the effect was different between scans with and without water suppression.

The observed transient B_0 field shift had the effect that the MEGA-PRESS editing pulse pair was effectively applied closer to the water signal than intended. For MM-suppressed GABA editing, the 1.9-ppm pulse in the ON experiment moves away from the 1.9-ppm GABA resonance, resulting in reduced GABA editing efficiency. At the same time, the 1.5-ppm pulse in the OFF experiment moves closer to the 1.7-ppm MM resonance, resulting in increased MM editing efficiency. The total 3-ppm signal in the difference spectrum will therefore be strongly reduced, as it contains less positive contribution from GABA, and a negative contribution from MM. This behavior explains the initial observation of nulled or even net-negative total signal in the difference spectrum, and is consistent with previous work underlining that editing pulse offsets drastically affect GABA quantification in the MM-suppressed editing experiment (13). The total signal from MM-suppressed experiments

is about 10 times more susceptible to frequency offsets than conventional editing without MM suppression, with a relative signal change of as much as 8–9% per Hz-off-resonance. A relatively moderate editing pulse Δf of $\sim \pm 4$ Hz will cause signal changes of about $\pm 30\%$ (compared to only about $\pm 3\%$ in the case of conventional editing). For editing pulse Δf of more than ~ 13 Hz, the negatively edited MM signal is expected to outweigh the positively edited GABA signal, giving a net-negative signal as observed, and providing no meaningful GABA estimate at all (see e.g. Figures 3C, 4B in reference (13)). This would be accentuated in older subjects who may have a lower ratio of GABA to MM than younger subjects (22, 23).

The magnitude of the eddy currents, their time constants, and differences in eddy-currents as a function of gradient amplitude and direction, will depend on a number of factors including the scanner, pulse sequence implementation, and the gradient hardware; the solution found in the current study may not be applicable to all scanners. We also note that the underlying cause of the frequency shift during editing pulses may be due to incorrect or incomplete eddy-current compensation ('pre-emphasis' (24) as implemented by the MRI manufacturer) as well as the eddy currents themselves; however, in our own case, we saw similar effects both before and after the gradient compensation was recalibrated by a service engineer. Further, we note that the two editing pulses within the MEGA-PRESS sequence are likely to experience different effective transient field shifts, as their timing relative to the various eddy-current inducing gradients (water suppression gradients and PRESS crusher gradients) is not equivalent. However, independent characterization of the offset behavior of each of the editing pulses is experimentally challenging, and would lie beyond the scope of this manuscript.

During the course of a multi-site project collecting MM-suppressed GABA-edited MRS data from 25 research sites worldwide on GE, Philips and Siemens scanners (25), nulled or net-negative GABA signals were observed in the data from at least three sites. These three sites all use our implementation of the MEGA-PRESS pulse sequence, while the same sequence delivers normal results on the majority of scanners. It is currently still unclear whether the eddy-current related effect can be attributed to the scanner type, scanner software version, or other site-specific parameters. It is difficult to retrospectively assess whether previous GABA MRS studies have been affected by eddy-current effects. Systematic over- or underestimation of GABA levels should be taken into account as a potential source of error in studies using MM-suppressed editing, while the concern is substantially reduced for studies that used conventional editing without MM suppression.

We suggest that sites implementing MM-suppressed editing of GABA should establish whether transient field shifts are present on their system. The key experiment is to perform a series of editing experiments using highly selective editing pulses with varying editing pulse frequency offsets in a phantom with a strong signal, such as NAA or water. The difference integral is expected to pass through a zero-crossing when the editing pulses are symmetric about the desired observed signal. If the observed zero-crossing point differs from this expectation, editing pulses are not being played out at the desired chemical shifts. If such an effect is observed, the next step (as presented here) is to establish the extent to which changing crusher gradient amplitude and/or rotation modulates the effect.

In conclusion, this study has determined that small shifts in the B_0 field due to gradient-induced eddy-currents can have significant effects on the performance of spectral-editing experiments using highly selective RF pulses. MM-suppressed GABA-editing is particularly sensitive to such effects (12, 13). Since frequency shifts of the order of 1–10 Hz do not significantly impact other MRI and MRS experiments, it is likely that such shifts exist on many scanners without the operators necessarily being aware of this. It is recommended that careful series of phantom experiments should be performed for each scanner on which highly selective editing experiments are to be performed, in order to check editing efficiency and MM suppression.

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Figure 1.

(A) Schematic diagram of the MEGA-PRESS sequence used in this study, including RF pulses for localization and editing, and pulsed field gradient pulses for slice selection and coherence selection. (B) Visualization of the symmetry-point offset of MM-suppressed MEGA-PRESS. (C) Water suppression module using the 'excitation' water suppression (proprietary Philips method). In Fig. 1C, RF pulse amplitudes have been scaled by a factor of 10.

Figure 2.

Results from MM-suppressed GABA editing *in-vivo* in one subject from 2 brain regions (supplementary motor, inferior frontal gyrus), at two time points 11 days apart, showing an apparently negative edited signal at 3 ppm (shaded area). The peak is labeled 'GABA', as it contains variable contributions from negatively edited macromolecules.

Figure 3.

(A) Results from experiments performed in an NAA phantom, offset series showing the expected behavior (black line) in the absence of eddy currents, and actual experimental data (gray line fit to open circles). (B) The frequency offset of the editing efficiency function changes depending on the crusher gradient amplitude: full amplitude (black, 10.0 Hz); 3/4-amplitude (dark gray, 7.4 Hz); half-amplitude (light gray, 0.4 Hz).

Figure 4.

(A) The frequency offset of the editing efficiency function changes depending on the coordinate-frame (orientation) of crusher gradients: no rotation (light gray, 10.4 Hz), 45° rotation about the caudal-cranial axis, i.e. in the axial plane (dark gray, 6.4 Hz), and 45° rotation about the left-right axis, i.e. in the sagittal plane (black, 0.4 Hz). (B) The frequency offset of the NAA editing efficiency function is different for scans with fixed crusher gradient coordinate frame (black, 0.1 Hz), and with the crusher gradient coordinate frame defined by voxel orientation (gray, 11.5 Hz). (C) The frequency offset of the water editing efficiency function remains within 2 Hz with fixed crusher-gradient coordinate-frame for different voxel rotations with respect to the left-right axis (black), the anterior-posterior axis (dark gray), and the caudal-cranial axis (light gray). Solid lines indicate a 45° rotation; dotted lines represent a 22.5° rotation.

Figure 5.

(A) The frequency offset of the editing efficiency function is different for scans with (above, NAA saturation series, minimum at $f = 1.0$ Hz) and without (below, water saturation series, minimum at $f = 10.2$ Hz) water suppression. (B) The frequency offset of the editing efficiency function is different for scans with different amplitudes of the gradients in the Philips 'Excitation' water-suppression module (cf. Fig. 1C). Zero-crossings appear at 0.4 Hz (full gradient, black), 2.0 Hz (3/4 gradient, dark gray), 3.3 Hz (1/2 gradient, medium gray), and 5.7 Hz (1/4 gradient, light gray).

Figure 6.

(A) Left column: Simulated spectra with 10-Hz symmetry-point offset (black) are consistent with phantom spectra (green) acquired without fixed crusher-gradient coordinate-frame. Right column: Simulated spectra with correct symmetry-point offset (black) are consistent with phantom spectra (green) acquired with fixed crusher-gradient coordinate-frame. (B) MM-suppressed *in-vivo* GABA spectra for three healthy subjects from midline parietal region with (red) and without (black) fixed crusher gradient coordinate frame, showing that fixing the coordinate frame restores the expected positive edited signal at 3 ppm.