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RESEARCH ARTICLE

Eddy current effects on a clinical 7T-68 cm bore scanner

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Abstract
Introduction Eddy currents induced by switching of magnetic field gradients can lead to distortions in short echo-time spectroscopy or diffusion weighted imaging. In small bore magnets, such as human head-only systems, minimization of eddy current effects is more demanding because of the proximity of the gradient coil to conducting structures.
Methods In the present study, the eddy current behavior achievable on a recently installed 7 tesla—68 cm bore head-only magnet was characterized.
Results Residual effects after compensation were shown to be on the same order of magnitude as those measured on two whole body systems (3 and 4.7 T), while using two to three fold increased gradient slewrates.

Keywords 7 Tesla · Head-only magnet · Eddy currents

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Introduction

Switching of magnetic field gradients induces, via time variation of the magnetic field, eddy currents (EC) in the various conducting structures of the magnet. In turn, these currents are the origin of field variations that may persist up to several seconds after the primary gradient has been switched off. A large part of these field variations can be described by a gradient present in the same direction as the primary gradient and a B_0-field shift. Reduction of eddy current effects is especially important for short echo-time spectroscopy [1] or diffusion-weighted imaging (DWI), where strong field-gradients are rapidly switched and when, as in the case of DWI, particularly sensitive readout methods, such as echo planar imaging (EPI), are commonly used [2].

Reduction of eddy currents can be achieved by active shielding of the gradient coil and by magnet design, e.g. increasing the magnet bore size with respect to the gradient coil dimension [3]. Residual gradients from eddy currents are suppressed by applying correction (or preemphasis-) currents in the respective gradient coil. Spatially homogeneous field-shifts have traditionally been minimized using a B_0-shim coil and, more recently, by matching the demodulation frequency of the scanner to the shifted B_0-field (information obtained from manufacturer). In small bore systems, proximity of conducting structures (such as the heat shield) to the gradient coil can lead to large eddy current effects when compared to whole body magnets, placing thereby higher demands on magnet and gradient coil design. We have recently installed an actively shielded 7 tesla scanner with a bore size of 68 cm, equipped with an actively shielded head gradient coil. The aim of this study was to determine to what extend eddy current fields can be minimized on such a system using the vendor-supplied hardware and careful adjustment of the preemphasis

compensation parameters using a localized method as described by Terpstra et al. [4].

Materials and methods

The study was carried out on an actively shielded 7T magnet (Magnex Scientific, Oxford, United Kingdom) with a room temperature bore of 68 cm diameter. The system design allowed for a cryostat length of only 2.2 m. The 2 tesla limit of the main magnetic field remains within the cryostat and the 5 Gauss line within a distance of 4.5 m (radial) to about 6.5 m (axial) from the isocenter. The head gradient coil integrated into the system is a recent design [5] allowing for maximum gradient strengths of 80 mT/m switched at slewrates of up to 700 mT/(m $*$ ms) with second order shim fields up to 14 mT/m^2. In this study, eddy currents from a gradient switched at 333 mT/(m $*$ ms), i.e., at about 48% of the maximum slewrate, were characterized.

Eddy current measurements and adjustment of new preemphasis parameters were performed in the magnet isocenter using an oil-filled spherical phantom (Siemens, Erlangen, Germany). A head volume coil resonator (InVivo, Orlando, USA) was used for rf- transmission and reception. The sequence used for eddy current measurement is described in detail by Terpstra et al. [4]. Briefly, at a variable delay τ after the end of a user defined test-gradient, a bar (side length 2 cm) was selected within the phantom using a STEAM sequence (TE = 10 ms, TR = 6.1 or 6.2 s, TM = 1 s). Signal was acquired in the presence of a read gradient, providing a representation of the sample profile along the bar after Fourier transform (FT). The direction of the test-gradient coincided with the readout direction. Therefore, eddy currents, caused by the test-gradient modify the phase distribution along this profile. A complex division of two acquisitions performed once with and once without application of the test-gradient retains only eddy current effects as a consequence of the test-gradient. Fitting of the phase evolution along the profile to 0th and 1st order (offset and linear evolution in space) was used to calculate B_0-shift and eddy current gradient, respectively, present at a delay τ after the end of the test-gradient. Higher order field variations were found negligible relative to the 0th and 1st order terms.

Eddy current gradient and B_0-shifts were measured at 36 different time delays ranging from 1 ms to 3 s after the end of a 10.2-mT/m test-gradient of 2 s duration. This test- gradient amplitude corresponds to about 13% of the strength maximal available on the system. According to our experience with the method used here, EC correction optimized for such a gradient strength leads to an acceptable compensation for the range of gradient configurations employed by many methods. Because of the long duration of the test-gradient, eddy currents induced by its rising edge were considered negligible at the time of application of the first rf pulse of the STEAM coherence generation. After complex division, zero-filling and FT, the resulting phase evolution was unwrapped and fitted in an area of ± 2.4 cm at the isocenter to determine eddy current gradient and B_0-shift.

In a first step, measurements were performed with the eddy current compensation disabled (correction amplitudes and time constants were set to zero). These measurements were then used to determine new parameters for the system's preemphasis unit. The temporal decay of eddy current gradient and B_0-shift values after the end of the test-gradient were fitted to a sum of exponentially decaying functions ($\sum_{i=1}^{N} A_i e^{-t/\tau_i}$, where N, number of exponentials; A_i, amplitude of one of the N exponentially decaying components fitted to either the eddy current gradient or the B_0-shift evolution; τ_i, decay time constant). The number of exponentials (N) was successively increased until a fit residual near or below 2 Hz/cm for the gradient and near or below 2 Hz for the B_0-shift at all times was obtained. Adjacent decay time constants were chosen at least three-fold different ($\tau_{i+1}/\tau_i \geq 3$) wherever possible (exception: y-axis, ($\tau_{slow}/\tau_{medium} \geq 2.6$).

The time constants determined as described previously were entered directly into preemphasis unit of the scanner. The amplitudes of the exponential decays were determined iteratively as described by Terpstra et al. [4] i.e., no further calibration of the preemphasis unit was performed. In this process, the amplitude corresponding to the time constant τ_i ($i = 1, 2$ or 3) was adjusted by minimizing eddy current effects occurring at times longer than $5 * \tau_{i-1}$ after the end of the test-gradient. Adjustments started with the amplitude corresponding to the longest time constant. Measurements of B_0-shift and residual gradients were repeated after the adjustment had been performed on all axes.

To examine the influence of residual eddy currents on peakshapes in a spectroscopy experiment, a water signal was acquired at an echo- time of 9.5 ms from a $2 \times 2 \times 2$ cm^3 volume (TR = 4 s, bandwidth = 1 kHz, 4 scans) using a spherical, well- shimmed water phantom. Furthermore, in vivo acquisitions were performed with an echo-time of 6 ms on a volume of $2 \times 2 \times 2$ cm^3 situated in the occipital lobe of a human subject [6] (TR = 4 s, bandwidth = 4 kHz, 64 scans). All spectroscopy acquisitions used the SPECIAL sequence [1] preceded by 1st and 2nd order shimming with FASTMAP [7]. In vivo, a home-built, unshielded, quadrature surface coil was used for signal transmission and reception. Water was suppressed using VAPOR [8]. Postprocessing of in vivo acquisitions consisted of two-times zero-filling, 2 Hz Gaussian weighting of the FID, Fourier transform and zero order phase correction. Human study conditions were approved by the local ethics committee.

For further comparison, B_0-shifts and eddy current gradients were measured on a 3T whole body scanner (Trio a Tim system, Siemens, Erlangen, Germany) with the pulse

sequence and similar experimental setup as described previously while keeping the standard preemphasis settings (i.e., no further adjustments performed). The test-gradient as produced by the body gradient coil, was switched at 170 mT/(m ∗ ms), which was the maximum slewrate available.

Results

The decays of B_0-shift and eddy current gradient on the uncompensated 7T system showed multi-exponential behavior on all axes (Fig. 1). Fit of these decays with two or three exponentially decaying functions was sufficient to achieve maximum (measured) residuals below 1 Hz/cm for the eddy current gradient and below 6 Hz for the B_0-shift at all times on all axes. As an example, eddy current fields produced by a z-axis test-gradient are illustrated in Fig. 1a (gradient) and b (B_0-shift). On this axis (z), before compensation, eddy currents led to a gradient of up to 47 Hz/cm (1% of the preceding test-gradient) and a B_0-shift of up to 160 Hz. Compensation reduced these effects about 50-fold to a maximal residual gradient of 1 Hz/cm (0.02% of the applied test-gradient) and a maximal B_0-shift <3 Hz. Results for x, y and z-axis are summarized in Table 1. In summary, compensating with a sum of two to three exponentials was sufficient to reduce eddy current effects on average 30-fold.

Quality of the eddy current compensation was evaluated by observing the lineshape of a locally acquired water signal at an echo-time of 9.5 ms. Linewidth after FASTMAP shimming was below 1 Hz. Only minimal alterations of the peak-shape were present (Fig. 2) and remain below 2% of the peak amplitude within ±1 Hz around the peak center.

Spectra acquired in vivo were thus devoid of any eddy current effects resulting in a high spectral resolution as evidenced by the myo-Inositol multiplet structure near 3.6 ppm and by the clean baseline between choline (3.2 ppm) and creatine (3.0 ppm; Fig. 3). Average linewidth of the metabolite signals in this spectrum was about 8 Hz (LC model analysis [9]). The amplitude of the remaining water signal in the spectrum was strongly reduced to below the NAA peak height and without further correction, the baseline was flat.

On the 3T whole body scanner using standard preemphasis settings, residual eddy current gradients remained below 1 Hz/cm (x-axis: 0.4 Hz/cm, y-axis: 0.5 Hz/cm, z-axis: 0.9 Hz/cm) and B_0-shifts below 9 Hz (x-axis: 4 Hz, y-axis: 1 Hz, z-axis: 9 Hz) at all measured delays following the test-gradient.

Discussion and conclusion

The present study shows that on a 7T scanner with 68-cm bore, eddy current effects can be minimized below a

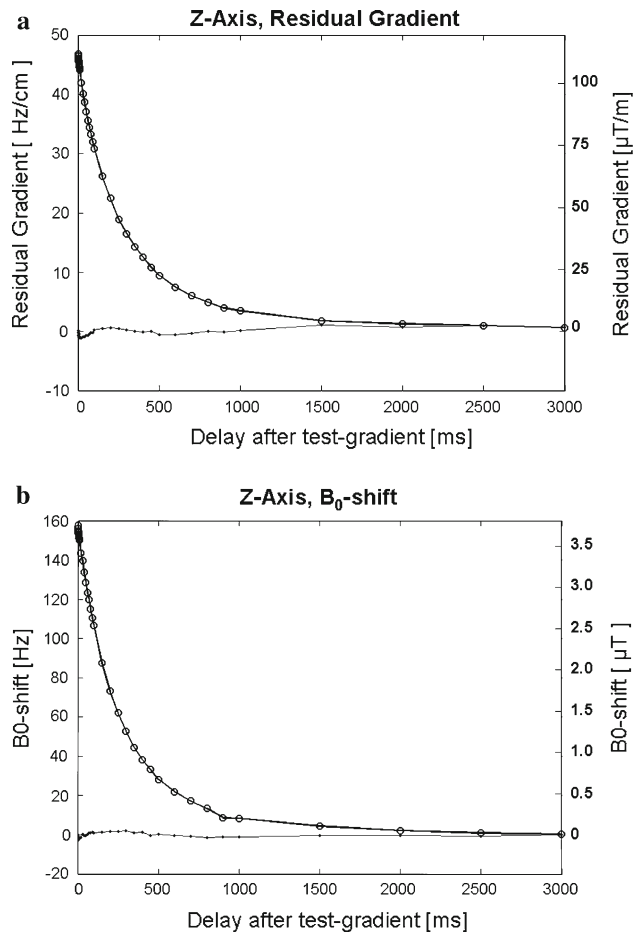

Fig. 1 Evolution of gradient (**a**) and B_0 field-shift (**b**) following the application of a z-axis test-gradient of 10.2 mT/m amplitude and 333 mT/(m*ms) slewrate. Shown are the values measured on the uncompensated system and after compensation using two time constants. Before compensation, eddy currents produced a gradient up to 47 Hz/cm (1% of the amplitude of the preceding test-gradient) and a B_0-shift up to 160 Hz. Compensation reduced the gradient to near 1 Hz/cm and the B_0-shift below 3 Hz at all times

B_0-shift of 6 Hz and below a residual gradient of 1 Hz/cm following a 10.2-mT/m test-gradient commuted at a slewrate of 333 mT/(m ∗ ms). The residual B_0-shift measured in the experiment remained slightly above predictions from the fit. Deviations may be caused by some compensation parameters entered iteratively into the preemphasis unit not representing exactly the amplitudes calculated (A_i) from the fit. Nevertheless, B_0-shifts and residual eddy current gradients remain almost negligible and are in size comparable to or even below values measured on a clinical 3 tesla whole body imager using standard preemphasis settings. Earlier measurements from a 4T whole body system, where a maximal B_0-shift of 19 Hz and a residual gradient near 3 Hz/cm [4] (corrected for the test-gradient amplitude used (13.2 mT/m)) were determined, further confirm this performance. While eddy currents on the 7T were comparable in size to those measured on the

Table 1 Time constants used for compensation of gradient and B_0-shifts caused by eddy-currents. Maximum values of eddy current gradients and B_0-shifts before and after compensation are indicated

	Time constants (ms)			Maximum before compensation	Maximum after compensation
	Slow	Medium	Fast		
Gradient					
x-axis	270	43	–	30 (Hz/cm)	1 (Hz/cm)
y-axis	576	214	67	21 (Hz/cm)	1 (Hz/cm)
z-axis	458	120	–	47 (Hz/cm)	1 (Hz/cm)
B_0-shift					
x-axis	586	182	–	156 (Hz)	6 (Hz)
y-axis	1121	318	104	86 (Hz)	3 (Hz)
z-axis	713	212	–	160 (Hz)	3 (Hz)

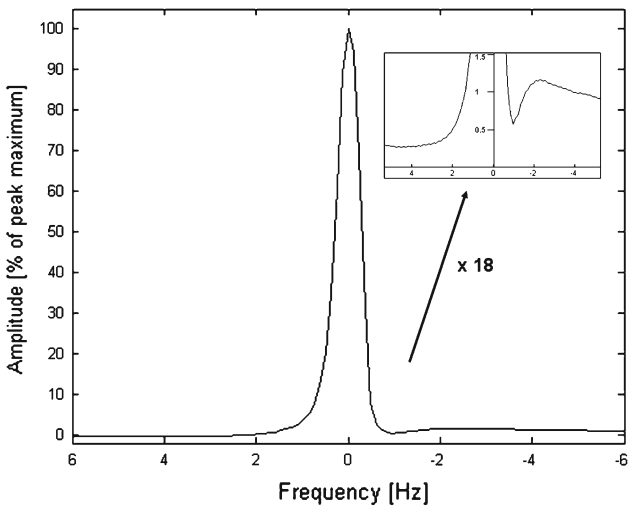

Fig. 2 Water signal acquired from a $2 \times 2 \times 2\,cm^3$ volume in a phantom at an echo-time of 9.5 ms using the SPECIAL [1] sequence. The frequency width at half max of the peak was below 1 Hz. Signal deformations caused by eddy currents remain below 2% of the peak amplitude within ±1 Hz around the peak center

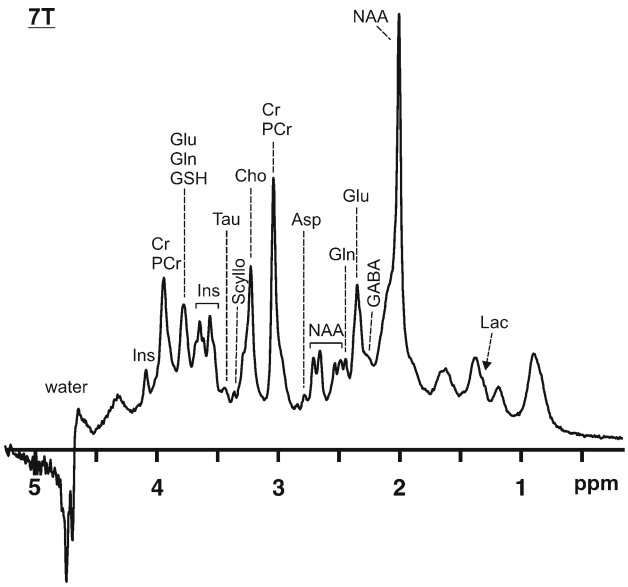

Fig. 3 Spectrum acquired at an echo-time of 6 ms from the occipital lobe of a healthy volunteer, using the SPECIAL sequence [6]. The average linewidth of the metabolite signals was about 8 Hz. Postprocessing consisted of two-times zero-filling, 2 Hz Gaussian weighting of the FID, Fourier transform and 0th order phase correction. The spectrum is devoid of any distortions due to eddy currents and high spectral resolution is evidenced by the myo-Inositol multiplet structure near 3.6 ppm and by the clean baseline between choline (3.2 ppm) and creatine (3.0 ppm)

whole body magnets, the slewrate used (333 mT/(m ∗ ms)) was nearly two to three times faster (3T: 170 mT / (m*ms), 4T: 100 mT/(m ∗ ms)).

Uncompensated, decaying behavior of eddy currents was well described by not more than three exponentially decaying functions. This rather low complexity allows for highly efficient eddy current compensation by at least a factor of 20. Low eddy currents effects demonstrated on the 7T system imply that such short bore magnets can be used with little compromise on the performance with respect to eddy currents. Minimal line distortions caused by eddy currents could only be detected on a very well-shimmed signal (<1 Hz, Fig. 2), and remained thus below average linewidths usually observed in vivo (8–9 Hz). Acquiring the in vivo spectra with a different coil (surface coil) than used for preemphasis adjustment (volume coil) did not lead to reduced spectral quality. Eddy currents that might be present in conducting structures of the volume or surface coil can therefore be assumed to be negligible. Localized spectra can be acquired in vivo at very short echo times (6 ms) devoid of any visible deformations from eddy currents. It should be noted that, to achieve a similar spectral quality on a very small bore animal magnet, demands on residual eddy current gradients are less stringent (i.e., larger residual gradients can be accepted), as, in general, acquisitions are performed on smaller volumes than in humans [4].

We conclude that eddy current effects remaining on the 7T system after compensation are not performance limiting for many in-vivo applications. In terms of eddy current behavior, the 7T/68-cm system can therefore be considered an interesting alternative to the installation of a whole body scanner.

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