Magnetic Resonance in Medicine 47:208–212 (2002)

Automatic Gradient Preemphasis Adjustment: A 15-Minute Journey to Improved Diffusion-Weighted Echo-Planar Imaging

Vincent J. Schmithorst* and Bernard J. Dardzinski

Image distortion caused by gradient eddy currents is a major problem in the use of diffusion tensor imaging (DTI), as using the uncorrected images for calculation of apparent diffusion coefficient (ADC) and diffusion anisotropy will result in areas of artificially increased anisotropy and ADC at the edge of the images, as well as decreased spatial resolution and accuracy in ADC computations overall. This distortion may be substantially reduced by careful adjustment of the gradient preemphasis unit. A completely automatic method of adjusting the preemphasis unit is proposed which finds the optimal settings for all three gradient directions in approximately 15 min by estimating the magnitudes of the eddy currents at various delay times after a test gradient. The pixel shifts in a 64 × 128 echo-planar diffusion-weighted image with a diffusion gradient strength of 30 mT/m were reduced to less than 0.2. Magn Reson Med 47: 208–212, 2002. © 2002 Wiley-Liss, Inc.

Key words: preemphasis; MRI; gradient; eddy current; diffusion imaging

Geometric distortion resulting from gradient eddy currents is a major source of image artifacts in diffusion-weighted echo-planar imaging (DW-EPI). Depending on the direction of the diffusion gradient relative to the image plane, the distortion will consist of shearing, stretching, or shift in the phase-encoding direction. Because the diffusion-weighted images are misaligned relative to images acquired without diffusion gradients, computed parameter maps such as apparent diffusion coefficient (ADC) or diffusion anisotropy maps will suffer from degraded resolution, lower accuracy, and visible areas of artificially increased ADC and anisotropy around the edges of the object. While the use of actively shielded gradients has greatly reduced the magnitude of eddy currents, significant distortion often still remains in DW-EPI images, which becomes more severe at higher field strengths.

Methods proposed for distortion correction include: postacquisition image warping (1,2), modifications of the DW-EPI pulse sequence (3–5), acquisition of calibration scans (6–10), and gradient preemphasis calibration (11). Gradient preemphasis calibration offers the significant advantage of eliminating the need for time-consuming image postprocessing, thereby allowing the use of diffusion-weighted imaging (DWI) and diffusion tensor imaging (DTI) in clinical settings. Additionally, by minimizing image distortion associated with gradient eddy currents during the image acquisition, postprocessing to remove any remaining distortion should result in near-perfect coregistration of the diffusion-weighted images.

Very accurate preemphasis and B_0 corrections are necessary to adequately correct for all image distortions in DW-EPI. For a typical 3 Tesla DW-EPI single-shot acquisition time of 60 ms and a field of view (FOV) of 20 cm, 10 cm from the isocenter, a gradient eddy current of 4 μT/m, or a B_0 offset of 0.4 μT, will produce an image shift of one pixel. The pixel shift is equal to the number of revolutions of dephasing over the acquisition time according to the Fourier shift theorem. For a typical diffusion gradient strength of 40 mT/m, the preemphasis unit must reduce the gradient eddy currents to less than 1/10000, or to 100 parts per million (ppm) of the original gradient strength to produce an image shift of less than one pixel.

Methods proposed for gradient preemphasis measurement and calibration include: use of a pickup coil (12); a localized stimulated-echo field-mapping sequence (13); the measurement of multiple free-induction decays (FIDs) of an extended sample (14), which requires accurate sample placement; and measuring FIDs of samples placed at various locations in the magnet (15,16). Recently, a fast method was proposed (11) tailored specifically for measuring eddy currents in DW-EPI sequences. However, because of the relatively long acquisition time (around 60 ms for a typical single-shot EPI sequence), and because an entire slice is excited, the sequence is vulnerable to susceptibility effects, leading to inaccurate estimates of the spin dephasing. The sequence is also unable to correct for any residual eddy currents remaining after the acquisition time, which may lead to distortion in multislice DW-EPI sequences.

A completely automated method for gradient preemphasis calibration is proposed that does not involve the use of specialized pulse sequences, extensive data postprocessing, custom samples, or specific sample placement. This method is able to compute the optimum preemphasis settings for all three gradient directions (x, y, z) in approximately 15 min. The B_0 adjustment may also be performed using a similar method. The method, with its fast calibration time, may be readily used for sequence-specific preemphasis adjustments for pulse sequences, such as EPI, that often use different ramp times rather than conventional sequences. In addition, preemphasis adjustment is often needed since the initial settings by the manufacturer may become nonoptimal in the presence of hardware drifts over time (11).

THEORY

The pulse sequence shown in Fig. 1 may be used to determine the strength of a gradient eddy current for various

Imaging Research Center, Children's Hospital Medical Center, Cincinnati, Ohio.

*Correspondence to: Vincent J. Schmithorst, Imaging Research Center, Children's Hospital Medical Center, 3333 Burnet Ave., Ste. R050A, Cincinnati, OH 45229. E-mail: vince@athena.chmcc.org

Received 12 June 2001; revised 20 July 2001; accepted 17 August 2001.

© 2002 Wiley-Liss, Inc.

DOI 10.1002/mrm.10022

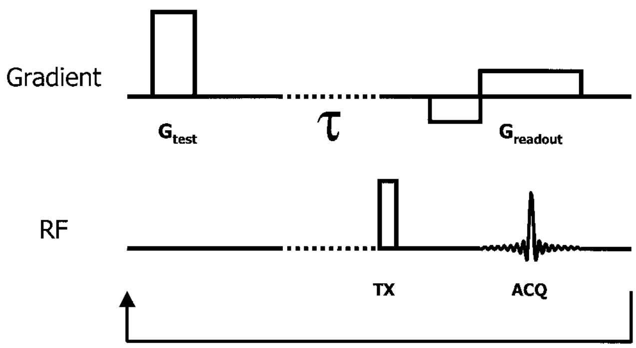

FIG. 1. Diagram of the pulse sequence used to estimate gradient eddy currents. τ is the variable delay.

delay times after the gradient is switched off, without the need for specific phantom placement. After taking the Fourier transform, the gradient eddy current (*EC*) may be approximated by

$$EC = \frac{m_{preemp}}{2\pi\gamma TE} \quad [1]$$

where m_{preemp} is the slope of the phase (in radians per unit distance), TE is the time between the midpoints of the RF transmit pulse and the acquisition window, and γ is the magnetogyric ratio. The slope may be found without the need for phase-unwrapping using a previously-described method (17). To correct for imperfect centering of the echo in the acquisition window and any eddy currents generated by the readout gradient, a reference scan is taken with zero gradient strength, and the phases of the reference scan are subtracted from the phases of all subsequent scans. The expression given in Eq. [1] is not exact, since the measured slope m_{preemp} is actually proportional to the integral of the eddy current across TE. This will result in a consistent overestimation at the time of the acquired echo if the eddy current is monotonically decreasing with time. Minimizing TE to the smallest value practicable can reduce this effect. However, this error should have minimal impact on the accuracy of the preemphasis calibration itself, because if the eddy current can be characterized adequately by a sum of decaying exponentials with a given set of time constants, so can its integral, and optimal preemphasis compensation will result in its minimization. To reduce the effect of any interactions in eddy currents caused by the test and readout gradients, the readout gradient should be set to a small fraction of the test gradient.

The pulse sequence in Fig. 2 will estimate the values of B_0 eddy currents at various delay times without specific phantom placement. The field shift (ΔB_0) can be approximated by

$$\Delta B_0 = \frac{m_b}{2\pi\gamma} \quad [2]$$

where m_b is the slope of the phase of the FID (in radians per second), and γ is the magnetogyric ratio. The expression given in Eq. [2] is exact in the limit of perfect preemphasis compensation or exact placement at isocenter of a perfectly symmetric phantom. In reality, residual gradient eddy currents will cause a shift in the absence of exact phantom placement, so the preemphasis adjustment should be performed prior to the B_0 adjustment, after which the errors will be minimal. A relatively large residual gradient eddy current of 1 μT/m combined with a phantom placed 5 cm away from isocenter will combine to produce an error of only .05 μT, or $< .02$ ppm at a main field strength of 3T. In practice, the errors will be much less for most measured data points.

METHODS

In order to find the optimal settings for the preemphasis unit, the pulse sequence in Fig. 1 is run with all preemphasis values set to zero. After finding the uncompensated gradient eddy currents $EC_0(\tau)$ at various delay times τ, a Levenberg-Marquardt least-squares fitting routine is used to estimate the three exponential constants to be used for fitting subsequent FIDs. The initial values of the time constants may be obtained using the space-state singular value decomposition method (18). Once the three exponential constants are found, these values are downloaded to the preemphasis unit and held constant for the remainder of the procedure. In principle, any number of exponential functions could be used in the fitting algorithm; our specific hardware configuration, however, is limited to three time constants.

After finding the optimum time constants, subsequent scans are obtained with the gains A_i for each time base i = 1, 2, 3 set to some arbitrary value (we used 1.0% of the maximum setting) with the remaining time bases held at zero. After computing the compensated eddy currents $EC_i(\tau)$, the response function $R_i(\tau)$ for each of the bases is given by $R_i(\tau) = EC_i(\tau) - EC_0(\tau)$. Solving the overdetermined system of equations

$$EC_0(\tau) = \sum_{i=1}^{3} A_i R_i(\tau) \quad [3]$$

via singular value decomposition yields the theoretical gain values A_i for minimizing $\chi^2 = \Sigma\ EC(\tau)^2$. The procedure may then be iterated by using the computed gain settings A_i as the baseline and repeating the steps de-

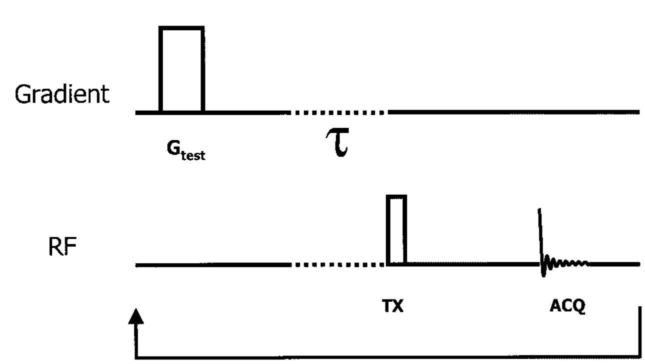

FIG. 2. Diagram of the pulse sequence used to estimate B_0 eddy currents. τ is the variable delay.

scribed above. Such iteration will be necessary if there is a nonlinear relationship between the gain settings and the current in the preemphasis unit. For optimum preemphasis adjustment the procedure should be iterated until there is no further improvement in χ^2. The procedure for finding the time bases and gains for optimum B_0 compensation is identical to that for the preemphasis, using the pulse sequence shown in Fig. 2. A flowchart describing the procedure is shown in Fig. 3.

The pulse programs described above were implemented on a Bruker 3 Tesla 30/60 Biospec Scanner (Bruker Medical, Karlsruhe, Germany) with a 33-cm-diameter actively shielded head gradient insert with an asymmetric z profile capable of delivering ± 45 mT/m. The parameters used were: gradient strength = 30 mT/m, gradient duration = 20 ms, acquisition size = 32 complex points, acquisition time = 2.56 ms (preemphasis), 1.28 ms (B_0), FOV = 25.6 cm (for preemphasis calibration, resulting in a read gradient strength of 1.0 mT/m). The delay times (τ) were determined via a geometric progression given by $\tau_k = \tau_{min} \cdot A^{(k-1)}$ where $A = (\tau_{max}/\tau_{min})^{1/(N-1)}$, N = the total number of delay times utilized, and $k = 1, 2, \ldots, N$. Values of τ used were: 2–150 ms for preemphasis, 2–150 ms for B_0 (x and y), and 12–750 ms for B_0 (z). The B_0 eddy current with an applied z gradient was found to have a much longer decay time. Postprocessing was performed using Interactive Data Language (Research Systems, Inc., Boulder, CO). Through the use of IDL's "SPAWN" command, and the interface between the scanner and the operating system, the routines were completely automated and run without any user interaction.

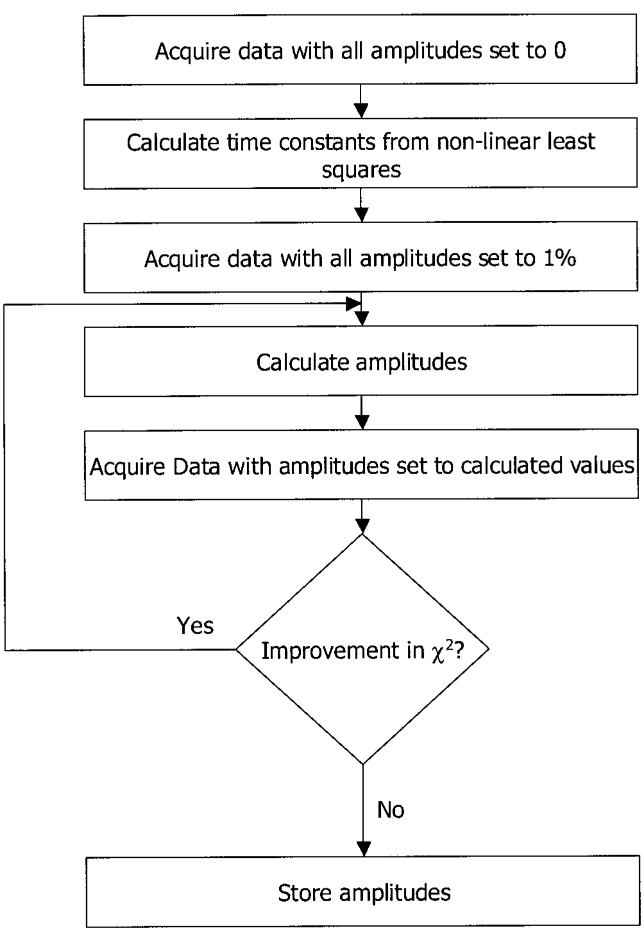

FIG. 3. Flowchart of the procedure used to automatically determine the optimal time constants and amplitudes of the preemphasis unit for a given gradient direction.

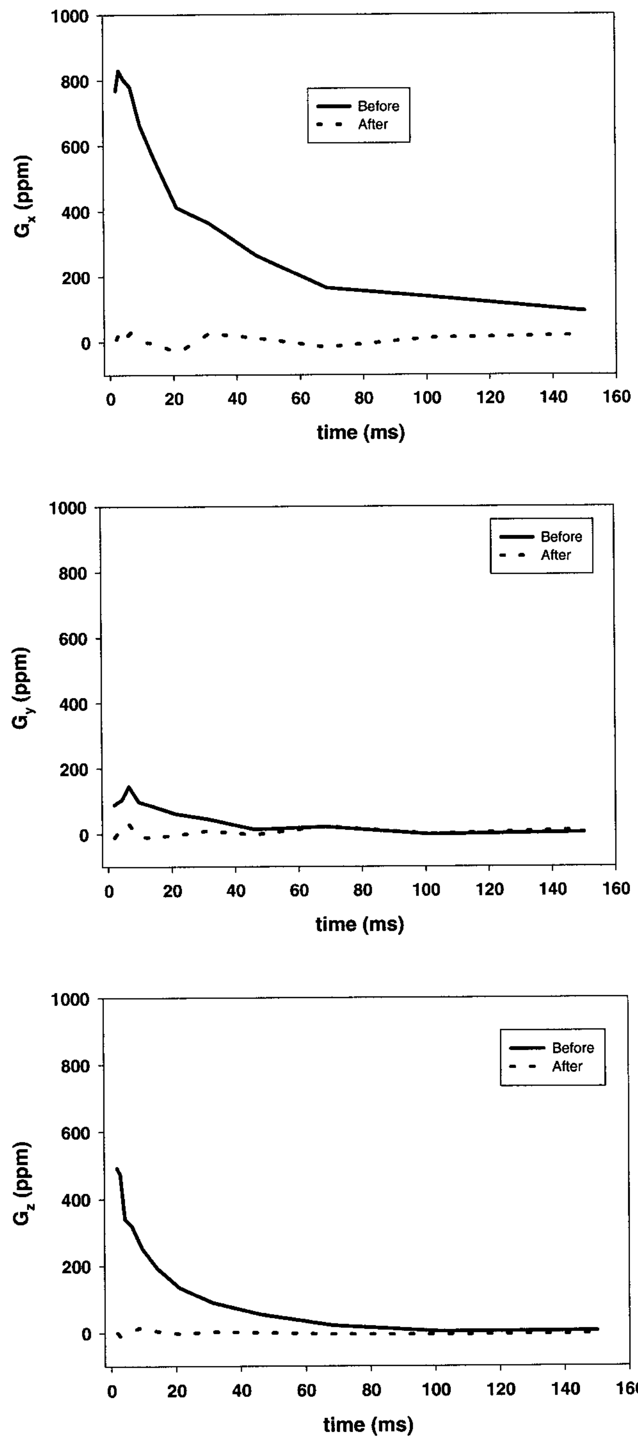

FIG. 4. Eddy currents generated by x, y, and z gradients of 30 mT/m strength and 20 ms duration with no preemphasis compensation (solid line), and with calculated preemphasis compensation (dashed line).

Table 1
Root Mean Square Compensated and Uncompensated Gradient Eddy Currents (in ppm) for an Applied Gradient of 30 mT/m

	X	Y	Z
Without compensation	556	77	260
With compensation	20	13	7

To determine image shifts, DW-EPI images were taken of a water phantom in all gradient directions (x, y, and z) with and without the determined preemphasis settings. The phantom was a 2.7 L sphere (18-cm-diameter MRS HD sphere, model 2152220; General Electric, Milwaukee, WI) with reduced T_1 and T_2 relaxation times typically used for spectroscopic evaluation. The imaging parameters were: bandwidth = 125 kHz, matrix = 64 × 128, FOV = 19.2 × 25.6 cm, slice thickness = 5 mm, Δ = 18.6 ms, δ = 10 ms, and diffusion gradient strength = 30 mT/m. To quantify the effects of the correction, the parameters of shift, shear, and stretch were estimated via the Levenberg-Marquardt procedure.

RESULTS

The optimal preemphasis settings for x, y, and z were determined as described above.

Shown in Fig. 4 are the results for the original eddy currents with no preemphasis compensation (solid lines), and the final results for the residual eddy currents (dashed lines). In each direction the final eddy currents after correction are uniformly < 1 μT/m, or 35 ppm of the original gradient strength of 30 mT/m in all directions. The root mean squared (RMS) uncompensated and compensated eddy currents are shown in Table 1. The method reduced the RMS eddy currents to a value of 20 ppm or better in all directions. The actual performance may be slightly better than estimated, since the residual eddy currents are systemically overestimated by Eq. [1].

The optimal B_0 settings were also determined via the proposed method. Shown in Fig. 5 are the results for the original B_0 with no preemphasis compensation (solid lines), and the final results (dashed lines). After 4 ms the final B_0 values after correction are uniformly <0.1 μT, or 4 Hz for applied gradients in the x and y directions. The original B_0 field for an applied gradient in the z direction was larger by approximately a factor of 10 than in x and y, and also decayed over a longer time period. The method uniformly reduced the residual B_0 field to <0.1 μT, or 4 Hz after 17 ms. The RMS uncompensated and compensated eddy currents are shown in Table 2. The method reduced the RMS eddy currents to better than 3 Hz in all directions.

The results found for the maximum pixel displacement (at the edge of the image) for the DW-EPI images taken of a water phantom show that the proposed method reduces the image shifts (Table 3) to 0.2 pixels or less, which is more than adequate for clinical DW-EPI applications. The pixel shifts in x and y reach the maximum value at the edge of the image, and will be less towards the center of the image.

DISCUSSION

Unlike previously proposed methods (11,13), the proposed method does not involve iteratively adjusting preemphasis settings until the optimum setting is found empirically; the method is fully automatic and runs with no user interaction. The method also benefits from improved SNR by utilizing the signal from the entire phantom rather than only from a localized rod (13) or a single slice (11). The performance of the method is comparable to the methods of Terpstra et al. (13) and Papadakis et al. (11) for

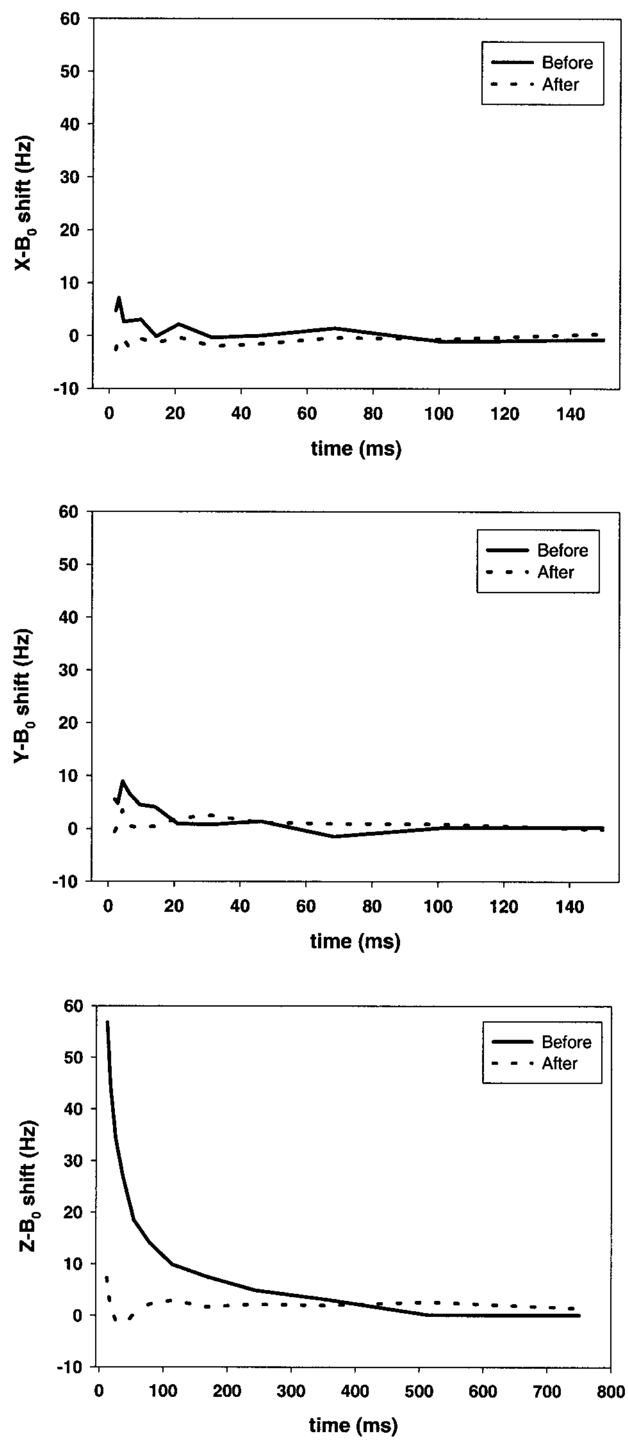

FIG. 5. Plots of B_0 shift generated by x, y, and z gradients of 30 mT/m strength and 20 ms duration with no B_0 compensation (solid line), and with calculated B_0 compensation (dashed line).

gradient preemphasis calibration. For B_0 compensation, the method is comparable to that of Terpstra et al. but not as accurate as that of Papadakis et al., which reduced the B_0 eddy currents to <0.05 Hz in all directions. The effectiveness of preemphasis compensation in general is dependent on how well the gradient or B_0 eddy currents can be characterized by a sum of decaying exponentials. B_0 eddy currents induced by applied gradients in the x and y directions display a ringing behavior for short delay times, indicating that the difference in accuracy may be partly system-related. The method of Papadakis is also unable to measure any eddy currents beyond approximately 60 ms, at which point susceptibility effects lead to decreased SNR. This method may still be preferable if very accurate B_0 compensation is necessary within a short time period; however, the proposed method reduces B_0 eddy currents to a few Hz or less, which is more than adequate for DW-EPI.

It is also worth noting that the ramp time of 180 μs used for the preemphasis calibration was higher by a factor of 2 than the ramp time of 90 μs used during the DW-EPI acquisitions, which indicates that the method estimates the optimum parameters to sufficient accuracy for a range of ramp times. This is consistent with the results of Papadakis et al. (11), who found that their preemphasis calibration, obtained with the ramp times used for the diffusion gradients, was still valid for other pulse sequences with fourfold shorter ramp times. However, since most systems allow for online swapping of preemphasis settings, the proposed method may be readily used for sequence-specific preemphasis adjustments.

CONCLUSIONS

A completely automatic method was implemented in order to find the optimal settings for the preemphasis unit calibration. This method does not require specific phantom placement, computationally intensive data postprocessing, or custom-built samples, and the pulse programs used involve only slight modifications from standard sequences. The method can be easily implemented with gradients and scanners from a variety of manufacturers. The optimal preemphasis settings for all three gradient directions were found in approximately 15 min. DW-EPI experiments on a water phantom demonstrate that the automated preemphasis routine reduced the image shifts uniformly to <0.2 pixels for a 30 mT/m diffusion gradient.

Table 2
Root Mean Square Compensated and Uncompensated B_0 Eddy Currents (in Hz) for an Applied Gradient of 30 mT/m

	X	Y	Z
Without compensation	2.9	4.2	25
With compensation	1.4	1.4	2.8

Table 3
Maximum Displacements (in Pixels) for Single-Shot Transverse DW-EPI Images of a Water Phantom Acquired Using a Diffusion Gradient Strength of 30 mT/m, 64 × 128 Matrix, and 125 kHz Bandwidth*

	X	Y	Z
Without compensation	5.0	1.6	9.6
With compensation	0.05	0.20	0.16

*Displacements result from shear for X diffusion gradient, stretch for Y diffusion gradient, and shift for Z diffusion gradient.

REFERENCES

1. Haselgrove JC, Moore JR. Correction for distortion of echo-planar images used to calculate the apparent diffusion coefficient. Magn Reson Med 1996;36:960–964.
2. Bastin ME. Correction of eddy current-induced artefacts in diffusion tensor imaging using iterative cross-correlation. Magn Reson Imaging 1999;17:1011–1024.
3. Alexander AL, Tsuruda JS, Parker DL. Elimination of eddy current artifacts in diffusion-weighted echo-planar images: the use of bipolar gradients. Magn Reson Med 1997;38:1016–1021.
4. Cercignani M, Horsfield MA. An optimized pulse sequence for isotropically weighted diffusion imaging. J Magn Reson 1999;140:58–68.
5. Heid O. Eddy current-nulled diffusion weighting. In: Proceedings of the 8th Annual Meeting of ISMRM, 2000, Denver. p 799.
6. Chen N-K, Wyrwicz AM. Distortion correction for diffusion weighted echo planar imaging. In: Proceedings of the 8th Annual Meeting of ISMRM, 2000, Denver. p 1709.
7. Jezzard P, Barnett AS, Pierpaoli C. Characterization of and correction for eddy current artifacts in echo planar diffusion imaging. Magn Reson Med 1998;39:801–812.
8. Bastin ME, Armitage PA. On the use of water phantom images to calibrate and correct eddy current induced artefacts in MR diffusion tensor imaging. Magn Reson Imaging 2000;18:681–687.
9. Calamante F, Porter DA, Gadian DG, Connelly A. Correction for eddy current induced Bo shifts in diffusion-weighted echo-planar imaging. Magn Reson Med 1999;41:95–102.
10. Horsfield MA. Mapping eddy current induced fields for the correction of diffusion-weighted echo planar images. Magn Reson Imaging 1999; 17:1335–1345.
11. Papadakis NG, Martin KM, Pickard JD, Hall LD, Carpenter TA, Huang CL. Gradient preemphasis calibration in diffusion-weighted echo-planar imaging. Magn Reson Med 2000;44:616–624.
12. Jensen DJ, Brey WW, Delayre JL, Narayana PA. Reduction of pulsed gradient settling time in the superconducting magnet of a magnetic resonance instrument. Med Phys 1987;14:859–862.
13. Terpstra M, Andersen PM, Gruetter R. Localized eddy current compensation using quantitative field mapping. J Magn Reson 1998;131:139–143.
14. Wysong RE, Lowe IJ. A simple method of measuring gradient induced eddy currents to set compensation networks. Magn Reson Med 1993; 29:119–121.
15. Liu Q, Hughes DG, Allen PS. Quantitative characterization of the eddy current fields in a 40-cm bore superconducting magnet. Magn Reson Med 1994;31:73–76.
16. Robertson S, Hughes DG, Liu Q, Allen PS. Analysis of the temporal and spatial dependence of the eddy current fields in a 40-cm bore magnet. Magn Reson Med 1992;25:158–166.
17. Ahn CB, Cho ZH. A new phase correction method in NMR imaging based on autocorrelation and histogram analysis. IEEE Trans Med Imaging 1987;MI-6:32–36.
18. Barkhuijsen R, de Beer R, van Ormondt D. Improved algorithm for noniterative time-domain model fitting to exponentially damped magnetic resonance signals. J Magn Reson 1987;73:553–557.