# Double-Spin-Echo Diffusion Weighting with a Modified Eddy-Current Adjustment

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## Introduction

Echo-planar imaging suffers from geometric distortions in the presence of eddy currents which in particular are pronounced after applying diffusion-weighting gradient pulses. Therefore, several diffusion-weighting preparations have been proposed in the past that effectively reduce these eddy currents (e.g. [1,2]). The most prominent [2] involves a double-spin-echo preparation with four diffusion gradients (Fig. 1a) whose durations are adjusted to a given eddy-current time constant such that the cumulative eddy currents with this time constant generated by all four pulses null after the last gradient lobe. However, because usually eddy currents with different time constants are present on a whole-body MR system, residual geometric distortions are typically observed. Here, it is shown that the residual geometric distortions can be reduced by adjusting the first two and the last two gradient pulses to different eddy-current time constants, respectively.

## Methods

Assuming exponentially decaying eddy currents and neglecting gradient ramp times, eddy currents of decay rate $\lambda$ cancel for two gradient pulses with opposite polarities, durations of $\delta_1 = \delta - \delta_2$ and $\delta_2$, and a gap of $d$ if $\delta_2 = \ln\left[e^{\lambda\delta}(1 + e^{\lambda d})/(1 + e^{\lambda(\delta+d)})\right]/\lambda$ (Maple, version 10).

In the standard preparation (Fig. 1a), all four gradient durations are adjusted to fill the entire time available between the excitation and the acquisition part with the diffusion gradients and to perfectly null eddy currents of a given decay rate. In the proposed modification (Fig. 1b), the first two and the last two gradients are adjusted to null eddy currents of different decay rates, respectively, according to the equation given above.
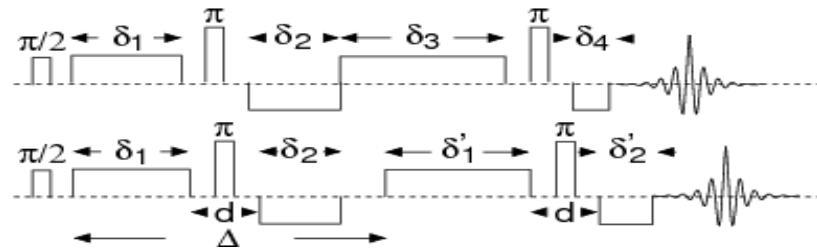


**Figure 1:** Basic pulse sequences for the (a) standard diffusion preparation and (b) the proposed modification. In (b), the first two and the last two gradients are adjusted to null eddy currents of different time constants according to the equation given above.

Measurements were performed on a 3T whole-body MR system (Siemens Magnetom Trio) using a standard twelve-channel head coil. Diffusion-weighted EPI data were acquired using $b$ values of 0 and 1000 s mm$^{-2}$ and diffusion weighting in three orthogonal axes at a spatial resolution of 2x2x5 mm$^2$. To analyze the eddy-current-induced geometric distortions, the standard deviation of the diffusion-weighted images was calculated on a pixel-by-pixel basis. Gradient durations were adjusted to eddy current time constants which yielded the minimum standard deviation averaged over the image. This adjustment was performed for each preparation, and for the proposed sequence of Fig. 1b for each gradient pair, independently.

## Results and Discussion

The results of the phantom experiments are summarized in Fig. 2. The standard Stejskal-Tanner preparation (Fig. 2a) shows the most prominent distortions. For the preparation of Reese *et al.* [2] (Fig. 1a), minimum distortions are observed for eddy-current compensations with time constants of 20 ms (Fig. 2b) and 60 ms (Fig. 2c) which may point to the presence of relevant eddy current with different time constants. For the preparation of Wider *et al.* [1] (Fig. 2d) more severe distortions are observed. This preparation is equivalent to that shown in Fig. 1b with $\delta_1 = \delta_2$ which corresponds to a compensation of eddy currents with infinite time constant ($\lambda = \infty$). The lowest level of distortions is observed for the proposed modification using time constants of 15 ms for the second and 90 ms for the first gradient pair (Fig. 2e). This may reflect the fact that the eddy currents with short time constants caused by the first gradient pair are already mostly decayed when the echo train starts. Although this setting does not perfectly null eddy currents of either of the two time constants, it offers the chance to decrease eddy currents of different time constants significantly which overall seems to improve the performance. The time constants determined (15 ms and 90 ms) can be regarded to be consistent with the two best time constants of the standard preparation (20 ms and 60 ms) considering that these minized the combined effect of major contributions with different time constants. A drawback of the modified adjustment is a usually increased echo time due to the modified pulse durations and the need for a proper refocusing.
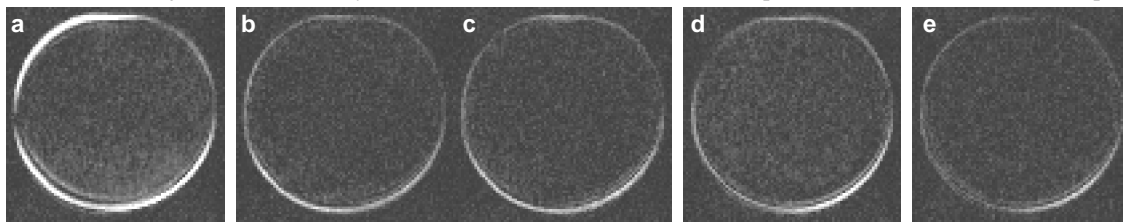


**Figure 2:** Maps of the standard deviation of the signal intensities observed in three images with orthogonal diffusion-weighting directions on a water phantom: (a) standard Stejskal-Tanner diffusion weighting, (b,c) the method presented by Reese *et al.* [2] for decay rates of (b) 20ms and (c) 60ms, (d) the method proposed by Wider *et al.* [1] and (e) the proposed modifications with decay rates of 15 ms and 90 ms. High values represent pronounced geometric distortions due to eddy-currents induced by the diffusion-weighting gradient pulses.

## References

[1] Wider G *et al.*, J. Magn. Reson. A **108**, 255–258 (1994)

[2] Reese TG *et al.*, Magn. Reson. Med. **49**, 177–182 (2003)