DWI Gradient Optimization for Large Spatial Coverage

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Introduction The spatial coverage per unit time, such as the number of slices per given TR, directly impacts the patient throughput. This parameter is even more pronounced in abdominal imaging where as many as slices are desired within a single breath-hold. In the case of diffusion-weighted-imaging (DWI), this measure is usually dominated by the gradient heating induced by the diffusion gradients (or motion probing gradient, MPG), due to their high amplitude and long duration *(1)*. Improving the number of slices per given TR by lowering the gradient strength is undesirable as it has adverse effects on the TE and hence image SNR. In this work, we propose a new design of MPG, which increases the maximal number of slices per given TR without prolonging the TE.

Theory The commercially used isosceles-trapezoidal design of MPGs, taking the single spin echo (SSE) case as an example, is depicted in Fig 1. For the MPG pairs in this form, the b-value is calculated as Equation 1*(2)*. An observation of Equation 1 and Fig 1 implies that, the shaded half of the gradient pairs contributes more to the b-value than the blank half, because they are located further away from each other. The blank half, on the other hand, contributes the same to the overall gradient heating as the shaded half. This means that the current isosceles shape is not optimal for MPG as it does not exploit the highest efficiency in terms of gradient heating.

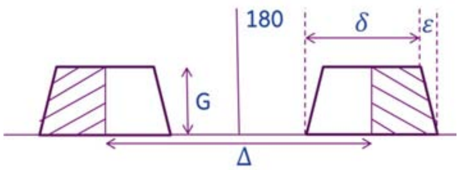


Figure 1. MPGs, shaped as isosceles trapezoids, in current commercial scanners;

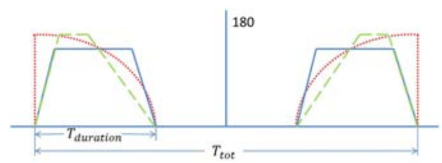


Figure 2. Traditional MPG (blue), ideal shape (red dotted), and a practical approximation (green dashed);

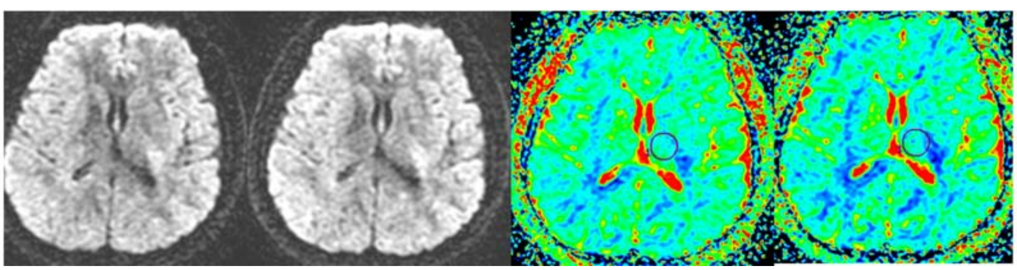
$$b = \gamma^2 G^2 [\delta^2 \left(\Delta - \frac{\delta}{3}\right) + \frac{\varepsilon^3}{30} - \frac{\delta\varepsilon^2}{6}]$$ **--- Equation 1**

$$\begin{cases} \gamma^2 \int_0^{T_{tot}} \left[\int_0^t G(t')^2 dt'\right] dt = b \\ T_{duration} = T \\ Minimize\ Gradient\ Heating\ \int_0^{T_{tot}} G(t)^2 dt \end{cases}$$ **--- Equation 2**

※b, T, and T_{tot} are given;

It is noticeable that, to keep a balance between the SNR and the spatial coverage in slice direction, in current commercial scanners there is usually a margin between the MPG amplitude in use and the system maximally allowed gradient strength. The proposed method exploits this margin and optimizes the MPG shape according to Equation 2, which implies to maintain the same b-value and the same MPG duration while minimizing the gradient heating level. By solving Equation 2 using binary search algorithm, a pair of optimal MPGs is obtained and depicted as the red dotted curves in Fig 2. Since gradient with such shape is difficult to implement, a robust approximation is made to mimic the ideal shape instead, shown as the green dashed trapezoids in Fig 2. The approximation is created such that the max slew rate is used for one ramp, the duration of the plateau is then fixed for the desired b-value, and the other ramp is setup accordingly.

Experiments & Results The proposed method was compared to traditional MPG on a GE 1.5T Optix scanner with both phantom and in vivo subjects. The experiments were performed on brain, spine, and abdomen, with clinical protocols. From the resulting images shown in Fig 3, it is observed that identical images were obtained with two MPG shapes, both qualitatively (SNR & distortion) and quantitatively (ADC). ***At the same time, as shown in Table 1, the maximal number of slices per given TR was increased by 7% in SSE case and by 21% in dual spin echo (DSE) case.***



Regular MPG, b = 1000, TE = 83.9ms | Optimized MPG, b = 1000, TE = 83.9ms | Regular MPG, ADC = 0.000809 | Optimized MPG, ADC = 0.000809

Figure 3. Optimized MPG yields image with quality and ADC both identical to the traditional MPG design.

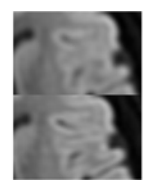


Figure 4. Optimized MPG induces less eddy current in SSE case, resulting in sharper structural details;

Traditional MPG
Optimized MPG

Table 1. Max number of slices per TR with traditional and optimized MPG, for both SSE and DSE cases. Here, TR = 6000ms, b = 1000;

	Traditional	Optimized
SSE	29	31
DSE	24	29

Discussion This article presents a MPG optimization method, and quantitatively demonstrates that the proposed method can significantly increase the spatial coverage in slice selection direction for DWI scans, especially in DSE case. At the same time, in comparison to the commercial scanners, the proposed method provides very consistent performance in SNR, distortion, and ADC values. In addition, since this method utilizes MPGs with very short duration in high-amplitude portion, it theoretically has less sensitivity to motion effects, which will be further explored in future study. Further study in this method could also include other approximations to the optimal MPG shape so that to minimize the eddy current with certain time constants throughout the acquisition train. Actually the gradient shape demonstrated in this article already shows benefits in eddy currents, as implied by Fig. 4, where sharper structures could be observed with optimized MPG due to reduced distortion.

Reference (1) S.Stefan, et al., MRI 19:1125-1128 (2001). (2)B.Matt, et al, Handbook of MRI Pulse Sequences, Elsevier Academic Press (2004).