Recipes of Diffusion Measurements with Oscillating Gradients

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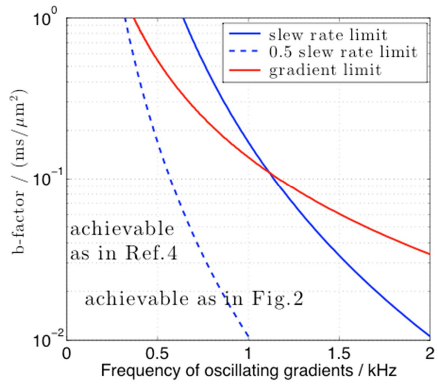
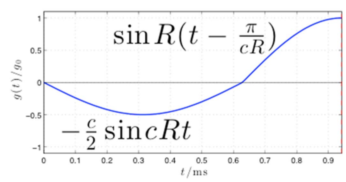
Target audience: Scientists performing diffusion measurements with oscillating gradients.

Purpose: Measuring diffusion using oscillating gradient trains[1-4] is becoming increasingly popular for probing the structure of biological tissues at the finest scale. This technique poses two typical challenges: (i) to achieve the maximal frequency using high-performance small-bore scanners and (ii) to perform measurements in human scanners. Here we discuss principles of optimal diffusion weighting for these two cases.

Theory and Method: Such measurements aims at probing the frequency-dependent diffusivity $D(\omega)$ (its precise content is discussed in Ref.5). The measurement sensitivity is governed by $F(\omega)=|\,q(\omega)|^2$, where $q(\omega)$ is the Fourier transform of time integrated gradient. Theoretically, for any given frequency, the ideal gradient shape is a cosine train, which in reality needs a ramp (apodization as in Ref.5). The most common implementation has been to use ramps with double the gradient frequency as proposed in Ref.3. This results in a two-fold reduction in the maximum frequency achievable (Fig.1). In order to relax this limitation, we propose ramps as described in Fig.2 where R is the maximal slew rate and c defines the frequency of the first sine-lobe. The ramp in Ref.4 corresponded to c=2. The condition of not exceeding the slew rate of the gradient train implies $c<\sqrt{2}$, the frequency of the ramp matches that of the cosine train when c=1. A ramp with $c=\sqrt{2}$ is currently implemented in our Bruker system.





↑ Fig.2: An example of the proposed ramps constructed from two sine lobes of different magnitudes, in this case of equal frequencies.

←Fig.1: Experimentally accessible b-values for a preclinical scanner with the gradient strength 1T/m, the slew rate 7T/m/ms and the duration of diffusion weighting 80ms. The dashed line is the upper limit when the ramp of Ref.4 is used. The proposed ramp extends this domain to the region between the dashed and solid lines.

Discussion: The proposed ramp modification is more relevant for high-performance hardware; the experimentally achievable domain is shown in Fig.1. Experimental feasibility is expressed via the b-factor as its product with the genuine diffusion coefficient that defines the effect magnitude of diffusion weighting. Decision about the affordable b-factor should be made in view of the signal-to-noise ratio of a specific experiment. Diffusion weighting with the proposed ramp extends the measurable frequency two-fold for b=0.1 ms/μm^2 and below. The choice of parameter c has a minor effect provided $c<\sqrt{2}$.

It is practical for imaging to apply a refocusing pulse at $T_E/2$, half the echo time; a gap for this pulse splits the gradient train in two. As discussed in Refs 6 and7, it is crucial to avoid splitting and broadening of the maximum of $F(\omega)$ at the target frequency. To do so, one has to apply the second gradient train in phase with the virtual continuation of the first one.

This requirement works out differently for the high-performance and for human scanners. While it is imperative to use frequency-matched refocusing gaps at high frequencies, this takes too much time for low-frequency measurements in human scanners. A solution is simply to use a brute-force interruption of the cosine gradient train using the shortest possible ramp. Even though it is unbalanced[7], and there will be a zero-frequency contribution to the diffusion weighting, with very high slew rate the effect becomes negligible. Furthermore when the slew rate is not an issue the cosine wave can be replaced with a trapezoidal form as well as the corresponding ramps in order to increase the b-factor[6,7]. However, fidelity of gradient performance should be should be inspected near the hardware limit of high-performance systems.

The smallness of achievable bD implies that the noise limits the measurements via the transverse relaxation, therefore the optimal gradient duration is about $1/T_2$.

Conclusions: The above discussion can be summarized as follows.

- In spin-echo type measurements the two gradient trains should be in phase with each other (Refs.6,7)
- On human scanners, the preferable gradient shape is the cosine-matched trapezoidal, which is switched and interrupted for the refocusing with the maximal slew rate (Ref.7).
- On high-performance preclinical scanner, use the ramp with variable magnitude to avoid the limitation by the maximal slew rate.
- Use the total gradient train duration about $1/T_2$

References: 1. Gross, Kosfeld, Messtechnik 77 (1969) 171–177; 2. Callaghan, Stepisnik JMR 1995 A117, 118–122; 3. Schachter et al. JMR 2000 147, 232–237; 4. Does et al. MRM 2003 49 206–215; 5. Novikov, Kiselev JMR 2011 210 2011 141–145; 6. Van et al. MRM 2013, DOI 10.1002/mrm.24632; 7. Baron et al. MRM, DOI 10.1002/mrm.24987.