A Spectral Filtering View of Diffusion Gradient Encoding

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Abstract: Diffusion imaging gradients serve to spectrally filter the temporally evolving diffusion tensor in the spectral domain. In this formulation, the design of diffusion sensitizing gradients is reduced to the problem of adequately sampling q-space in the spectral domain and hence one of designing a suitable filter. The practical limitations imposed by the requirement for delta function type diffusion sensitizing gradients to adequately sample q-space, can be relaxed if these impulse gradients are replaced with chirped oscillatory gradients. It is well known that in many systems of interest, dispersion of velocity will itself produce a peak in the velocity correlation function near DC, while restricted diffusion will manifest itself in the dispersion spectrum at higher frequencies. In this abstract, chirped diffusion sensitizing gradients are proposed and analytically and through experiments, shown to yield an efficient sampling of q-space in a manner that asymptotically approaches that using delta function diffusion sensitizing gradients. The challenge is the consequent reduction in diffusion sensitivity. This problem is addressed by restricting the available gradient power to a chirp spectral bandwidth corresponding to only the diffusion time scale of the underlying restrictive geometry. Simultaneous imaging of diffusion and flow at microscopic resolution scale and at temporally resolvable diffusion timescales thus becomes possible in-vivo. Simulations and experiments validate the proposed approach.

Methods: The Fourier transform relationship between the NMR echo signal and the underlying probability distribution of spin displacement, $P(\vec{R},\Delta)$ in a restrictive geometry is possible as long as the q wave vector is not a function of the spin displacement vector $\vec{R}$. In the very short pulse regime, this condition is easily satisfied. However, in practice, the pulse width is fairly large relative to diffusion time ($\delta \leq \Delta$)and under such conditions, q is a spatial-temporal wave vector $q = q(\vec{R},t)$ and hence the Fourier relationship often expressed as the echo signal and the diffusion propagator, $E_{\Delta}(g) \approx \int P(\vec{R},\Delta) e^{i2\pi q \cdot \vec{R}} d\vec{R}$ does not hold. In this case, the spectrum of displacements are not resolvable since the wave vector is spatially varying and hence the propagator $P(\vec{R},\Delta)$ becomes weighted by a kernel with a quadratic phase factor in $\vec{R}$. To increase the level of diffusion weighting, and hence the size of imposed phase in q space, we can increase the pulse width to δ' as in Fig. 1, for example in HARDI, Q-ball and DSI methods. However, in these cases, the region of equal diffusion weighting that maximizes the resolvability of the higher displacement time regimes is proportionally reduced to $\Delta' - \delta' << \Delta - \delta$. For a pulse of duration δ, this steady-state condition persists for a duration $\Delta - \delta$ in which random displacements in this interval are weighted equally such that the detected signal is attenuated in direct proportion to the displacement distance $\vec{R}$. However, all displacements that take place before this steady-state condition is reached are weighted in proportional to the prevailing gradient strength and hence the ability to uniquely resolve spin displacements is completely lost. It is clear from Figure 1 that in order to increase the level of diffusion weighting while at the same time ensuring that the wave vector q is the same across the entire displacement spectrum, we require that $g \to \infty$ while $\delta \to 0$. This is indeed the q-space approach first proposed by Callaghan et al.[1]. In this work, we showed that these impulse gradients can be replaced with chirped gradients which are shown to asymptotically approximate the short pulse field gradient requirement when integrated over a few cycles of the chirp waveforms as long as the chirp bandwidth spans the underlying frequency spectrum of the diffusion dynamics D(w). As long as the resulting gradient spectrum is spectrally flat over the range of D(w), the result is the same as using short diffusion pulses which are flat over all possible diffusion spectral frequencies. Displacement and probability maps from 2D CGSE in-vivo experiments were calculated using the method proposed. Figure 3 shows a sample probability map of an axial slice through the brain showing a resolution far surpassing HARDI or maximum amplitude and temporally longer PGSE diffusion gradient methods such as those in DSI and Q-ball.

Results:

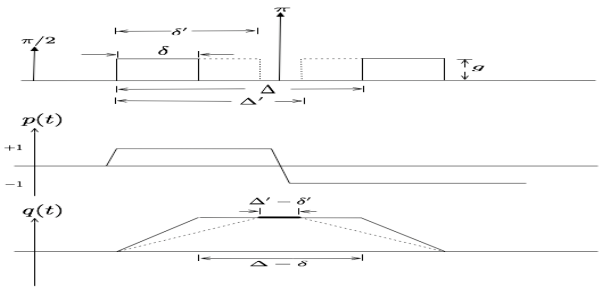

Figure 1

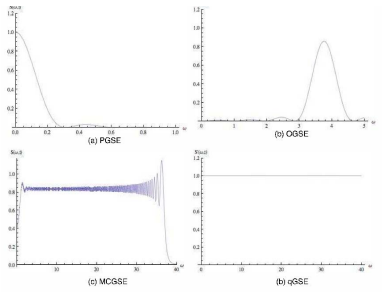

Figure 2

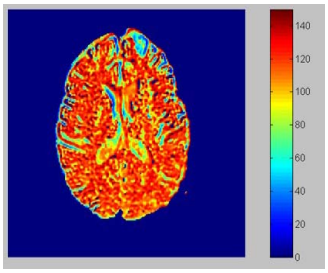

Figure 3

Figure 1: Evolution of the magnetization helix wave vector q in a standard PGSE sequence. In this case, plot of the temporal evolution q shows that spins are not equally weighted during the interval Δ. Displacements that take place close to the 180^0 pulse are weighted more than those that take place close to the 90^0 pulse. This spatially varying q vector invalidates the Fourier transform relationship between the echo signal and the probability of spin displacement due to diffusion.

Conclusions: It was shown that using the CGSE diffusion gradients at a specific chirp rate, determined by the underlying pore geometry, makes it a practical alternative to the ideal delta-function pulse gradient. It is the higher frequency lobes in the spectrum of the CGSE that allow sampling of the short time diffusion components. However, these higher frequency lobes are generated at ever decreasing diffusion sensitizing power which reduces the effective bandwidth of the probed diffusion spectrum D(w). This consequent reduction in diffusion probing power inherent in CGSE is overcome with the proposed MCGSE encoding scheme which is shown to be tunable to any desired diffusion spectral bandwidth. By spreading the available the available power to the spectral range of diffusion dynamics being probed, MCGSE provides an efficient and practical implementation of q-space techniques on a conventional scanner. With current gradient strength technology, diffusion displacements on the order of a few microns can be measured with the MCGSE method proposed and demonstrated here.

Figure 2: Spectrum of the diffusion sensitizing gradient showing range of diffusion spectrum sampling in case of: (a) pulsed gradient experiment (b), oscillating gradient encoding pulse (OGSE) (c), modified chirped gradient pulse (MCGSE) and idealized delta encoding approach corresponding to the interrogation of all possible diffusion time scales in (d). The spectral response shows the diffusion time scales probed by the various sensitizing techniques. Ideally, the delta function gradient encoding (d) probes all time scales while the conventional PGSE approach (a) is dominated by low to DC diffusion temporal changes and OGSE (b) probes diffusion time constants that are resonant with the oscillating gradient frequency. By sweeping over a range of frequencies, the chirp gradient approach (c) can be made to asymptotically approach the case in (d) but at the expense of diffusion encoding sensitivity. This issue is resolved by tuning the bandwidth of the pulse to be coincident only with D(w) as well as increasing the gradient power with frequency. Figure 3 shows the probability of zero displacement (restriction) map extracted from q-space analysis using chirped diffusion gradients. The contrast between gray and white matter is pronounced. The probability of zero displacement is much higher in the white matter than in the gray matter. Images were acquired with diffusion time of 100ms. The vertical scale shows increasing probability of restriction-arbitrary units.

References: [1] P. Callaghan, JMR A. 113 (53), 59 (1995).