Delay-Insensitive Variable-Rate Selective Excitation (DIVERSE)

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Purpose: Variable-rate selective excitation[1,2] (VERSE) is a powerful technique that allows RF pulse designers to vary the selective excitation gradient to reduce peak B_1 and SAR. While the profile dependence on off-resonance for VERSE pulses has been previously discussed[1], this work concentrates on the profile dependence on gradient-RF system delay, showing there is high sensitivity to this delay. We further present a novel design method, time-optimal delay-insensitive variable-rate selective excitation (DIVERSE), which shows improved robustness to gradient-RF system delay.

Methods: The contribution to the final transverse magnetization $M_{xy}(z,t)$ at time T from the segment [t, t+dt] of an RF pulse $B_1(t)$ of duration T in the presence of a time-varying gradient $G_z(t)$ can be approximated in the small-tip-angle regime as:

$$M_{xy}(z,t) = iM_0\gamma B_1(t)dt \cdot e^{izk_z(t)}, \quad \text{where } k_z(t) = -\gamma\int_t^T G_z(s)ds$$

If we assume a delay ∂ between the gradient and RF, caused either by system delays or eddy current effects, then the magnetization $M_{xy,\partial}(z,t)$ will be given by:

$$M_{xy,\delta}(z,t) = iM_0\gamma B_1(t)dt \cdot e^{izk_z(t+\delta)}.$$

The difference $|M_{xy,\partial}(z,t) - M_{xy}(z,t)|$ can be simplified using a Taylor series expansion for $k_z(t+\partial) \approx k_z(t) + \partial k_z'(t) = k_z(t) - \gamma\partial G_z(t)$ to:

$$|M_{xy,\delta}(z,t) - M_{xy}(z,t)| \propto |B_1(t)| \cdot |zG_z(t)|. \qquad [1]$$

As a consequence of [1], we introduce an additional constraint on VERSE'd gradient and RF waveforms for DIVERSE pulses such that $|B_{1,v}(t)|\cdot|G_{z,v}(t)| \le K_{dv}B_{1,max}G_{max}$, where K_{dv} is ≤ 1; and $B_{1,max}$ and G_{max} are the system limits. Introducing this term as an additional gradient constraint in the arc-length-based time-optimal VERSE approach[3] ensures time-optimality of the DIVERSE pulses. A DIVERSE pulse with K_{dv}=1 is equal to a minimum-time VERSE (MT-VERSE) pulse[3].

Results: Figure 1 shows VERSE designs of a spin-echo pulse with system limits of $B_{1,max}$<0.21G, G_{max}<4.5G/cm, and S_{max}<14G/cm/ms. The DIVERSE design with K_{dv}=10% reduces the RF pulse duration to 62% that of the non-VERSE 4.6-ms pulse. The relative duration for the DIVERSE pulse can be reduced to 47% by setting K_{dv}=20%, while the MT-VERSE relative pulse duration is only 37%.

Figure 2 illustrates the Bloch-simulated slice profile dependence on gradient-RF delay for the 10% DIVERSE and MT-VERSE pulses. The MT-VERSE pulse shows substantial sensitivity to delay when the RF pulse is modulated to offset the slice 6 cm from isocenter, while the DIVERSE pulse is much more robust. Figure 3 validates the simulations with experimental slice profiles acquired on a GE Discovery MR750 when a 4μs delay is intentionally introduced in the gradient-RF timing.

Figure 4 shows the T_2 (b_0) phantom images acquired 6 cm off isocenter with a diffusion-weighted EPI sequence using a single refocusing pulse. An intentional 4μs delay was introduced in the gradient-RF timing. The 10% DIVERSE image shows improved signal level and a sharper slice profile as expected.

Discussion and Conclusions: A novel approach for VERSE pulse design is presented that reduces sensitivity to gradient-RF delays. The constraint parameter K_{dv} can be adjusted to tradeoff reduction in pulse duration versus insensitivity to gradient-RF delay. Future work will evaluate DIVERSE pulses in simultaneous multislice DW-EPI sequences[4] where there is a need to reduce the duration of high peak B_1 multislice spin-echo pulses.

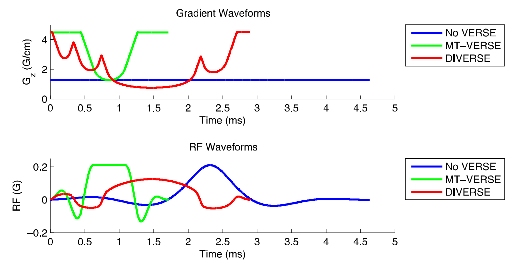

Figure 1: Gradient and RF waveforms for a refocusing pulse (time-bandwidth=5, 2-mm slice thickness) without VERSE (blue), and corresponding minimum-time VERSE (green) and DIVERSE (red) pulses with limit $|B_{1,v}(t)|\cdot|G_{z,v}(t)| \le$ 10% $B_{1,max} \cdot G_{max}$.

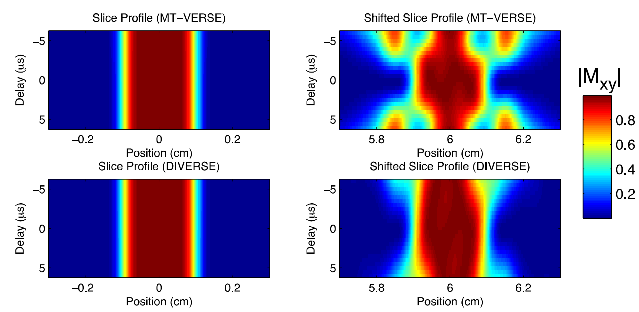

Figure 2: Simulated slice profile $|M_{xy}(z)|$ dependence on gradient-RF delay for the MT-VERSE and 10% DIVERSE pulses.

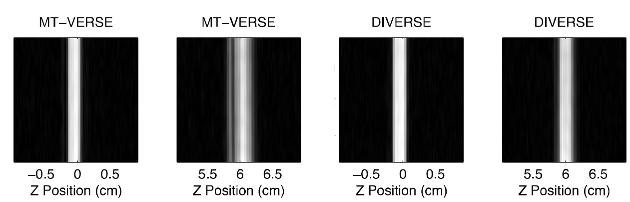

Figure 3: Experimental slice profiles for the MT-VERSE and 10% DIVERSE pulses at 0cm and 6cm from isocenter with an intentional 4μs gradient-RF delay introduced.

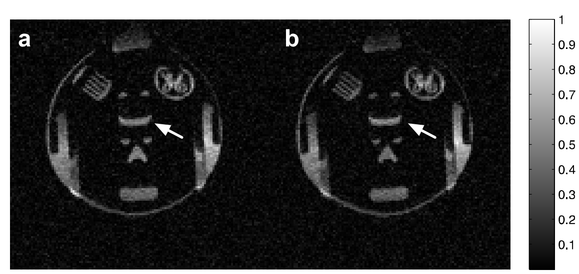

Figure 4: T_2 (b_0) images acquired 6 cm off isocenter with a diffusion-weighted EPI sequence using a single refocusing pulse that is the a) MT-VERSE or b) 10% DIVERSE pulse. The DIVERSE image shows 9% greater average signal and has improved slice sharpness as shown by the slice profile indicator of the phantom (arrow).

References: [1] Conolly *et al.*, JMR, 78(3):440–458, 1988. [2] Hargreaves *et al.*, MRM, 52(3):590–7, 2004. [3] Lee D *et al.*, MRM, 61(6):1471–9, 2009. [4] Setsompop *et al.*, MRM, 67(5):1210–24, 2012. [This work partly supported by NIH R01 EB008108, NIH R01 EB009756, NIH P41 EB015891.]