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Fast Measurement of Very Slow Flow by Distortion-Induced Phase

Introduction: **Measurement of very slow flow is difficult with MRI because of the strong flow-encoding gradients required for conventional phase-contrast techniques. Here, a new technique is presented that directly measures the instantaneous rate of change of frequency (RCF) of spins through the linear combination of three steady-state echoes. This rate of change corresponds to the rate of flow (µm / sec) along the spoiler direction when a gradient-spoiled pulse sequence is used. Multiple echoes are collected to remove phase contributions from other sources. Rather than inverting phase-encoding gradients, as is done in phase-contrast flow imaging, collection of higher-order steady-state echoes allows isolation of the desired phase.**

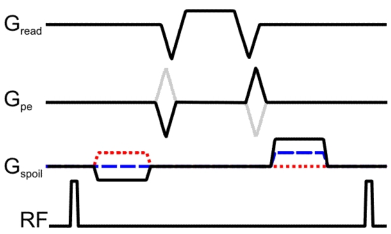

Figure 1: Waveforms to select each of three steady-state echoes. Dotted, dashed, and solid lines select 1^{st}, 0^{th}, and -1^{st} order echoes, respectively.

Methods: In gradient-spoiled imaging (GRE, GRASS, FISP), different steady-state echoes may be recalled by manipulation of spoiler gradients before and after readout (Fig. 1). When the Larmor frequency is fixed, the magnetization phase in the m^{th} echo, $\angle M_m$, is given by [1]:

$$\angle M_m = \theta_{F1} - m(\theta_{F1} + \theta_{F2}) + \theta_C,$$

where θ_{F1} and θ_{F2} represent free precession before and after TE, and θ_C arises from the excitation coil phase profile. If the Larmor frequency is slowly changing during imaging, an asymmetric distortion arises in the steady-state spin profile $h(\theta)$ as a function of precession (Fig. 2) [2]. When the conjugate symmetry of the steady-state profile is disturbed, its Fourier-series expansion $\{H_m\}$ is no longer real-valued. This results in an additive echo-dependent phase term ϕ_m: $\angle M_m = \theta_{F1} - m(\theta_{F1} + \theta_{F2}) + \theta_C + \phi_m$.

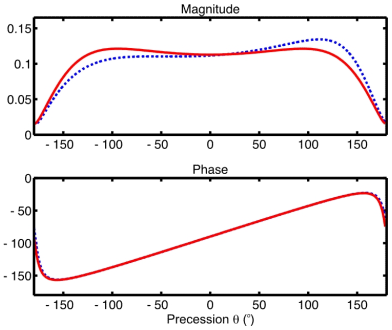

Figure 2: Steady-state signal h(θ) *as a function of precession. The magnitude (top) becomes distorted as resonant frequency increases linearly (dashed line).*

The ϕ_m terms are proportional to the time rate of change of resonant frequency for a particular spin, and can be calculated from the corresponding Fourier series coefficients ($\phi_m = \angle H_{-m}$) for a given rate of change of Larmor frequency. To isolate this term, three echoes must be acquired; for maximum signal, the three lowest-order echoes, m={-1,0,1}, were chosen. Residual phase is then calculated pixel-by-pixel:

$$\theta_{res} = \angle M_1 + \angle M_{-1} - 2\angle M_0 = \phi_1 + \phi_{-1} -\square\phi_0 \approx -\square\phi_0.$$

For validation purposes, only one echo was collected in each TR interval, as shown in Figure 1, but multiple echoes may also be collected along the same readout for increased scan efficiency [3]. Each 2DFT scan used a 20° tip, TR=6 ms, TE=3 ms, and a 128x128 image was reconstructed every 3 sec. Validation scans were performed on a copper sulfate solution (T1/T2 = 850/375 ms).

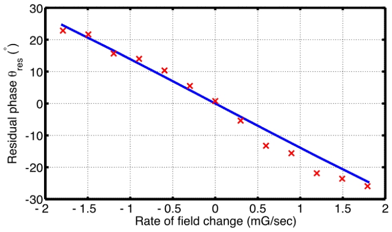

Figure 3: Image phase as a function of magnetic field increase. Measured values ('x') match well with theory (solid line).

Results: Figure 3 shows measured image phase when the transmission and reception frequencies were modulated to mimic PRF shifts. For RCF corresponding to 120 µm/sec of flow, over 20° of phase (θ_{res}) was observed. The signal is nearly linear over this broad range and uncorrupted by other phase sources.

In a second experiment, ice was added to the copper sulfate phantom and subsequently a sequence of images was acquired (Fig. 4). Convective flow was observed greater than 300 µm/sec in the direction of the spoiler gradient (up / down in Fig. 4). As time progressed, flow decreased and stabilized as the ice melted. These images show high SNR and illustrate the utility of the technique for measurement of convective flow.

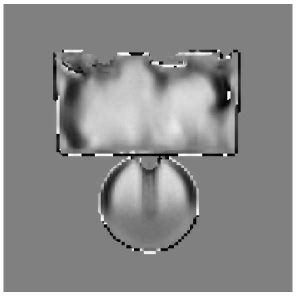

Figure 4: Phase image depicting convective flow (down=white; up=black) due to ice.

Discussion: The phase induced by perturbation of the steady state profile can also be viewed as an accumulation of phase errors in the sum of previous echoes that dictate the steady state. Viewed in this way, pixel-by-pixel image phase corresponds to a moving average of flow over time for a given spin, with the averaging window weighted primarily by T2. This effect may limit the effective temporal resolution of the method in certain cases. In addition to convective flow, this technique may find application in measurement of perfusion or CSF flow.

Conclusion: Through acquisition of multiple steady-state echoes, a unique source of phase in gradient-echo images can be used to rapidly visualize extremely slow flow with good SNR. More generally, the technique may be applied in a number of contexts where a small but consistent shift in frequency exists. In particular, the technique may be exploited to measure temperature changes due to the proton resonant frequency shift in water.

References:

1. Kim DJ, *et al.* MRM 19(1): 20-30, 1991.
2. Foxall DL. MRM 48(3): 502-508, 2002.
3. Zur Y, *et al.* MRM 16: 444-459, 1990.