Imaging Pseudo-Echoes Produced by a Frequency-Swept Pulse

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Synopsis: Frequency-swept pulses, like the hyperbolic secant (HS1) pulse, are not typically employed for excitation in MRI. When used for excitation in gradient-echo imaging, the HS1 pulse does not produce a proper echo because the magnetization phase varies quadratically in space. Here, the phase profiles of HS1 are described analytically. It is shown that HS1 produces a "pseudo-echo" when used for excitation in a gradient-echo sequence. An image reconstruction method is developed to allow 3D pseudo-echo imaging using a sliding window function. This method makes it possible to take full advantage of HS1 for slab-selective 3D MRI.

Introduction: Adiabatic passage pulses, such as the hyperbolic secant (HS1), are widely used for slice-selective inversion because they tolerate B_1 inhomogeneity and offer the capability to excite broad bandwidths in a highly selective manner with low peak B_1 power (*1*). Although the HS1 pulse lacks B_1-insensitivity when the RF power is below that needed to fully invert magnetization, the pulse produces a similar desirable profile of transverse magnetization. Despite this, the HS1 pulse is not generally used as an excitation pulse because the phase of the transverse magnetization varies quadratically across the slice at all times, and so, is never in phase. In gradient-echo imaging with HS1 excitation, only a "pseudo-echo" is generated. Recently, it was recognized that some applications, such as slab-selective 3D MRI, can benefit from the quadratic phase because it reduces the receiver dynamic range requirements (*2*). Here, the phase variation produced by HS1 excitation is analytically described, and a procedure to reconstruct 3D pseudo-echo images is described that employs a time-dependent sliding window for apodization. The method is demonstrated by simulation and in 3D gradient-echo imaging of human breast.

Theory: In the frequency-modulated (FM) rotating frame, the HS1 pulse can be described by AM and FM functions: $\omega_1(t)=\omega_1^{max}\mathrm{sech}(\beta\tau)$, $\omega_2(t)= A\tanh(\beta\tau)$, where τ is normalized time ($=2t/T_p-1$) for t in the range $[0,T_p]$, A is the amplitude of frequency sweep, and β is a dimensionless truncation factor (usually, $\mathrm{sech}(\beta)=0.01$). When an HS1 pulse of length T_p is applied in the presence of a gradient G, spins at position x are rotated to the transverse plane at time $t = T_p(4\beta)^{-1}\ln((A+\gamma Gx)/(A-\gamma Gx))+T_p/2$, and the phase of spin isochromat at position x after the pulse can be written as:

$$\phi_1=\frac{\pi A T_p}{\beta}\ln\left(\frac{A\cdot\mathrm{sech}(\beta)}{\sqrt{A^2-(\gamma Gx)^2}}\right)-\frac{\pi T_p\gamma Gx}{2\beta}\ln\left(\frac{A+\gamma Gx}{A-\gamma Gx}\right)+\pi T_p\gamma Gx+\frac{\pi}{2} \quad [1]$$

In Eq.[1], the first and second terms show that the phase profile of HS1 is "quadratic-like" in terms of x. The third linear term shifts the vertex of this phase profile. It is important to note that the spin isochromat at the vertex is locally rephased, which localizes the signal to the position of the vertex (*3*). Following excitation ($t'=0$), a rephasing gradient $-G$ is applied in the x direction. Since the phase accumulation of spins at position x during the rephasing gradient is $\phi_2 = -2\pi\gamma Gt'$, the total phase accumulation of spins at position x becomes $\phi(x,t)=\phi_1+\phi_2$. Thus, by setting the partial derivative of $\phi(x,t)$ with respect to x to be zero, the rephasing time of spins at position x can be shown to be $t_{rephase}= -T_p(4\beta)^{-1}\ln((A+\gamma Gx)/(A-\gamma Gx))+T_p/2$. Accordingly, spins at position x mainly contribute to the pseudo-echo at their unique rephasing time. It is interesting that the rephasing time is symmetric with the excitation time. Given that the ith isochromat rephrases at time t_i, a sliding window $W(t-t_i)$ can be applied to the pseudo-echo. For each position of the sliding window, a discrete Fourier transform is performed to pick up the spin density of the selected isochromat. Then, this value is assigned to the pixel corresponding to the selected frequency for reconstructing the image.

Methods: The program for the described image reconstruction method was developed using MATLAB 6.1. To test the performance of pseudo-echo imaging using HS1, two different simulated 1D pseudo-echoes were generated using Bloch equation. As a sliding window, a Gaussian function ($\exp[-(t-t_i)^2/(2\sigma^2)]$, $\sigma=T_p/4$) was used. The first simulation was used to show how well a 1D object can be reconstructed from a pseudo-echo and to compare sliding window apodization with a fixed window (i.e., conventional apodization). An object with uniform spin density was assumed. The HS1 pulse used T_p=1ms, $2A$=15kHz, and ω_1^{max}=2,340Hz for 90° flip angle. The number of pixels was 64. The second simulation of a nonuniform object was performed to investigate how well the sliding window apodization reduces the "bleed effect" caused by echo truncation. Finally, the method was used for fat-suppressed 3D FLASH imaging of human breast following injection of Gd-DTPA. To reduce peak power, slab selection was performed with the HS2 pulse (T_p=1ms, $2A$=15kHz, and ω_1^{max}=1,023Hz for 30° flip angle) in the medial to lateral direction. As a sliding window, an AM function of HS2 ($\mathrm{sech}(\beta\tau^2)$) was used. The SNR was measured with and without apodization.

Results: The first simulation shows that the uniform object could be reconstructed from the pseudo-echo and that the sliding window yields a more accurate representation of the object than the conventional apodization (Fig.1). In the second simulation, the bleed effect was suppressed using a sliding window (Fig.2). In case of 3D breast images, the image reconstruction using a sliding window (Fig.3) improved SNR over the image processed with conventional apodization, as well as the image reconstructed without apodization. SNR values were 45, 70, and 71, corresponding respectively to images without apodization, with a fixed window, and with a sliding window.

Conclusion: The phase profiles produced in the slab-selective direction with HS1 excitation were shown to be "quadratic-like". In a 3D gradient-echo sequence, HS1 produces a pseudo-echo as a consequence of the shifting vertex of the quadratic phase profile, and thus localizes signals from different isochromats at different times. A new image reconstruction method was developed using a sliding window applied at the rephasing time of each isochromat in the pseudo-echo. The bleed effect in an object profile reconstructed using a sliding window was reduced. The reconstruction and apodization procedures presented here make it possible to take full advantage of frequency-swept pulses in slab-selective 3D MRI. Among the many adiabatic passage pulses existing, only the HS1 pulse was treated here. However, the analysis is easily extended to include other pulses, including HS2.

References: (1) M.Garwood & L.DelaBarre, *JMR* 153, 155-177 (2001) (2) L.DelaBarre *et al*, *ISMRM* (2001) (3) J.Pipe, *MRM*.33, 24-33 (1995)

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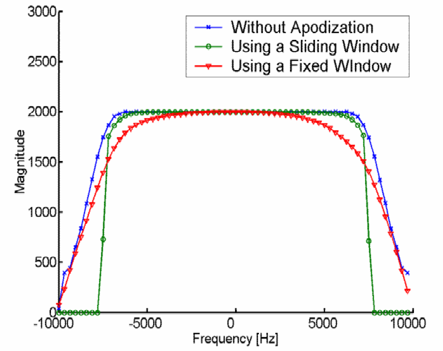

Fig.1 Reconstructed profiles with/without apodization using a sliding and a fixed window: An object with uniform spin density

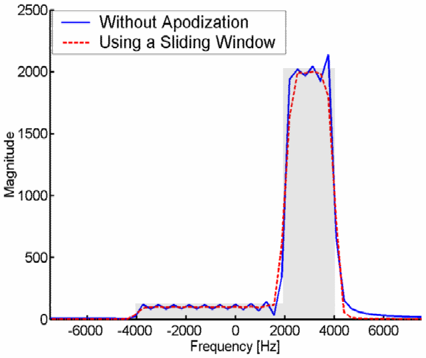

Fig.2 Reconstructed profiles with/without apodization using a sliding window: An object with non-uniform spin density

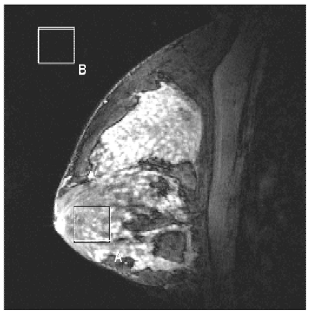

Fig.3 A breast image reconstructed using a sliding window: Background noise and main signal for calculation of SNR were selected in box A and B, respectively