Spin Echoes in the Weak Dephasing Regime

Jakob Assländer[1], Simone Köcher[2], Steffen Glaser[2], and Jürgen Hennig[1]
[1]*Dept. of Radiology - Medical Physics, University Medical Center, Freiburg, Germany,* [2]*Dept. of Chemistry, Technische Universität München, Germany*

Introduction: Spin echo pulse sequences assume a totally dephased spin ensemble at the time of the refocusing pulse, as shown by Erwin Hahn [1]. In this work, spin echo forming pulses are proposed that work in the regime of weak dephasing (total dephasing over all isochromats < 2π) and refocus all spin-isochromats within a defined range of Larmor frequencies. The echo time (TE) can be chosen rather freely without any boundaries to lower values. An upper boundary for TE is given by geometrical considerations. Throughout this paper TE is measured starting from the end of the pulse. It is shown that TE can be longer than the pulse itself, if a flip angle $\alpha \neq \pi/2$ is chosen. Finally, it is shown at the example of lung pulmonary imaging that the signal to noise ratio (SNR) is enhanced due to suppression of the T_2'-decay at TE.

Theory: For a general description, the dimensionless phase slope $R = 1/T_P \cdot d\varphi/d\omega$ is defined, where T_P denotes the length of the pulse, φ the phase of a particular spin-isochromat with the Larmor frequency ω at the end of the pulse [2]. The echo time is given by $TE = -R \cdot T_P$. After instant excitation from thermal equilibrium, the phase of a spin-isochromat is given by $d\varphi = d\omega \cdot t$, independently of α. The Euclidian distance between an isochromat with $d\omega$ and the on-resonant isochromat ($\omega_0 \equiv 0$) is given by $d\delta = d\omega \cdot t \sin\alpha$. By differentiation it is easy to show that the Euclidian distance grows fastest at $\alpha_{max} = \pi/2$, resulting in $d\delta_{max} = d\omega \cdot t$. Describing this Euclidian distance in spherical coordinates, the corresponding phase $d\varphi_{max} = d\omega \cdot t/\sin\alpha$ depends on the flip angle. Flipping the magnetization after the time T_P of free precession at $\alpha = \pi/2$ to the final flip angle α_f, the maximum phase slope is given by

$$|R_{max}| = \frac{1}{T_P} \cdot \frac{d\varphi_{max}}{d\omega} = \frac{1}{\sin\alpha_f}$$

(Fig. 1). The absolute value is used, since in this geometrical consideration the pulse amplitude (B_1) can be arbitrarily big, allowing for an arbitrarily fast inversion of the phase-slope. By this geometrical considerations, an upper boundary for $|R|$ is given. The maximum echo time is $TE_{max} = T_P$ when a spin ensemble is excited to $\alpha_f = \pi/2$. For other flip angles, however, the time between the end of the pulse and the echo can be longer than the length of the pulse itself. This stands in contrast to Hahn echoes (regime of complete dephasing). The usual $\pi/2$-π-sequence can be considered as a composite pulse, where $R = -1$ is fixed in the approximation of delta-pulses and $R > -1$ for pulses of finite length.

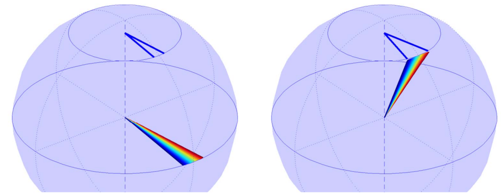

Figure 1: A spin ensemble dephases at $\alpha = \pi/2$ (left) and is flipped to $\alpha \neq \pi/2$ thereafter (right). By this transformation, the phase difference of the spin isochromats is amplified. The blue triangle shows the phase projected to the plane of precession at α.

Methods: In order to demonstrate the feasibility, two exemplary pulses were calculated using optimal control [3, 4]. The pulses were optimized for $R = -1.3$ and $R = -2$ over a range of 7854 rad/s (1250 Hz), and 3142 rad/s (500 Hz), respectively, at a flip angle of 0.026 rad (1.5°). Bloch simulations were performed to show the spectral response. The broadband pulse was implemented in a 3D FLASH sequence with TR = 3.5 ms, TE = 0.43 ms, Res. = (3 mm x 3 mm x 6 mm), FOV = (768 mm x 384 mm x 240 mm), BW = 1760 Hz/px. The echo was acquired asymmetrically, 36 data points before the echo, 128 thereafter. Lung imaging was performed in a volunteer at full inspiration with a 3T TIM Trio (Siemens, Erlangen, Germany). Excitation was done with the body coil. For signal reception, a spine array and a body coil array was used. A reference dataset was acquired with a 100 us block pulse and the same parameters otherwise (TE was the same measured from the end of the pulse).

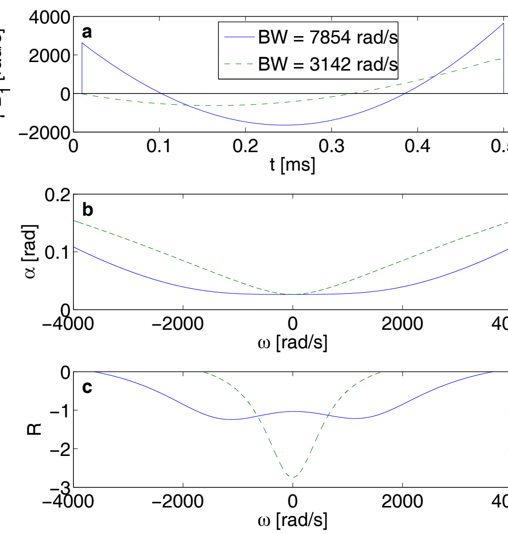

Figure 2a: Real part of exemplary rf-pulses. The imaginary part of the pulses is negligible. **b**: Spectral response: The broader pulse has a fairly constant flip angle over approx. 4000 rad/s, while the pulse with a smaller bandwidth shows significant variations of the flip angle. **c**: The broader pulse results in R-values slightly smaller than -1, while the less broad pulse shows R-values down to -3.

Results: Fig. 2 demonstrates that within Bloch's law of spin precession $|R| > 1$ is possible for small flip-angles. Fig. 3 shows a spin echo FLASH image in comparison to a standard FLASH with block pulse excitation. The SNR in a region of interest (ROI) in the upper left lung is increased by a factor of 1.5.

Discussion: By geometrical considerations and Bloch simulations it was shown that spin echo forming excitations pulses with $|R| > 1$ are feasible. However, even for $-1 < R < 0$ a reduction of α_f allows for longer TEs when the pulse amplitude is limited (not shown here). For the imaging experiment TE < T_P was chosen in order to approximately refocus also far off-resonant spin isochromats, which exhibit $R > -1$. Proposed pulses can be included in standard gradient echo sequences like FLASH, converting them into spin echo sequences. Contrary to trueFISP sequences, which also form spin echoes [5], only longitudinal magnetization is used for each excitation. Therefore, the contrast mechanism of a FLASH sequence is maintained, with T_2*- replaced by T_2-decay. Low flip angles maintain the longitudinal magnetization, allowing for smaller TRs than Hahn echo pulse sequences, which require high flip angles for reasonable SNR [6]. The particular α was chosen to be smaller than the Ernst angle due to SAR issues. Further optimization in that regard is part of future work, as well as implementing an inversion recovery snapshot FLASH for quantitative T_1-measurements [7].

Figure 3: 3D FLASH images acquired with the proposed pulse with BW = 7854 rad/s (left) and a block pulse for reference (right). Both images are equally scaled. The yellow boxes define the ROI for the SNR comparison.

References: [1] Hahn, E.L. PR 80(4): 580-594 (1950); [2] Gershenzon, N.I., et al., JMR 192(2): 235-243 (2008); [3] Conolly, S. et al., IEEE MI 5(2): 106-115 (1986); [4] Janich, M.A., et al. JMR 213(1): 126-135 (2011); [5] Scheffler K., et al., MRM 49(2): 395-397 (2003); [6] Assländer, J., et al., Proc. ISMRM #4249 (2013); [7] Jakob P.M., et al., JMRI 14(6), 795-799 (2001).

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