Spin Echoes in the Regime of Weak Dephasing

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Introduction: The vast majority of spin echo (SE) experiments are based on Hahn's theory [1]. His finding was that any sequence of two radio frequency (RF)-pulses results in a spin echo under the assumption of a complete dephasing of the entire magnetization between the two pulses. As a supplement to Hahn's theory, this article explores the possibilities and boundaries of spin echo pulses in the regime of weak dephasing. A theoretical framework can be derived based on the assumption of an infinitesimally small amount of dephasing [2]. In proof-of-concept experiments, it is shown that SE-pulses in the regime of weak dephasing provide potential for combining the enhanced signal and reduced artifacts of spin echoes with the speed and flexibility of the fast low angle shot (FLASH) sequence.

Theory: Throughout this abstract, the echo time is defined to be the phase slope at the end of the RF-pulse: $TE = d\varphi/d\omega$. Thereby, φ denotes the phase of a particular spin isochromat with the Larmor frequency ω. Following this definition, the echo time is measured from the end of the RF-pulse. Based on geometrical considerations, one can show that in the extreme case of an infinitesimally small amount of dephasing, the maximal echo time is given by

$$|TE_{max}| = T_P \cdot \frac{1}{|\sin \alpha_t|},$$

where T_P describes the length and α_t the total flip angle of the RF-pulse. For a detailed derivation please refer to [2]. The basic concept of the derivation is shown in Fig. 1: The magnetization dephases after excitation from thermal equilibrium with a flip angle of $-\pi/2$. Rotating it back towards the z-axis, the Euclidean distance between the tips of the magnetization vectors is maintained. This results in an amplification of the phase difference between different isochromats. In Fig. 1 (b), the magnetization is flipped beyond the z-axis, inverting the phase slope and resulting in a spin echo formation after some time of free precession. The maximum echo time is $TE_{max} = T_P$ when a spin ensemble is excited by $\alpha_t = \pi/2$. 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's theory: The usual $\pi/2$-T_P-π-sequence can be considered as a composite pulse, where $TE = T_P$ is fixed in the approximation of delta-pulses and $TE < T_P$ for pulses of finite length.

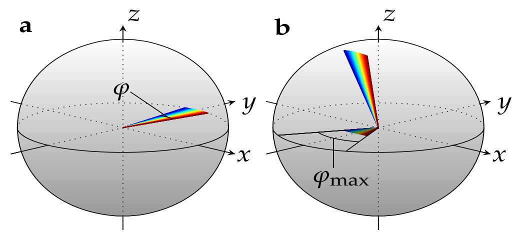

Fig. 1 (a): Magnetization that was excited by $-\pi/2$ from thermal equilibrium and precessed freely thereafter. **(b)**: The same magnetization after rotating it to $\alpha_t = \pi/10$ along with the projection of the magnetization onto the x-y-plane.

Methods: Two representative pulses were calculated using optimal control [2-4]. The pulses were optimized for $TE = 4.3 \cdot T_P$ and $1.3 \cdot T_P$ with $T_P = 150\,\mu$s and $500\,\mu$s, respectively. The target bandwidth was 3000 rad/s and $\alpha_t = 3.5°$. Pulse amplitude and energy deposition was limited in order to meet hardware and safety limitations [2]. The $500\,\mu$s pulse was implemented as a non-selective excitation pulse in a 3D FLASH sequence with $TR = 8$ ms, $TE = 0.63$ ms, res = $(1.3\text{ mm})^3$, FOV = (512 mm x 256 mm x 256 mm), $t_{dwell} = 5.8\,\mu$s and 4 repetitions. The echo was acquired asymmetrically, 24 data points before the echo, 192 thereafter. A volunteer's head was imaged with a 3T TIM Trio system (Siemens, Erlangen, Germany). The experiment was repeated with a $100\,\mu$s rectangular pulse and the same parameters otherwise.

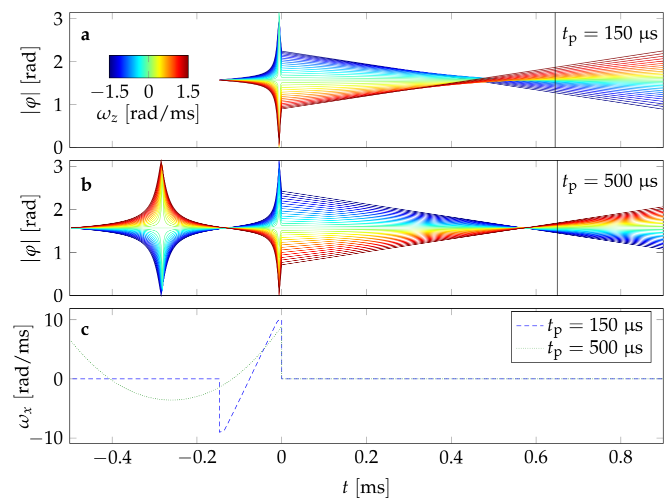

Fig. 2: The subplots **(a)** and **(b)** depict the absolute value of the phase evolution during and after the application of the two RF-pulses **(c)** to longitudinal magnetization. The color coding corresponds to the Larmor frequency. The vertical lines indicate the designated echo times.

Results: The phase evolution during and after the pulses is displayed in Fig. 2 along with the pulse shapes themselves. Both pulses amplify the phase dispersion by bringing the magnetization close to the z-axis. Fig. 2 (a) depicts a variation of the echo time as a function of the Larmor frequency. A complete spin echo is never formed and the time of minimal dispersion occurs earlier than the designated echo time. The 500 ms pulse forms one echo during the RF-pulse and another one slightly before the designated echo time (b). Therefore, the desired echo time is not reached in these particular examples. However, TE is larger than the pulse duration in both cases. Please note, the achievable echo time is severely limited by the pulse amplitude and energy deposition. Fig. 3 shows a SE-FLASH image in comparison to a standard FLASH. Besides magnetization transfer effects visible as decreased signal in white matter, one can observe increased signal in the bone marrow (arrows), as well as between the teeth (insert). The displayed sagittal and transversal slices comprise a tooth implant fixed by a metal screw. In the gradient echo FLASH image, this causes signal attenuation (a), whereas the magnetization is rephrased in the proposed spin echo FLASH image where signal intensity is maintained (b).

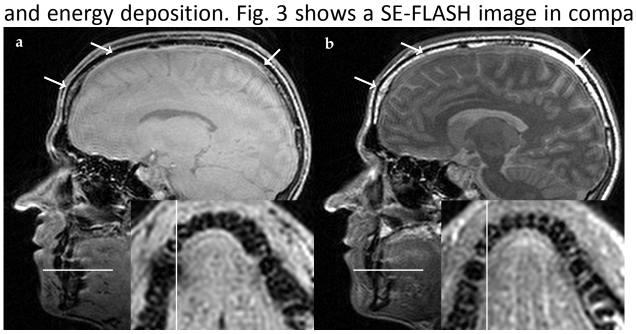

Fig. 3: A sagittal slice of a volunteer's head, acquired with a standard rectangular RF-pulse **(a)** and with the proposed $500\,\mu s$ delayed-focus pulse **(b)**. The arrows highlight the bone marrow in the skull. The white lines indicate the position of the inserted transversal and the sagittal slice, respectively.

Discussion: Spin dynamics in the regime of weak dephasing were investigated. It was shown how the echo time can exceed the pulse duration, contradicting Hahn's theory. The feasibility of combining the enhanced signal and reduced artifacts of spin echo imaging with the speed and flexibility of the FLASH sequence was confirmed in proof of concept experiments with the proposed pulses.

References: [1] Hahn, E.L. (1950), PR 80(4): 580-594; [2] Assländer, J. et al. (2015), MRM doi: 10.1002/mrm.25579; [3] Conolly, S. et al., (1986), IEEE MI 5(2): 106-115; [4] Janich, M.A. et al. (2011), JMR 213(1): 126-135. **Acknowledgement:** This work was supported by the European Research Council Advanced Grant 'OVOC' grant agreement 232908.