Accelerated Radiation-Damping for Increased Spin Equilibrium (ARISE): A new method for controlling the recovery of longitudinal magnetization

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Introduction The efficient use of longitudinal magnetization is a key consideration in MRI pulse sequence design, as the amount of longitudinal magnetization available for excitation directly affects image sensitivity. In conventional multi-shot sequences, M_z must either be used sparingly, with only a small amount tipped away from the z-axis per excitation (as in FLASH), or fully excited but with a lengthy repetition period (TR) to ensure sufficient T_1 recovery. Driven Equilibrium and Fast Return sequences have been devised to hasten the return of the M_z by rotating the magnetization back to equilibrium after the readout. However, such methods are limited to use in spin echo sequences by off-resonance effects. Steady State Free Precession (SSFP) uses full refocusing and RF phase cycling to recycle M_z efficiently with high flip angles and fast TR. Although the most efficient sequence in MRI, SSFP typically achieves a steady state of only ~$M_0/4$ *in vivo* and suffers from off-resonance banding artifacts.

We introduce a new method for accelerating the return of M_z that is independent of the externally applied RF pulses, allows full use of M_0, and shows improved off-resonance performance. The Accelerated Radiation Damping for Increased Spin Equilibrium (ARISE) method uses an external feedback circuit to strengthen the radiation damping (RD) field. The enhanced RD field rotates the magnetization back to the +z-axis at a rate considerably faster than T_1 relaxation. We characterize this method in phantom imaging at 3T and show that a short period of feedback (10ms) applied in a crushed gradient echo sequence is sufficient to recover more than 99% of the longitudinal magnetization despite the long T_1 of the phantom.

Theory and Methods Understood for decades, RD is a phenomenon in which the nuclear magnetization acts back on itself via the induced currents in the RF coil (1) and has been demonstrated for frequency-dependent contrast (2). The return to equilibrium occurs at a characteristic rate distinct from T_1 relaxation. For clinical MRI scanners operating at 1.5 or 3 T, the efficiency and quality factor (Q) of the RF coil are insufficient to induce a strong intrinsic RD field. However, we show that an RF feedback circuit can reinforce the current and thus enhance the RD effect. We compare our results with those obtained by modeling the modified Bloch equations (1).

The feedback circuit (Fig. 1) consisted of an amplification stage, an attenuation stage, a phase shifter set to provide positive feedback, switches to close the feedback loop during the feedback time T_{FB}, and an untuned coupling loop to allow the amplified, phase-shifted RF power to reinforce the current in the RF coil. The circuit provided ~30 dB of gain and a maximum power of ~30mW.

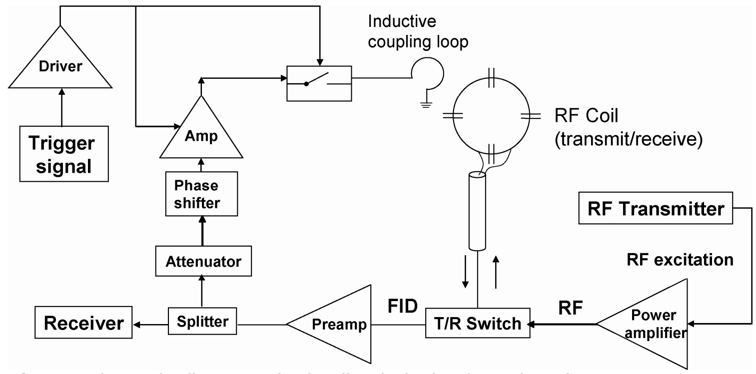

Fig. 1. Schematic diagram of a feedback device for enhancing RD.

The feedback device was tested on a 3 T Siemens Magnetom Trio using a 60mm dia. cylindrical Gd-doped water phantom (T_1=865ms, T_2*=130ms). A modified gradient echo sequence was used to characterize the feedback circuit. Following a 90° rectangular pulse, the feedback field was switched on for duration T_{FB}. A strong crusher gradient was applied after the T_{FB} period to eliminate any residual net transverse magnetization. After this fixed 50ms saturation preparation period, the longitudinal magnetization was read out using a 30° slice-selective pulse and gradient echo readout. After 3 s, the sequence was repeated to obtain a 64 × 64 image.

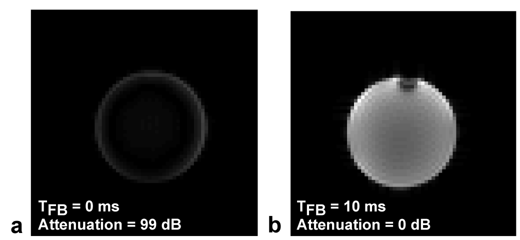

Fig. 2. Phantom image with (a) no feedback effect and (b) accelerated RD (16x brighter).

Results Figure 2 compares representative images taken with no significant feedback (Fig. 2a) and with accelerated RD (Fig. 2b). The image intensity increased by >16 times (from 6% to 99% of M_0). Figure 3 shows simulated and experimental plots of the amount of recovered longitudinal magnetization as a function of feedback duration for a fixed, optimized feedback phase and different feedback strengths. The experimental data showed the expected exponential recovery of the M_z with longer feedback times T_{FB}. Furthermore, attenuation of the feedback strength caused the growth of M_z to decrease. As the gain of the feedback circuit was increased, a higher percentage of the magnetization was recovered. With the highest gain, more than 99% of M_0 was recovered for $T_{FB} \geq$ 10ms. Off resonance effects were probed by altering the system frequency by ±100Hz. With full gain (0 dB attenuation) and T_{FB} = 10 ms, this resulted in less than 3% change in the signal intensity.

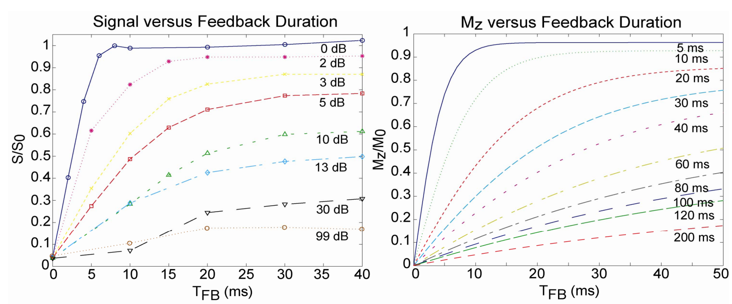

Fig. 3. Signal vs feedback duration for different levels of RD gain or RD time constant. Left: Experimental results. Right: Bloch simulation results.

Discussion and Conclusion We show that the ARISE method can return the full longitudinal magnetization to the +z-axis in 10 ms using accelerated RD, suggesting that a sequence designed to accelerate recovery of M_z with RD can recycle the full equilibrium magnetization with short TR (~15–20ms) with 90° pulses even for tissues with long T_1.

The self-generated nature of the RD effect provides several advantages. First, the RD field acts as a resonant excitation of the spins that maintains the correct frequency and phase needed to rotate the coherent transverse magnetization to +z. Unlike SSFP, which is known to be sensitive to off-resonance effects, the ARISE "flip-back" is generated by the spins themselves and shows little off-resonance degradation. Second, the RD effect turns itself off once the magnetization has been brought back to +z (no remaining net transverse magnetization) and is thus self-regulating in strength and duration. Finally, placing the feedback circuitry under pulse sequence control allows precise control of the timing and duration of the accelerated return to equilibrium. Thus, the ability to control the strength and timing of the RD effect is an important feature contributing to its utility as a building block in MRI pulse sequences.

References (1) Bloembergen N, Pound RV. Phys. Rev. 1954;95:8-12. (2) Huang SY et al., MRM 2006;56:776-786.