Balanced Steady-State Feedback Radiation Damping: Balanced SSFR

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INTRODUCTION
The SNR efficiency in MR experiments is intrinsically limited by longitudinal-, and transverse spin relaxation mechanisms. This becomes particularly limiting for unbalanced, short repetition time (TR) sequences, where incomplete $T_1$-relaxation results in a steady-state signal that is only a small fraction of the available thermal equilibrium magnetization.

Radiation damping (RD) is a second-order effect where the signal-induced current in the receiver coil is strong enough to act back on the signal-generating spins [1]. According to Lenz’s law, the RD field acts in a way to oppose its original cause. In that sense it can be understood as a self-regulating flip-back pulse causing the transverse magnetization to return to equilibrium more rapidly than it otherwise would. Generally, signals are sufficiently strong to produce RD only in very high-Q coils with high filling factors, such as in high-resolution NMR spectrometers.

Recently, active feedback loops have been introduced into the transmit-receive RF signal path as a means to either cancel [2-3], or amplify [4-6] the RD effect. For instance, Huang et al [6] used RD feedback to actively control the recovery of longitudinal magnetization immediately following a non-selective saturation pulse. Here we investigate RD feedback as a means to achieve increased SNR efficiency for short-TR, gradient-echo (GRE) sequences.

MATERIALS and METHODS
The signal-induced RD feedback effect renders the spin-dynamics non-linear, which can be seen from the modified Bloch equations, according to:

$$\frac{\partial m}{\partial t} = \left[ \delta \omega z + \gamma B \right] \cdot \left[ \frac{m}{T_2} - \frac{m}{T_1} \right] - \frac{m}{T_2} \cdot \frac{m}{T_1} \cdot \frac{y}{T}$$

with $m=M/M_{thermal}=[m_x,m_y,m_z]$ the normalized magnetization, $\delta \omega$ the off-resonance, $B_{RF}$ the 1st order transmit RF-field, and $B_{RD}$ the 2nd order RD feedback field.

The RD feedback is mediated via an untuned, circular coupling to the primary, transmit-receive, linear birdcage coil [6]. The RD strength, characterized by the time constant $\tau_{RD}$ and the RD phase $\varphi_{RD}$, are adjustable via voltage-controlled phase shifters and attenuators (Minicircuits, NY, USA).

RESULTS
Simulations based on the modified Bloch equations have been performed to analyze the spin dynamics and SNR efficiency of RD feedback (cf. Fig. 1 middle row). The SNR efficiency was found to improve with shorter time intervals between the RF excitation and start of the RD feedback pulse. The steady-state signal was found to be off-resonance sensitive, which could be improved by spoiling. FID measurements were obtained for an acquisition period of ~16.4ms starting 1ms after the RF pulse (cf. Fig. 1 bottom row). The RD feedback gain (~17.5dB) and phase were manually adjusted in prescan-mode by maximizing the initial FID amplitude. For these measurements the steady-state signal enhancement factor with active RD feedback was found to be ~1.25, as compared to ~1.75 for the simulations. Similar average SNR enhancement factors were found for images obtained from the 3D GRE acquisition (cf. Fig. 2).

DISCUSSION and CONCLUSIONS
In this work a novel method has been introduced, which improves the SNR efficiency for short-TR sequences, using actively-controlled RD feedback. The steady-state SNR efficiency and off-resonance behavior were found to improve for shorter time intervals between the excitation and the RD feedback pulse. The limiting case of a short, intense RD pulse immediately following the RF excitation close to 100% SNR efficiency and no off-resonance sensitivity is expected. In order to maximize the NMR signal that drives the RD feedback, the spins have been rephased following the image encoding using balanced gradient waveforms. By nature the RD effect is not volume selective; i.e. it acts on all spins within the sensitivity region of the RF coil. For slice selective imaging, the RD effect needs to become volume selective in order to be useful. This might be possible by applying a slice selection gradient simultaneous to the RD, similar to what is done for slice selective excitation.

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REFERENCES: