Low-frequency RF coil loading measurements to guide field-cycled MRI system design

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Introduction: Conventional MRI uses a single superconducting magnet to both polarize the nuclear magnetic moments in a sample and to provide the magnetic field environment under which an image is acquired. In field-cycled MRI, these two tasks are accomplished by two actively controlled resistive magnets [1,2]. A high-field (~1 T) polarizing magnet is used to induce magnetization, while a low-field (~0.1 T) homogeneous readout magnet is applied during image acquisition. The signal-to-noise ratio (SNR) of a field-cycled MRI system is different from conventional MRI. The ability to vary the strength of the two magnets in field-cycled MRI suggests there is an optimal frequency range over which SNR would be maximized. The authors have previously presented various designs for field-cycled MRI systems intended for small animal imaging, based on electromagnetic, SNR, and thermal considerations [2,3]. The results of the RF coil loading measurements presented here will be used to guide future design studies.

Theory: In whole-body MRI, at clinical field strengths, losses in the receiver coil are typically dominated by coupling to the sample. As the system is scaled down in both size and field strength, losses from the receiver coil begin to dominate over losses from the sample, and SNR depreciates rapidly. In field-cycled MRI, the ability to vary the strength of the readout field allows a readout field strength to be chosen which will provide the highest SNR without the drawbacks associated with high-field imaging, such as increased susceptibility artifacts, acoustic noise, and absorbed power.

The effective resistance of an RF receiver coil is attributed to losses imposed by the coil itself, inductive and capacitive coupling to the sample, and radiation. There are two SNR regimes in MRI: coil noise dominance (CND) and body noise dominance (BND). The SNR equations for field-cycled MRI are different from conventional MRI. In the CND regime: $SNR_{CND} \propto \omega_r^{3/4} B_p B_1$, where B_p is the strength of the polarizing field, ω_r the frequency of the readout field, and B_1 the RF field efficiency. In the BND regime: $SNR_{BND} \propto B_p$.

SNR increases with readout-field-strength until the RF coil becomes dominated by inductive losses, at which point the SNR will become independent of readout-field-strength. The quality factor, Q, of a receiver coil is a measure of coil losses. The loading factor, $lf = 1 - Q_{loaded}/Q_{unloaded}$, provides a measure of the amount of noise contributed by the sample to the RF coil. We choose to take an lf of less than 0.5 to indicate CND, and conversely an lf of greater than 0.5 to indicate BND.

Method: Measurements of Q were conducted on saddle and solenoid coils over a frequency range of 2 - 20 MHz. Q measurements were acquired when coils were empty and when loaded with phantoms of varying sodium chloride (NaCl) concentrations. Measurements were repeated with and without an RF shield. The technique used to measure Q was based on the experimental setup described by Hoult [4].

Three saddle coils, with diameters of 8.89 cm, 11.4 cm, and 14.0 cm, were constructed of 0.53-mm-thick, 12.7-mm-wide copper strips, and had length to diameter aspect ratios of 1:1. Two solenoid coils were constructed using equivalent copper strips, and had diameters of 8.89 cm and 11.4 cm. Faraday shields were placed between solenoid RF coils and their respective samples. RF shields had diameters 140% the diameter of their respective RF coil, were 25.4 cm long, and were made of 0.53-mm-thick continuous copper sheet. Three sets of phantoms were constructed with diameters 67% that of their respective RF coil. For each given diameter, four phantoms were made with NaCl concentrations of 0 mM (distilled water), 50 mM, 150 mM, and 500 mM. In all, loading measurements were taken on five coils, with and without a shield, loaded with three different phantoms. Over 750 Q measurements were taken.

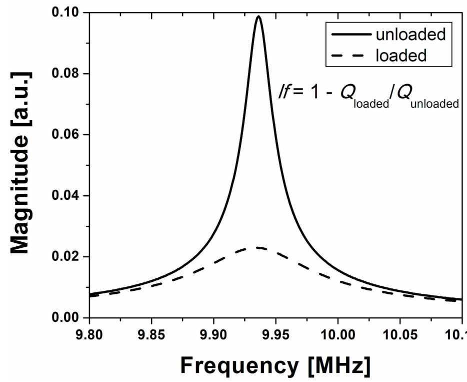

Figure 1 Q-curves for the 11.4-cm-diameter saddle coil when unloaded and loaded with a 500 mM NaCl phantom. The loading factor is calculated from the unloaded and loaded Q values, which were 485 and 119, respectively, resulting in an lf of 0.75.

Results and discussion: An example of a Q measurement is given in figure 1. The loading factors, as a function of frequency, for the unshielded 8.89-cm-diameter saddle coil are given in figure 2. Table 1 summarizes the SNR transition frequencies. Physiological NaCl concentrations are between 50 - 150 mM. The shielded cases, in this NaCl concentration range, are given in bold lettering in table 1. Table 1 shows the CND-BND transition to be between 10 - 30 MHz. Once in the BND regime, there is little benefit in SNR to acquiring at higher frequency. From figure 2, it is clear that at an operating frequency of 5 MHz, the field-cycled MRI system will be coil-noise-dominated for that coil. In the CND regime, field-cycled MRI systems can be designed according to the method described by Gilbert *et al.* [3].

Being in the CND regime implies that there are benefits to be gained by increasing the readout frequency into the CND-BND transition regime. An increase in readout frequency would have potential implications on system design. The field-cycled MRI system would now be based on the BND-SNR relationship, implying the polarizing field should be made as large as possible as long as the readout frequency remains sufficiently high to achieve BND. An increase in readout-field-strength to between 10 - 30 MHz would increase SNR, although it would present practical challenges, such as increased system size and heating. The results presented here are critical to the design of future field-cycled MRI systems.

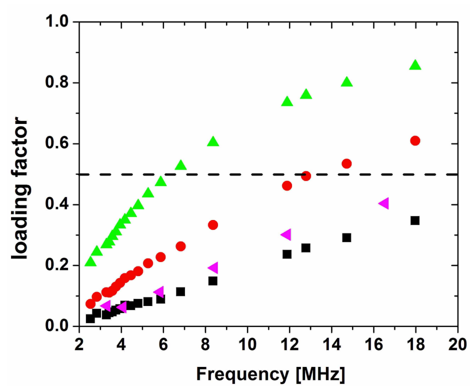

Figure 2 Loading factors for the unshielded 8.89-cm-diameter saddle coil when loaded with 50 mM (■), 150 mM (●), and 500 mM (▲) NaCl solutions, as well as with a human forearm (◄).

References

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Table 1 Summary of SNR transition frequencies, in MHz. The values given in bold lettering are in the typical range for physiological loading. The RF coils will be shielded inside the scanner.

NaCl conc. (mM) / diam. (cm)		Unshielded				Shielded		
		50	150	500	forearm	50	150	500
Saddle	8.89	26*	13	7	20	**>40***	**25***	14
	11.4	22	10	5	-	**>30***	**17**	8
	14.0	14	7	3	-	**24***	**15**	7
Solenoid	8.89	16	8	4	-	**26***	**14**	7
	11.4	11	4	3	-	**20***	**10**	5

* indicates an extrapolated vale