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A method to assess the loss of a dipole antenna for ultra-high-field MRI

G. Chen^{1,2,*}, C. M. Collins^{1,2}, D. K. Sodickson^{1,2}, and G. C. Wiggins¹

¹Center for Advanced Imaging Innovation and Research (CAI2R) and Bernard and Irene Schwartz Center for Biomedical Imaging, Department of Radiology, New York University School of Medicine New York, NY, USA

²The Sackler Institute of Graduate Biomedical Sciences, New York University School of Medicine, New York, NY, USA

Abstract

Purpose—To describe a new bench measurement based on quality (Q) factors to estimate the coil noise relative to the sample noise of dipole antennas at 7T.

Methods—Placing a dipole antenna close to a Highly Conductive Sample Surrogate (HCSS) greatly reduces radiation loss, and using Q_{HCSS} gives a more accurate estimate of coil resistance than Q_{unloaded} . Instead of using the ratio of unloaded and sample-loaded Q factors, the ratio of HCSS-loaded and sample-loaded Q factors should be used at Ultra-High Fields (UHF). A series of simulations were carried out to analyze the power budget of sample-loaded or HCSS-loaded dipole antennas. Two prototype dipole antennas were also constructed for bench measurements to validate the simulations.

Results—Simulations showed that radiation loss was suppressed when the dipole antenna was HCSS-loaded and, coil loss was largely the same as when the dipole was loaded by the sample. Bench measurements also showed good alignment with simulations.

Conclusion—Using the ratio $Q_{\text{HCSS}}/Q_{\text{loaded}}$ gives a good estimate of the coil loss for dipole antennas at 7T, and provides a convenient bench measurement to predict the body noise dominance of dipole antenna designs. The new approach also applies to conventional surface loop coils at UHF.

Keywords

Radio Frequency coil; dipole antenna; Q -factors; Ultra-High-Field (7T)

Introduction

In design and manufacture of RF coils for MRI, a benchtop method for evaluating the relative sources of RF power loss can be very valuable in comparing different designs and

*Corresponding author: Gang Chen, gang.chen@nyumc.org, Address: 660 1st Avenue, 4FL Room 420, New York, NY 10016, Phone: 212-263-3347.

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identifying inconsistencies in manufacture. In particular, gaining a sense of power lost in the coil relative to power lost in the sample has been of interest so that coil loss can be minimized. At current clinical field strengths, the standard workhorse RF coils are surface coil loops and birdcage volume coils. Both designs are resonators for which the quality (Q) factor is defined as¹

$$Q = 2\pi f_r \times \frac{\text{Stored energy}}{\text{Power loss}}. \quad [1]$$

In practice, the Q factor of an RF coil is more often defined as $Q = f_r / \Delta f$, where f_r is the resonant frequency, and Δf is the full width at half maximum of the coil resonance, which can be measured by S_{12} between a pair of inductive probes loosely coupled to an isolated surface coil². The contribution of coil noise to the detected signal is well understood, and is easily characterized by the Q -ratio, i.e. the ratio of the Q of the coil in free space divided by the Q when it is placed next to the body. The noise attributed to coil losses is given by³

$$\frac{\text{Coil noise}}{\text{Total noise}} = \frac{\sqrt{r_{\text{sample}} + r_{\text{coil}}} - \sqrt{r_{\text{sample}}}}{\sqrt{r_{\text{sample}} + r_{\text{coil}}}}, \quad [2]$$

where r_{coil} and r_{sample} are the equivalent resistances representing power loss in the sample and the coil, respectively. At low frequencies, because radiation loss is negligible, Equation [2] can also be written as³

$$\frac{\text{Coil noise}}{\text{Total noise}} = 1 - \sqrt{1 - (Q_{\text{loaded}} / Q_{\text{unloaded}})}. \quad [3]$$

The Q -Ratio is a widely used metric for predicting the performance of surface coils⁴.

Analysis of the Ultimate Intrinsic SNR (UISNR) demonstrates that, at ultra-high field (UHF), detectors with uniform loops of current are insufficient to capture all of the available SNR^{5,6}. As an alternative to loop coils, electric dipole antennas have been introduced⁷, which can provide additional SNR^{8,9}, and are used increasingly in UHF MRI^{10–17}. Dipole antennas differ from conventional surface coil loops in many ways. The most common dipole antenna consists of a single long conductor with a gap in the middle, usually bilaterally symmetrical, with power fed or signal detected across the gap¹⁸. Dipole antennas are extremely common in telecommunications, and the half-wavelength self-resonant dipole antenna is considered one of the most efficient designs for far-field applications¹⁹. However, for MRI, simulations show that shortening the dipole antenna can provide higher SNR for a particular depth of interest and higher SAR-normalized B_1^+ in transmission, compared to a half-wavelength self-resonant dipole^{13,20–22}. Many modifications of dipole dimensions or shapes have been proposed by different groups to improve SAR-normalized B_1^+ or SNR performance for particular regions of interest^{12,13,21,23–25}.

In free space, an electric dipole antenna is a very efficient radiator and radiation resistance is the dominant source of loss²⁶. By contrast, at low frequency, unloaded surface coil loops act as energy storage devices whose losses are dominated by resistive losses in the coil itself²⁷. However, past research has shown that when a dipole antenna is well loaded by the sample, radiation loss is significantly diminished^{22,26}. Because of the inconsistent contribution of radiation loss in unloaded and loaded cases, it is not possible to assess the body noise dominance of a dipole antenna by conventional Q ratio measurements.

For an electric dipole antenna in free space, several approaches have been proposed to measure the coil loss^{28–31}. Wheeler suggests that enclosing the dipole antenna within a conducting cage (a “Wheeler cap”) will eliminate the radiation loss without significantly changing resistive loss²⁸. The size of the cage should be big enough to keep the resonant frequency the same as in free space. The Q measurement of the dipole antenna in the “Wheeler cap” indicates the coil loss. However, when a dipole antenna is tuned in close proximity to a conductive sample, such as the human body, removing the sample will result in a change of the resonant frequency. Because Q factor is frequency-dependent, Q_{unloaded} cannot be compared to Q_{loaded} when they are measured at different frequencies.

As more dipole antenna designs have emerged, there is increasing need for a convenient and accurate bench measurement, similar to the $Q_{\text{unloaded}}/Q_{\text{loaded}}$ ratio at low fields, to predict the body noise dominance and evaluate coil resistance of dipole designs. Although bench measurements like Q ratio of single element doesn't directly connect to the SNR performance of the whole array, such metrics are still very helpful when comparing different antennas in the design process. For example, various coil designs consisting of either FR4 circuit board or copper wire were compared using Q ratios to determine the coil with best body noise dominance before the construction of 96-channel head array at 3T³². Moreover, the conventional Q ratio method also fails to accurately predict the performance of surface loop coils at UHF, because the radiation loss of unloaded loop coils also increases greatly as frequency increases. Even at 3T, radiation loss accounts for 38% of unloaded resistance for a 14cm square surface coil³³.

In this work, we propose a new approach using a measure of Q factor when the antenna is loaded by a Highly Conductive Sample Surrogate (HCSS), which was a piece of copper board in our experiments and simulations. We show that the ratio of $Q_{\text{HCSS}}/Q_{\text{loaded}}$, which is easy to measure on the bench, provides much more accurate estimation of coil noise than does the ratio of $Q_{\text{unloaded}}/Q_{\text{loaded}}$. Simulations and experiments were carried out in a variety of configurations to validate this new approach.

Theory

Placing dipole antennas close to a HCSS, the radiation loss is greatly reduced. The resonant frequency of the HCSS-loaded dipole can be made to match the frequency when it is sample-loaded by adjusting the distance between the dipole and the HCSS. If the coil resistance is kept the same between the sample-loaded case and HCSS-loaded case, and if the HCSS succeeds in reducing radiation loss to a negligible level, the noise attributed to coil loss can be defined by replacing Q_{unloaded} with Q_{HCSS} .

$$\frac{\text{Coil noise}}{\text{Total noise}} \approx 1 - \sqrt{1 - (Q_{\text{loaded}}/Q_{\text{HCSS}})} \quad [4]$$

An accurate and easy approach to quantify the coil loss and to predict body noise dominance at UHF can be generalized as follows: 1) Tune the antenna to the phantom and measure Q_{loaded} , which includes both coil loss and sample loss. 2) Remove the phantom and put the antenna above a conductive surface, the so-called HCSS. 3) Adjust the distance between the antenna and the HCSS to maintain the tuned frequency. 4) Measure Q_{HCSS} , which primarily reflects the coil loss in this configuration. 5) Compute the ratio $Q_{\text{HCSS}}/Q_{\text{loaded}}$.

Methods

Finite Element Method (FEM) simulations were performed with Microwave Studio (CST, Darmstadt, Germany) with Perfectly Matched Layer (PML) boundaries placed a quarter wavelength (based on the central frequency) from the model. To investigate the power losses of dipole antennas when loaded with a phantom having electrical properties similar to human tissue, a 250-mm-long dipole antenna was modeled. Two shortening inductors were placed 30mm away from the central feed point, symmetrically on each side, and the dipole was modeled as an 8 mm wide copper sheet ($\sigma = 5.85 \times 10^7$ S/m) on a 26-mm-wide and 0.8-mm thick FR4 board ($\epsilon_r = 4.3$, loss tangent = 0.02), as shown in Figure 1(a).

The dipole antenna was placed at various distances above a 292mm×190mm×508mm torso-shaped phantom with tissue-like properties ($\epsilon_r = 40.5$, $\sigma = 0.58$ S/m), and was tuned to 297.2 MHz in each case by changing the inductance of the shortening inductors. The lumped inductors were modeled as lossy elements using the quality factor, which was measured when the inductor was combined with a capacitor into a resonant LC circuit³⁴. To exclude the resistance due to the ceramic chip capacitor in the circuit, the quality factor of the inductor Q_{ind} is given as,

$$Q_{\text{ind}} = 1 / \left(\frac{1}{Q_{\text{circuit}}} - \frac{1}{Q_{\text{cap}}} \right) \quad [4]$$

where Q_{circuit} and Q_{cap} is the quality factor of the whole LC-circuit and the capacitor in the circuit, which was retrieved from a capacitor modeling software CAPCAD (<http://www.dliextra.net/capcad/Default.aspx>) provided by the capacitor manufacturer Dielectric Laboratories (Cazenovia, NY USA). The measured quality factor Q_{circuit} was 250 around 300 MHz, and the typical Q_{cap} of 1500 for a 6.8 pF capacitor at same frequency was used, resulting in $Q_{\text{ind}} = 300$, and the ohmic loss of the inductor was modeled as a series resistor with $R = 2\pi Lf/Q_{\text{ind}}$. A 50 Ω port was placed across a gap at the center of the dipole. Frequency-domain simulations were carried out from 250 MHz to 350 MHz. The simulations were repeated with distances between the dipole and the surface of the phantom of 10, 20, 30, 40, and 50 mm. The power losses due to the radiation, sample and the coil itself were quantified as equivalent series resistors seen at the feed point of the antenna. Because of $P = I^2 R$, the equivalent resistance of each loss mechanism (radiation, dissipation

in coil, dissipation in sample) is proportional to its associated power loss. The equivalent resistance of each loss mechanism was computed as its associated fraction of the total power loss multiplied by the coil input impedance. The individual equivalent resistance was plotted as a function of the distance to the sample.

For each simulated sample-loaded dipole, the same dipole was also simulated next to a HCSS or in free-space, in the absence of the torso phantom. For the HCSS-loaded dipole simulation, the dipole antenna was placed above a 360 mm×450 mm copper sheet ($\sigma = 5.85 \times 10^7$ S/m), as shown in Figure 1(b), and was tuned to 297.2 MHz by adjusting the distance to the board, without further changing the tuning inductors. The equivalent resistances due to radiation and to the coil for each simulation were computed and compared with those of the sample-loaded dipole. If the HCSS was made of superconductors, it would not bring in any loss when measuring the HCSS-loaded Q factor, but, as we modeled HCSS as copper boards in simulations, they still presented some minor resistances, which were also recorded for evaluation. For the unloaded dipole, the same set of simulations was repeated with the HCSS removed, and the equivalent resistances were computed for the frequency at which each dipole antenna resonated. These frequencies were now different for each antenna, since each had been tuned with a different effective load before the sample was removed.

The simulations were also repeated for a series of dipole antennas with length 100, 150, 200, 250, 300, 350 and 400 mm, all placed 20 mm above the torso phantom. In each simulation, the dipole antenna was tuned to 297.2 MHz by adjusting the shortening inductors. The ohmic loss of the inductors was modeled in the same way as described above, and was changed according to the inductance. The equivalent resistances were computed as a function of the length of the dipole antennas. Corresponding HCSS-loaded and unloaded dipoles were also simulated as described above. To compare the surface current distribution in the sample-loaded and the HCSS-loaded cases, the sample-loaded 250 mm long dipole simulation with 20 mm distance was repeated with a 1 A current source instead of an S-parameter source, along with the corresponding HCSS-loaded dipole simulation.

To validate the simulations, we constructed and tested two dipole antennas with different lengths, and compared simulations to bench measurements of the experimental antennas. The two experimental dipole antennas were measured 250 mm and 120 mm long respectively, and were both constructed with 8-mm-wide copper conductors on a 26-mm-wide and 0.8-mm-thick FR4 board using a circuit prototyping system (T-Tech, Inc. Norcross, Georgia USA) (Figure 2a). A 60 mm×14 mm×200 mm Teflon block was placed under each circuit board as a spacer. A torso-shaped phantom matching the simulations described earlier was used for bench measurements. When loaded with the phantom, the 250 mm long dipole antenna was tuned to 297.2 MHz by adjusting the shortening inductors, as shown in Figure 2b. The same dipole was then placed above a 360 mm×450 mm copper board, and tuned to 297.2 MHz by changing the distance to the shield without further adjustment of the inductors (Figure 2c). In both bench measurements, the dipole antenna was connected to a network analyzer (Agilent Technologies, Inc., Santa Clara, CA USA). The sample-loaded or HCSS-loaded Q factor was measured by S12 through a pair of well-decoupled probes (S12 = -70 dB at 297.2 MHz). For comparison, the resonant frequency,

and Q factor were also measured when the dipole was in free space. Simulations as described above were performed with similar configurations as for the bench measurements (Figure 2d, 2e). The Teflon block ($\epsilon_r = 2.1$, loss tangent = 0.0002) was also added into simulations to approximate the bench measurements. The Q factors were measured through S12 from a pair of simulated decoupled probes (S12 = -76 dB at 297.2 MHz) (Figure 2d, 2e). Similar bench measurements and simulations were then repeated for the 120 mm long dipole antenna.

Results

Figure 3 shows the equivalent resistance of each source of power loss for the inductor-shortened dipole antenna as a function of the dipole-to-sample distance. For each simulation of a HCSS-loaded dipole antenna, the distance to the HCSS is different from the distance of that dipole to the phantom, since the distance to the HCSS is adjusted specifically to tune each dipole to the frequency associated with a given dipole-to-sample distance. The values of radiation and coil resistance in the HCSS-loaded case are plotted on the same axis as for the sample-loaded case, with each dipole tuning being identified by its “distance to the phantom.” For the sample-loaded dipole placed 10 mm above the phantom, it must be placed 7 mm above the shield to be re-tuned to 297.2 MHz. The required distance to the HCSS increases to 38 mm for the dipole antenna placed 50 mm above the phantom. For the unloaded dipole simulations, the resonant frequencies move higher than 297.2 MHz, ranging from 351 MHz to 303 MHz for the dipole antennas originally positioned from 10 mm to 50 mm above the phantom.

Figure 3(a) shows the equivalent resistance due to the sample and radiation loss for the simulated shortened dipole antenna at different heights above the torso shaped phantom. The blue diamonds indicate the equivalent resistances due to the presence of the sample; the green diamonds, squares and triangles indicate the radiation loss when the dipole antenna is sample-loaded, HCSS-loaded and unloaded, respectively. The sample resistance decreases from 38.8 Ω to 13.3 Ω when the dipole is moved from 10 mm to 50 mm above the phantom, indicating the decrease of the loading. The radiation resistance provides dominant contribution to all unloaded dipole simulations, accounting for at least 89% of total power loss, and resulting in low Q of unloaded dipole antennas. The radiation resistance rapidly decreases to 1.3 Ω – 3.1 Ω when the dipole is loaded with the phantom, which is further diminished to 0.02 Ω – 0.6 Ω when the dipole is loaded with the HCSS.

Figure 3(b) shows the equivalent resistances due to the coil loss. The coil resistance of sample-loaded dipole antennas increases from 2.06 Ω to 3.05 Ω when the dipole antenna is moved from 10 mm to 50 mm above the phantom, which matches the value of corresponding HCSS-loaded dipole antenna with an average difference of 1%. The coil resistance of the simulated unloaded dipole antennas is slightly higher than that of the loaded dipole antenna, with 3% difference on average, largely due to the change in resonant frequency. The extra resistance due to the presence of the HCSS remains at a negligible level, providing 0.01 Ω at maximum, and should not alter the measurement of the HCSS-loaded Q factor. The coil loss itself is the sum of various contributions, including resistance from the copper conductors, FR4 circuit board, and resistance from the tuning inductors,

which are shown in Table 1 for the loaded-dipole antennas. The FR4 substrate and shortening inductors altogether provide most contribution to the total coil loss. The increased the coil loss at different distance is largely due to the need to increase inductance (and associated loss) to retune each dipole for increasing offsets from the sample. The copper conductors only present minor resistances in our simulations.

Figure 4 shows the equivalent resistances of the simulated dipole antenna with various lengths, all at 20mm from the phantom in the loaded case. As in Figure 3, the diamonds, squares and triangles indicate that the dipole is sample-loaded, HCSS-loaded or unloaded respectively. The sample resistance increases from 13.67 Ω to 45.55 Ω as the dipole length increases from 100 mm to 400 mm, and provides more contribution than coil resistance when the dipole length is 150 mm or more (Figure 4(a)). The sample-loaded radiation resistance varies from 0.5 Ω to 3.6 Ω , which is much smaller than the sample resistance in the same simulation. As is seen in Figure 3(a) for dipoles close to the sample, radiation resistance is reduced to a minimal level when the dipole is HCSS-loaded, providing 0.08 Ω on average, and the extra resistance due to the presence of the HCSS also remains at a negligible level, providing 0.02 Ω at maximum. For the unloaded dipole simulations, the resonant frequencies range from 305 MHz to 320 MHz, and the unloaded radiation resistance increases from 6.76 Ω to 59.45 Ω when the dipole length increases from 100 mm to 400 mm.

Coil resistance is significant when the dipole is very short (Figure 4(b)). The equivalent resistance is 20.89 Ω , and accounts for 70% of the total power loss for the 100 mm long dipole antenna. The excessive loss is mainly due to resistance from the FR4 circuit board (13.20 Ω equivalent resistance), and resistance from the tuning inductors (7.54 Ω equivalent resistance), as shown in Table 2. When the dipole length increases to 200 mm, the equivalent resistance in the FR4 circuit board and tuning inductors decreases to 2.14 Ω and 1.64 Ω , respectively. The coil resistance of HCSS-loaded dipole antennas matches that of corresponding sample-loaded dipoles. The values from unloaded dipole simulations are modestly higher than those of sample-loaded dipole antennas, once again because of the change in frequency. The maximum difference is about 13%, when the dipole antenna is 100 mm long.

Figure 5 shows the surface current maps of the dipole antenna when placed 20 mm above the phantom, and the same dipole when loaded with HCSS. A similar current distribution observed in the figures suggests that the dipole antenna is tuned to the same resonant mode and the effective resistance of the coil should be similar in both cases.

Table 3 compares Q factors between simulations and bench measurements. For the HCSS-loaded dipole antennas, the simulations match the bench measurements closely, and the measured HCSS-loaded Q factors are only 3% and 6% higher than the numbers predicted by simulations for the 250 mm and 120 mm dipole antenna respectively. The experiment-simulation differences of sample-loaded Q factors increase to 16% and 8% when the dipole antennas are loaded with the phantom, which may be attributed in part to the limited measurement accuracy of the dielectric properties of the phantom, and in part to imperfect modeling of precise experimental antenna structure, lumped elements, etc. Generally, the

simulations predict the bench measurements nicely. The simulated Q ratios were 15.6 and 4 for the 250 mm and 120 mm long dipole antennas respectively, suggesting that the sample noise is more dominant for the long dipole than the short one. When the constructed prototype dipole antennas are placed in free space, the resonant frequency shifts to 336.8 MHz and 319.4 MHz, and unloaded Q factors are 17 and 76 for the 250 mm and 120 mm long dipole respectively. Because the radiation loss is dominant when the dipole is in free space, the simulated $Q_{\text{unloaded}}/Q_{\text{loaded}}$ ratios of 1.4 and 2.1 do not estimate the coil loss correctly. Using the information available in this last simulation, we can show that the Q ratio in equation (4), equal to 0.031, is much closer to the quantity these equations are intended to approximate – i.e. the quantity in equation (2), which is equal to 0.028 – than it is to the quantity in equation (3), which is equal to 0.47.

Discussion

For a dipole antenna with a typical length (250 mm) for MRI, sample loss is dominant when it is placed in close proximity to the sample. However, coil loss still provides a notable contribution to the total power loss, which needs to be considered when designing a dipole antenna. Unchanged coil resistance from loaded to HCSS-loaded configurations in simulations provides confidence for experimental use of the HCSS-loaded to sample-loaded Q ratio. As radiation resistance is suppressed when the dipole is loaded with HCSS while coil resistance remains largely the same, the measure of HCSS-loaded Q factor gives direct access to the coil resistance. From Figure 3, the ratio of $r_{\text{HCSS}}/r_{\text{loaded}}$, which ranges from 0.05 to 0.19 (corresponding to a $Q_{\text{HCSS}}/Q_{\text{loaded}}$ ratio ranging from 20 to 5.26), provides a close approximation to the actual value of $r_{\text{coil}}/r_{\text{loaded}}$, which ranges from 0.05 to 0.16 (corresponding to a $Q_{\text{coil}}/Q_{\text{loaded}}$ ratio ranging from 20 to 6.25). As can be seen from Figure 3, that HCSS actually suppresses radiation loss more than sample loading, but effect is minor. In contrast, the ratio of $r_{\text{unloaded}}/r_{\text{loaded}}$ ranges from 0.76 to 1.30, and does not provide a close estimate of the relative coil loss.

These results suggest that the ratio of $Q_{\text{HCSS}}/Q_{\text{loaded}}$ gives accurate estimates of the degree of sample loss dominance when the dipole is heavily loaded by the sample. For lightly loaded dipole antennas, this proposed new ratio overestimates the coil loss, since radiation loss is no longer completely suppressed, and therefore the new ratio underestimates coil performance in lightly loaded cases. Nevertheless, the $Q_{\text{HCSS}}/Q_{\text{loaded}}$ ratio can still serve as a useful lower limit when estimating the coil performance even in lightly loaded cases.

As can be seen from Figure 4(b), HCSS-loaded coil losses remain the same as sample-loaded coil losses for a wide range of dipole antenna lengths. Because the dipole antennas are placed close to the sample, radiation resistance is suppressed to a minimal level and can be ignored when estimating the coil loss. The ratio of $r_{\text{HCSS}}/r_{\text{loaded}}$ in simulation ranges from 0.60 to 0.02 (corresponding to a $Q_{\text{HCSS}}/Q_{\text{loaded}}$ ratio ranging from 1.67 to 50) as the dipole length increases from 100 mm to 400 mm. This provides an accurate estimation to the value of $r_{\text{coil}}/r_{\text{loaded}}$ in simulation, which ranges from 0.60 to 0.02 (corresponding to a $Q_{\text{coil}}/Q_{\text{loaded}}$ ratio ranging from 1.67 to 50).

Even for dipole antennas in close proximity to the sample (20 mm), sample loss dominance is no longer maintained for the shortest simulated dipoles. This suggests that careful consideration of noise balance will be required when an array design includes extremely short dipole elements, as in the case of a many-element dipole array. Considerations of sensitivity would lead one to fit as many dipole elements as possible in a limited space; however, a balance must be struck between the number of total elements and the size of each element to maintain sample loss dominance for the array as a whole³². For design situations of this sort, the $Q_{\text{HCSS}}/Q_{\text{loaded}}$ ratio can be a particularly useful assessment tool.

Nevertheless, we don't intend to overstate the importance of the proposed metric in the optimization of dipole antennas. A designs and implementations of dipole elements and arrays near completion, their performance should be assessed comprehensively based on image-based measurements in phantoms or in vivo measurements of B_1^+ , SAR, SNR, etc., as appropriate to the intended application. Dipole antennas having higher proposed Q ratios don't necessarily present higher power efficiency or SNR performance in a given application than those with lower Q ratios. As an analogy at lower fields, loop coils of large size usually present higher unloaded/loaded Q ratio than those of smaller size, however the latter often produce higher SNR and are more power efficient than the former very near the coil.

Note that when the dipole antenna is 100 mm long, the equivalent resistance from the FR4 circuit board is 13.20 Ω , much larger than the resistance from the lossy tuning inductors (7.54 Ω), and the circuit board becomes the major source of coil noise. The resistance due to the FR4 board is quickly reduced to 2.14 Ω when the dipole length is extended to 200 mm. When the coil loss is of particular concern, some other suitable substrates with much lower loss like Rogers RO4003 (loss tangent = 0.0027), and Taconic RF-35 (loss tangent = 0.0011), should be considered. In future designs for short dipoles, using heavy wire or tubing to replace circuit board might also result in lower loss.

When a dipole antenna is loaded with HCSS, depending on how close the dipole is to the shield, the dipole can be tuned to different resonant modes. The goal for relevant noise comparisons is to tune the dipole to the same mode as when it is loaded by the sample. In our simulations, we therefore examined the surface current maps in both loaded and HCSS-loaded configurations, and confirmed that the current patterns were indeed similar, as shown in Figure 5. Normally it is difficult in practice to tune the HCSS-loaded dipole antennas to entirely distinct modes by adjusting the distance, but it is still worth spot-checking the current distribution to avoid inaccurate estimation of coil loss. The current distribution along a dipole antenna can be evaluated on the bench as the change in S_{12} between the uncoupled inductive probes as they are moved along the length of the dipole.

As was mentioned earlier, the radiation loss of unloaded loop coils also increases greatly as frequency increases. At sufficiently high frequency, therefore, the conventional ratio of $Q_{\text{unloaded}}/Q_{\text{loaded}}$ will likely underestimate the performance of loop coils, since the radiation loss represented in Q_{unloaded} will be greatly reduced when measuring the Q_{loaded} . Although only dipole antennas were analyzed in this work, the same procedure for measuring $Q_{\text{HCSS}}/Q_{\text{loaded}}$ may also be applied to loop coils at high frequencies.

Conclusion

We introduce a new metric to evaluate the performance of RF coils for MRI at UHF. Considering dipole antennas in particular, radiation loss becomes significant or even dominant for unloaded dipoles at high frequencies, while radiation loss for the most part remains minimal when dipole antennas are heavily loaded with a lossy dielectric sample. The ratio of $Q_{\text{unloaded}}/Q_{\text{loaded}}$ fails to estimate coil performance correctly because of the imbalance of radiation loss in the unloaded and sample-loaded measurements. As coil noise is one of few parameters that can be optimized independently during coil design, the proposed ratio of $Q_{\text{HCSS}}/Q_{\text{loaded}}$, which enables accurate and convenient measurement of relative coil noise, can be a useful design tool and a convenient metric for predicting coil performance or comparing different coil designs.

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(a)

(b)

Figure 1.

Simulation setup for a 250-mm-long inductor-shortened dipole antenna above a torso-shaped phantom with tissue-like properties (a), and above a flat copper plate (HCSS) (b). Dipole conductors and the HCSS are shown in gold, FR-4 boards are light gray, and the phantom is cyan. Red and blue connectors are feed ports and shortening inductors, respectively.

Figure 2.

a) Two experimental inductor-shortened dipole antennas (120 mm and 250 mm); The 250 mm dipole antenna on top of torso shaped phantom (b), and HCSS (c), and simulations of equivalent configurations (d,e).

Figure 3.

Equivalent resistances due to (a) sample and radiation loss, and (b) coil loss of the simulated 250-mm-long inductor-shortened dipole at various heights above the torso-shaped phantom, and corresponding resistances when HCSS-loaded or unloaded. Note that the coil loss is very close in sample-loaded and HCSS-loaded cases, while radiation loss was greatly reduced from unloaded to HCSS-loaded cases.

Figure 4.

Equivalent resistances due to (a) sample and radiation loss, and (b) coil loss of simulated inductor-shortened dipole antennas with various length, all placed 20 mm above the torso shaped phantom, and corresponding resistances when HCSS-loaded or unloaded. Note that the coil loss is very close in sample-loaded and HCSS-loaded cases, while radiation loss was greatly reduced from unloaded to HCSS-loaded cases.

Figure 5. Surface current distribution of the sample-loaded dipole when placed 20 mm above the torso-shaped phantom (top), and of the corresponding HCSS-loaded dipole antenna (bottom). Both were driven with 1 A current source.

Table 1

Break down of coil loss as seen from the feed point of dipole antennas at various heights.

Distance to the phantom (mm)	Substrate loss (Ω)	Inductor loss (Ω)	Conductor loss (Ω)	Total coil loss (Ω)
10	1.21	0.70	0.15	2.06
20	1.42	1.05	0.16	2.63
30	1.51	1.18	0.15	2.84
40	1.57	1.30	0.16	3.03
50	1.59	1.30	0.16	3.05

Table 2

Break down of coil loss as seen from the feed point of dipole antennas at various lengths.

Dipole length (mm)	Substrate loss (Ω)	Inductor loss (Ω)	Conductor loss (Ω)	Total coil loss (Ω)
100	13.20	7.54	0.15	20.89
150	4.05	2.93	0.13	7.11
200	2.14	1.64	0.14	3.92
250	1.42	1.05	0.16	2.63
300	1.02	0.60	0.17	1.79
350	0.86	0.32	0.19	1.37
400	0.71	0.08	0.22	1.01

Table 3

Q factors in experiments and equivalent simulations of dipole antennas at different lengths.

	Bench measurements			Simulations		
	Shortening inductors (nH)	Phantom-loaded Q	HCSS-loaded Q	Inductor's resistance (Ω)	Phantom-loaded Q	HCSS-loaded Q
250 mm dipole	47	14	193	0.29	12	188
120 mm dipole	180	39	152	1.12	36	143