Estimation of losses in strip and circular wire conductors of radiofrequency planar surface coil by using the finite element method

# Giulio Giovannetti1,2 | Nunzia Fontana3 | Agostino Monorchio4 | Michela Tosetti5,6 |

Gianluigi Tiberi5,6 

1Institute of Clinical Physiology, National Council of Research, Pisa, Italy

Abstract

An accurate coil design is a fundamental task to maximize signal-to-noise ratio in magnetic resonance applications. Coil design techniques take advantage of com- puter simulations especially when coil size is comparable to the radiofrequency (RF) wavelength. In particular, the estimation of the losses within the conductors as well as the radiative losses, both as a function of frequency, is instrumental to a complete coil performance characterization. However, the cross-sectional shape

of the conductors strongly affects the radiofrequency coil’s performance, espe-

cially at those frequencies where conductor losses represent the dominant power dissipation mechanism. Indeed, at radiofrequencies, the current flowing in the conductor is distributed in the proximity of its surface instead of being uniformly distributed over the cross section; it follows that an accurate conductor losses esti- mation can be performed only in the case of wire conductors by using analytical formulations. For strip conductors, although different theoretical approaches have been proposed in literature by taking into account the losses, no closed-form expression for conductors resistance is available which takes into account both classical and lateral skin effects. In this work, finite element method (FEM) simu- lations have been performed for estimating conductor and radiative losses in pla- nar surface loops made of strips and circular wires; the results have been compared against analytical formulations and literature data. Workbench tests per- formed on two circular coil prototypes, the first one constituted by a strip and the second one by circular wire conductors, tuned at 63.9 MHz and 127.8 MHz, showed a good agreement with FEM simulations.

KEYWO R DS

coil losses, numerical methods, radiofrequency coils, strip, wire

2Fondazione G. Monasterio CNR - Regione Toscana, Pisa, Italy

3Consorzio Nazionale Interuniversitario per le Telecomunicazioni, Pisa, Italy

4Department of Information Engineering, University of Pisa, Pisa, Italy

5Laboratory of Medical Physics and Biotechnologies for Magnetic Resonance, IRCCS Stella Maris Foundation, Pisa, Italy

6Imago7 Foundation, Pisa, Italy

1. | INTRODUCTION

Signal-to-noise ratio (SNR) in magnetic resonance (MR) experiments depends on the coil resistance and the biologi- cal sample induced resistance.1 In particular, at lower radiofrequencies the SNR is mainly determined by the coil

losses2 and SNR can be improved by using high-quality factor (Q) coils, whereas at higher RF frequencies, the sam- ple losses are dominant3 as it generally happens for 1.5 T and 3 T 1H coils design.

Coil resistance strongly depends on conductor geometry. In particular, conductors commonly employed for coils

manufacturing can be categorized into two groups depend- ing on their cross-sectional shape: circular rod shapes (also referred to as *circular wires*) and rectangular shapes (*strips*). Another factor influencing the RF energy loss is radiation resistance, which takes into account an effect known as the *antenna effect*,4 that potentially limits the efficiency of high-field MR experiments.

For optimizing RF coil performance, a design process

section, but its density *J*z decreases exponentially with the distance *y* from the boundary surface, as follows:

*Jz*ð*y*Þ¼ *Jz*ð0Þ*e*—ð1þ*j*Þ*y*=d (1)

where d is the distance at which the current density vector decreases to 1/*e* of its value *J*z(0) at the boundary surface. This distance is the *penetration depth*7:

based on an accurate simulation is highly desirable, since numerical simulations are routinely widely employed in

d ¼ rﬃﬃﬃﬃqﬃﬃﬃﬃﬃﬃ

(2)

the design process. As a matter of fact, current design techniques take advantage of computer simulations for preliminary testing different coil geometries. In particular, numerical methods allow the simulation of coil behavior in the presence of realistic loads and the investigation of coil efficiency at high magnetic fields. In a previous work,5 authors proposed the use of a numerical approach based on finite element method (FEM) for separately esti- mating the conductor and radiative losses in circular wire loop RF coils for MR applications. Such loss estimations have been compared to analytical calculations for differ- ent tuning frequencies (5.7-128 MHz); experimental results performed on a circular wire coil prototype revealed a better agreement with FEM simulations than analytical calculations.

p*f* l0

This paper, which completes the results of,5 starts with a brief review of the conductor resistance theoretical calculation by taking into account the current distribution inside the conductor cross section. Afterwards, FEM sim- ulations were performed for coil losses estimation in strip and circular wire loops from 5.7 MHz to 128 MHz. Sim- ulation results have been initially compared against analytical formulations and literature data and succes- sively validated through workbench tests performed on two circular coil prototypes with identical dimensions, one constituted by strips and the other one by circular wires.

1. | METHODS

# | Classical and lateral skin effect

The conductor resistance for unit length can be estimated by using the classic formula *R =* q*/S* by taking into account the conducting pathway geometry, where q is the conductor resistivity (1.68 10—8 m O for copper) and *S* is the cross-sectional area.6 In particular, when a direct cur- rent (DC) flows through a conductor, the resistance per unit length (*R*DC) can be calculated using *S =* p*a2* for a circular wire with radius *a* and *S = wt* for a strip with width *w* and thickness *t*.

· ·

An alternating current (AC) flowing in a conductor along the z-axis is not uniformly distributed across its

where *f* is the coil tuning frequency and l0 is the free space permeability (4p10—7 Henry per meter). By using Equa- tion 2, the current can be considered confined in a region near the surface whose thickness is given by d. The conduc- tor volume in which flows the AC current is then limited by the penetration depth value producing the *classical skin effect*.8

For a circular wire conductor of radius *a*, the conductor losses for unit length can be calculated as:

*R*clas wireð*f* Þ¼ q : (3)

— 2p*a*d

For strip conductors of width *w*, if the strip thickness *t* is greater than at least twice the penetration depth, the con- ductor resistance can be evaluated as:

*R*clas stripð*f* q (4)

— Þ¼ 2*w*d

otherwise, the current flows in the total conductor cross- sectional area and the resistance value can be calculated as:

*R*clas stripð*f* q : (5)

Þ¼— *tw*

In real cases, the tendency of the current density to con- centrate towards the surface is stronger at the points where the curvature is greatest. Therefore, the current concentra- tion is expected to be enhanced at conductor edges. This phenomenon is referred to as *lateral skin effect*,9 implying that the current distribution in a strip is less uniform than in a circular wire.

In open literature, different theoretical approaches have been proposed for taking into account the skin effect losses in strip conductors. A good summary of the different meth- ods for estimating conductor losses in RF coils for NMR applications is included in a recent review.10 However, no closed-form expression for strip conductors’ resistance, tak-

ing into account both classical and lateral skin effects, is

available.

In Ref. [11], the authors proposed a theoretical-experi- mental hybrid method, which can distinguish and quantify the different skin effect contributions to the strip conductor resistance. Two 7.5 cm radius circular loops were built with different conductor geometry: the first loop was con- stituted by a 0.45 cm width and 40 lm thick strip, and the

second one employed a 0.1 cm radius circular wire conduc- tors. Such cross-sectional sizes for the two conductors guaranteed the same coil *L* inductance value, according to the relationship allowing the evaluation of the equivalent width *w* to a circular wire of radius *a*:

*w* ¼ 4:482 · *a*: (6)

The strip coil resistance was calculated as the sum of the lateral skin effect and the classical skin effect resistances:

*R*coil—strip ¼ *R*clas—strip þ *R*lat—strip (7)

where *R*clas-strip can be evaluated using Equations (4) or (5), whereas the circular wire coil resistance is equal to the classical skin effect resistance due to the absence of con- ductor edges in such conductor:

*R*coil—wire ¼ *R*clas—wire (8)

*R*clas-wire can be theoretically calculated with Equation 3. From quality factor measurements, by remembering that

*Q* 2p*fL*=*R*tot,12 the total loss resistances *R*tot for both coils were estimated as:

¼

The test results of both coils, tuned at 5.7 MHz, showed that the circular wire coil provided better performance, with a 59% Q increase with respect to the strip coil. Moreover, the two contributions of the different skin effects for the strip coil assumed very similar values; the classical skin effect and the lateral skin effect resistance contributions being equal to 51% and 49% of the strip coil resistance, respectively.11

The same two circular coils have been employed in a more recent work13 for evaluating the coil resistance at dif- ferent tuning frequencies used in clinical scanner (21- 128 MHz, corresponding to 0.5-3 T static field). Results on the frequency dependence of the lateral skin effect resis- tance showed a proportionality very close to the square of the frequency, demonstrating that in all frequency range routinely used in MR clinical scanner, the lateral skin effect is the dominant mechanism and it is not neglectable especially at high MR frequencies.

# | Coil losses estimation with HFSS FEM

To evaluate FEM capability in coil losses prediction and

*R*tot—strip

2p*fL*

¼ *Q*strip

(9)

to compare the results given in5 obtained by using CST MW Suite (CST-Computer Simulation Technology AG,

*R*tot

2p*fL*

—wire ¼ *Q*wire

(10)

Darmstadt, Germany), a 7.5 cm radius circular coil made with a 0.1 cm radius copper circular wire, identical to

The total loss resistances, for unloaded coil condition, comprise losses within the coil conductors (*R*coil) as well as radiative, tuning capacitors and soldering losses (*R*extra). By neglecting these latter, the radiative resistance *R*irr of a small loop can be calculated as4:

2 2p*r* 4

the one employed in the cited study, was simulated with HFSS (Ansys, Canonsburg, PA, USA). Successively, a second 7.5 cm radius circular coil constituted by a cop- per strip (4.482 mm width 9 0.04 mm thickness), whose size satisfied Equation 6 for guaranteeing the same inductance of the circular wire coil (*L* = 0.44 lH11,13),

was simulated with the same tool. Both coils were simu-

*R*irr ¼ 20p k

(11)

lated as purely inductive, without tuning capacitors. For both coils, the impedances were calculated at different

which is valid when a loop can be classified as small

(*2*p*r* k)*.*

If we consider that the coil, constituted by circular wire conductors, is affected by classical skin effect only, the term *R*extra can be calculated as:

*R*extra ¼ *R*tot—wire — *R*clas—wire (12)

and this term can be considered the same for both coils, being identical in size and tuned with the same capaci- tors.

The strip coil resistance can then be evaluated as:

*R*coil—strip ¼ *R*tot—strip — *R*extra (13)

By using Equation 7, the lateral skin effect contribution can be evaluated as:

*R*lat—strip ¼ *R*coil—strip — *R*clas—trip (14)

frequencies (*f* = 5.7, 21.3, 42.6, 63.9, 85.2, and

127.8 MHz). Lumped port (S-port) has been used as a feeding source, as shown in Figure 1. Lumped port allows calculating the S parameters of the electromag- netic model based on a defined reference impedance (50 O) and also allows calculation of the corresponding input impedance. Because a single source was used, the solver only calculated the S11 parameter and the corresponding Z11 input impedance.

The evaluated real part of the impedance corresponded to *R*tot, constituted by coil resistance (*R*coil) and radiative losses (*R*irr), which can be calculated separately with HFSS. As in the previously cited work,5 the simulations were performed using an adaptive tetrahedral mesh with an automatic con- vergence detection. The mesh adaptation procedure provided a minimum edge length of 9.8 lm and 8 lm for the circular wire and the strip coil, respectively.

# 2.3 | Workbench measurements

Two purely inductive 7.5 cm radius circular loops were built for workbench measurements. The first coil was developed using a circular rod with a radius of 0.1 cm (Figure 2a), whereas the second one employed a copper foil 0.45 cm wide and 40 lm thick (Figure 2b). Both coils were identical to the ones employed in the literature.11,13

*R*tot of the two coils was experimentally measured at 63.9 and 127.8 MHz with a workbench instrumentation consist- ing of an E5071C ENA Series Network Analyzer (Agilent Technologies, Santa Clara, CA, USA) and by connecting the loops to the analyzer after performing a proper calibration. The analyzer was set in averaging mode (64 averages) for improving measurements sensitivity, and its resolution was 10 mO.

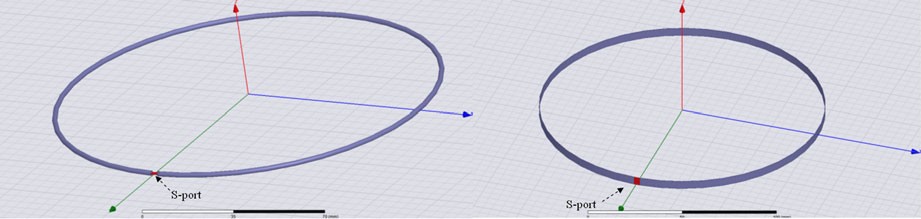
# | RESULTS AND DISCUSSIONS

Tables 1 and 2 show, respectively, circular wire and strip coil simulation results obtained by HFSS FEM at different frequencies and a comparison against previous results avail- able in the literature for the circular wire5 and strip10,11,13 coil.

HFSS-FEM simulations for the circular wire coil are in good agreement with results obtained with FEM in5: for example, at 63.9 MHz, the deviation in *R*coil estimation was 1.1%, whereas for *R*irr and *R*tot the deviations are 5.9%

FIGURE 1 7.5 cm radius circular loops: (a) circular wire coil, (b) strip coil.

The S-ports are indicated by arrows



**(A)**

**(B)**

and 0.4%, respectively. A maximum difference value between the two simulators of 5.2% was measured at

127.8 MHz for *R*tot estimation.

HFSS simulations performed with the strip coil under- lined the higher losses of the coil constituted by such con- ductor with respect to the circular wire one; this difference is due to the current distribution inside the strip, as theoretically anticipated. In particular, *R*coil for strip coil was greater than 46% at 63.9 MHz and 56% at 127.8 MHz with respect to the circular wire coil. Conversely, *R*irr for strip coil was approxi-

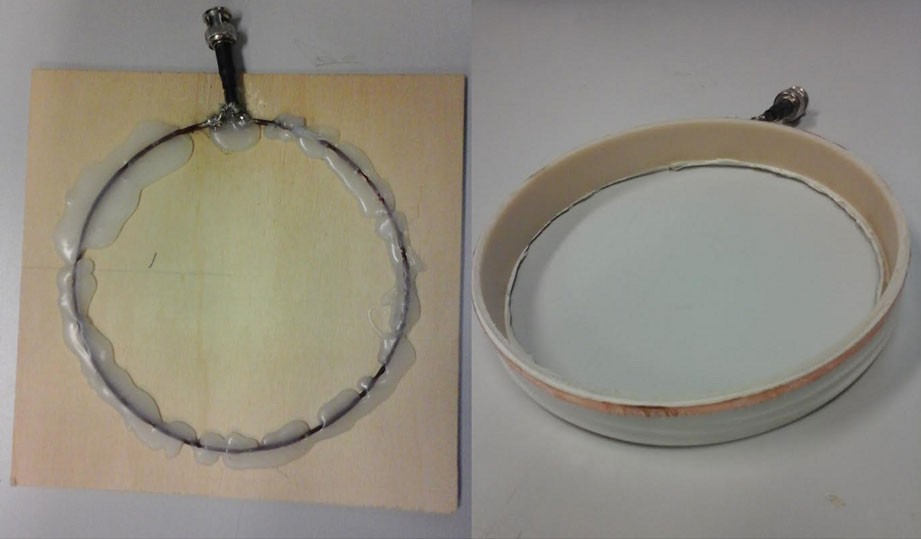
mately the same of the circular wire coil. If we compare the results to the “hybrid” approach,10,11,13 we can conclude that HFSS predicted the losses within the strip conductors with a relative difference below 12.5% up to 85.2 MHz, whereas this difference increased to 23% at 127.8 MHz. However, it

is important to underline that strip conductor resistances esti- mated in Refs [11,13] have been obtained with the approxi- mation that the term *R*extra (see Equation 12) was the same for both strip and circular wire coils, by neglecting differ- ences in capacitor and soldering losses.

Regarding the radiative losses, the relative difference between analytical formulation and HFSS FEM was

<0.01% at 5.7 MHz for both strip and circular wire coils, and it increased to 78% and 75% at 127.8 MHz for the strip and circular wire coils, respectively. As described in Ref. [5], these enhancements in relative differences with frequency depending on the fact that the analytical formu- lation of Equation 11 holds true for *2*p*r<*k*/10* and, thus, only within 63.9 MHz for the simulated geometry.

FIGURE 2 Circular loop prototypes:



**(A)**

**(B)**

(a) circular wire; (b) strip

TABLE 1 Wire circular coil losses estimation with HFSS for different frequencies compared with previous results available in the literature.5 Experimental results are also reported in the last column

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| f (MHz) | *R*tot-wire (mO) | *R*coil-wire (mO) | *R*irr-wire (mO) | *R*tot-wire (mO)5 | *R*coil-wire (mO)5 | *R*irr-wire (mO)5 | *R*tot-wire-meas (mO) |
| 5.7 | 47.1415 | 47.1402 | 0.0013 | 47.4 | 47.3967 | 0.0013 |  |
| 21.3 | 92.7440 | 92.4932 | 0.2508 | 92.5 | 92.2487 | 0.2513 |  |
| 42.6 | 139.0481 | 134.8499 | 4.1982 | 139.8 | 135.6479 | 4.1521 |  |
| 63.9 | 196.3033 | 173.3885 | 22.9148 | 197 | 175.3694 | 21.6306 | 260 |
| 85.2 | 294.2984 | 213.7000 | 80.5984 | 304 | 218.9712 | 85.0288 |  |
| 127.8 | 871.8268 | 310.7969 | 561.0299 | 919.8 | 345.1090 | 574.69 | 950 |

TABLE 2 Strip circular coil losses estimation with HFSS for different frequencies compared with previous results available in the literature.10,11,13 Experimental results are also reported in the last column

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| f *R*tot-strip *R*coil-strip *R*irr -strip *R*tot-strip *R*coil-strip *R*irr -strip *R*tot-strip-meas  (MHz) (mO) (mO) (mO) (mO)10,11,13 (mO)10,11,13 (mO)10,11,13 (mO) | | | | | | | |
| 5.7 | 96.5491 | 96.5478 | 0.0013 | 86.0013 | 86 | 0.0013 |  |
| 21.3 | 125.4227 | 125.1710 | 0.2517 | 143.247 | 143 | 0.247 |  |
| 42.6 | 191.5050 | 187.2880 | 4.2170 | 188.958 | 185 | 3.958 |  |
| 63.9 | 276.6058 | 253.5560 | 23.0498 | 287.036 | 267 | 20.036 | 300 |
| 85.2 | 402.3586 | 321.0986 | 81.2600 | 428.324 | 365 | 63.324 |  |
| 127.8 | 1055.5281 | 485.4261 | 570.1020 | 950.577 | 630 | 320.577 | 1020 |

The experimental measurements, performed at two char- acteristic frequencies (1H MR imaging at 1.5T and 3T) for both coils, provided values of *R*tot equal to 260 mO at

63.9 MHz and 950 mO at 127.8 MHz for the circular wire coil, whereas for the strip coil the measurements provided 300 mO at 63.9 MHz and 1020 mO at 127.8 MHz. These experimental values included further resistive losses account- able to the solder joints between the coil and the cable for the connection with the analyzer (Rsol = 25 mO and 60 mO estimated at 64 MHz and 128 MHz,14 respectively)

The experimental values confirmed the higher losses of the coil constituted by strip conductor. In particular, *R*tot for strip coil was greater than 15% at 63.9 MHz and 7% at

127.8 MHz with respect to the circular wire coil. More- over, experimental results were in good agreement with HFSS simulations at both frequencies for strip and circular wire loops.

Although it is evidenced in the literature10 that strip conductors have larger losses than circular wire, generally, conductor loss models only consider the classical skin effect and neglect the discontinuities appearing at the con- ductor boundaries which determine the lateral skin effect.15 To the best of our knowledge, only some preliminary stud- ies were performed with numerical simulations, like the one employing finite-difference time-domain (FDTD) method, which showed that the conductor geometry, the computational mesh, and the software tool employed for the coil simulation strongly influence the results.16

The proposed approach and the relative literature cited for comparison purpose neglected sample losses, which can be dominant when the sample dimensions are not small compared to the wavelength, ie, at high-field MR imaging. Therefore, the presented simulation results are mainly use- ful when an optimal coil design is a necessary constraint for minimizing the coil noise with respect to the sample noise. Moreover, in a real situation, capacitor and soldering losses can reduce coil overall performance. The use of high-quality capacitors is absolutely necessary to obtain high-performance coils, especially for lower frequency designs. Their losses can be estimated from capacitor data- sheets by using the dependence of capacitor equivalent series resistance (ESR) with the frequency according to the f1/2 law.17 As an example, capacitor losses were 12 mO and 30 mO for tuning the simulated coils at 21 and 64 MHz, respectively.18 Regarding resistive losses attribu- table to the solder joints connecting the coil components, they can be extrapolated from literature data, resulting 10 mO and 25 at 21 and 64 MHz, respectively.14,19

Although the sum of capacitor and soldering losses might become comparable to the reported differences between loss resistance within the strip and circular wire conductors, the use of circular wire increases coil perfor- mance, providing a gain in Q factor on the order of 29% at

21 MHz, which corresponds to an SNR gain of 13%, since SNRap*Q*.2 The same calculation performed at 64 MHz

ﬃﬃﬃﬃ

provided 32% and 15% for Q factor and SNR gain,

respectively. Moreover, the test results of the two built coils at 5.7 MHz11 showed that the circular wire coil pro- vided better performance which can be quantified in an SNR gain of 26% with respect to the strip coil.

Finally, it is important to highlight that a limitation of the present study is that it is specialized to planar surface coils only, where all proximity effects among conductors, which can significantly influence inner current distribution, are neglected.

Moreover, when we move to clinical applications, loop coils have larger diameters, increased sample volume and resistance, and coil noise should be compared to the sam- ple noise. Changing from strip to wire loops, makes sense only if the Q increase in imaging conditions, ie, in the presence of the sample.

Future work is in progress on the issue regarding the evaluation of the region in the frequency-loop diameter plane where the use of a wire gives a noticeable advantage respect to the strip.

# 4 | CONCLUSIONS

This paper proposed the application of numerical simula- tions for estimating conductor losses in RF coils for MR applications, whose design is a fundamental task for maxi- mizing the SNR.

A FEM-based numerical approach was employed for separately estimating the conductor and radiative losses in two planar surface loops characterized by different cross- sectional shapes (circular wire and flat strip).

Simulation results confirmed the lower losses of the coil constituted by a circular wire conductor, essentially due to the inner current distribution with respect to the strip one, as theoretically predicted. Loss estimations were initially compared against analytical calculations and literature data at different tuning frequencies. Conductor losses calculated with FEM showed a good agreement with literature data, whereas radiative losses were in agreement with small loop radiation equation at lower frequencies; indeed, as the fre- quency increases, the small loop approximation does not hold, and such equation led to an underestimation of radia- tive losses.

Experimental validation performed on two planar sur- face coil prototypes confirmed the accuracy of FEM in coil losses estimation for both conductor geometries and explained the difference in coils built using circular wire and flat strip conductors.

We believe that the present paper may be useful for researchers working in the field of MR coil design and development, since the causes of the circular wire and strip differences are deeply investigated and backed up with measurements.

LIST OF DEFINITIONS

*R*clas-wire, classical skin effect resistance contribution for circular wire conductors; *R*clas-strip, classical skin effect resistance contribution for strip conductors; *R*lat-strip, lateral skin effect resistance contribution for strip conductors; *R*coil, loss resistance within the coil conductors for a general coil; *R*coil-wire, loss resistance within the circular wire conductors, equal to *R*clas-wire; *R*coil-strip, loss resistance within the strip conductors, including *R*clas-strip and *R*lat-strip; *R*extra, radiative, tuning capacitors and soldering loss resistance, equal to *R*irr when neglecting these lasts; *R*tot, total loss resistance for a general coil, including *R*coil and *R*extra; *R*tot-wire, total loss resistance for the circular wire coil, including *R*coil-wire and *R*extra; *R*tot-strip, total loss resistance for the strip coil, including *R*coil-strip and *R*extra; *R*irr, radiative resistance for a general coil; *R*irr-wire, radiative resistance for the circular wire coil; *R*irr-strip, radiative resistance for the strip coil; *R*tot-wire-meas, experimentally measured total loss resistance for the circular wire coil; *R*tot-strip-meas, experimentally measured total loss resistance for the strip coil.

ORCID

*Giulio Giovannetti* <http://orcid.org/0000-0002-4317-4161>



*Gianluigi Tiberi* <http://orcid.org/0000-0001-8787-1295>

REFERENCES

1. Hoult DI, Lauterbur PC. The sensitivity of the zeugmatographic experiment involving human samples. *J Magn Reson*. 1979;34:415-433.
2. Claasen-Vujcic T, Borsboom HM, Gaykema HJG, Mehlkopf T. Transverse low-field RF coils in MRI. *Magn Reson Med*. 1996;36:111-116.
3. Hoult DI, Richards RE. The signal-to-noise ratio of the nuclear magnetic resonance experiment. *J Magn Reson*. 1976;24:71-85.
4. Mispelter J, Lupu M, Briguet A. *NMR Probeheads for Biophysi- cal and Biomedical Experiments*. London: Imperial College Press; 2015.
5. Giovannetti G, Tiberi GL, Tosetti M. Finite element method- based approach for radiofrequency magnetic resonance coil losses estimation. *Conc Magn Reson Part B*. 2016;46B:186-190.
6. Gerling D. Approximate analytical calculation of the skin effect in rectangular wires. *Int Conf Electr Mach Syst ICEMS*. 2009; 1-6.
7. Chen C, Hoult DJ. *Biomedical Magnetic Resonance Technology*. Bristol: IOP; 1989.
8. Matick RE. *Transmission Lines for Digital and Communication Networks*. New York, NY: McGraw-Hill; 1969.
9. Belevitch V. The lateral skin effect in a flat conductor. *Philips Tech Rev*. 1971;32:221-231.
10. Giovannetti G, Tiberi GL. Skin effect estimation in radiofre- quency coils for nuclear magnetic resonance applications. *Appl Magn Reson*. 2016;47:601-612.
11. Giovannetti G, Hartwig V, Landini L, Santarelli MF. Low-field MR coils: comparison between strip and wire conductors. *Appl Magn Reson*. 2010;39:391-399.
12. Jin J. *Electromagnetic Analysis and Design in Magnetic Reso- nance Imaging*. Boca Raton, FL: CRC Press; 1999.
13. Giovannetti G, Hartwig V, Landini L, Santarelli MF. Classical and lateral skin effect contributions estimation in strip MR coils. *Conc Magn Reson Part B*. 2012;41B:57-61.
14. Kumar A, Edelstein WA, Bottomley PA. Noise figure limits for circular loop MR coils. *Magn Reson Med*. 2009;61:1201-1209.
15. Kuehne A, Goluch S, Waxmann P, et al. Power balance and loss mechanism analysis in RF transmit coil arrays. *Magn Reson Med*. 2015;74:1165-1176.
16. Kuehne A, Waiczies H, Moser E, Laistler E, Skin effect estima- tion accuracy in FDTD coil simulations. In Proceedings of the ISMRM, Milan, Italy p. 1363 (2014).
17. Yeung D, Hutchison JMS, Lurie DJ. An efficient birdcage res- onator at 2.5 MHz using a novel multilayer self-capacitance con- struction technique. *MAGMA*. 1995;3:163-168.
18. American Technical Ceramics – Quick reference product selec- tion guide. [www.atceramics.com](http://www.atceramics.com/). Accessed July 20, 2017.
19. Giovannetti G. Comparison between circular and square loops for low-frequency magnetic resonance applications: theoretical

performance estimation. *Conc Magn Reson Part B*. 2016;46:146- 155.