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Advanced Design of Birdcage RF Coil for Various Absorption Regions at 3T MRI System

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Abstract: ***Purpose:*** The purpose of this study was to design and build an optimized birdcage resonator configuration with a low pass filter, which would facilitate the acquisition of high-resolution 3D-images of small animals at 3T MRI system. ***Methods and Materials:*** The birdcage resonator with 12-element structures was built, in order to ensure B1 homogeneity over the image volume and maximum filling factor, and hence to maximize the signal to noise ratio (SNR) and resolution of the 3-dimensional images. The diameter and length of each element of a birdcage resonator were as follows: (1) diameter 13 cm, length 22 cm, (2) diameter 15 cm, length 22 cm, (3) diameter 17 cm, length 25 cm. Spin echo pulse sequence and fast spin echo pulse sequence were employed in obtaining MR images. The quality of the manufactured birdcage resonators was evaluated on the basis of the return loss following matching and tuning process. ***Results:*** The experimental MR images of phantoms by the various manufactured birdcage resonators were obtained to compare the SNR in accordance with the size of objects. The size of an object to that of coil was identified by parameters that were estimated from the images of a phantom. First, the diameter of the birdcage resonator was 15cm, and the ratio of the tangerine to the birdcage resonator accounted for approximately 27%. The Q factor was 53.2 and the SNR was 150.7. Second, at the same birdcage resonator, the ratio of the orange was approximately 53%. The SNR and the Q parameter was 212.8 and 91.2, respectively. ***Conclusion:*** The present study demonstrated that if birdcage resonators have the same forms, SNR could be different depending on the size of an object, especially when the size of an object to that of coil is approximately 40~80%, the former is bigger than the latter. Therefore, when the size of an object to be observed is smaller than that of coil, the coil should be manufactured in accordance with the size of an object in order to obtain much more excellent images.

Keywords : Birdcage Resonator, 3 T, Signal-to-Noise Ratio (SNR)

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INTRODUCTION

The introduction of very high-field whole-body magnetic resonance imaging (MRI) systems, 3T and above, is a logical step to achieve high-resolution images *in vivo*. Very high-field MRI systems (3T and above) provide the increased signal-to-noise ratio (SNR) required to produce small field-of-view images with improved spatial resolution. The higher SNR and improved tissue contrast obtained from this high-field system, coupled with the optimized coil size, improves visualization of the structural detail in a small animal, which is not seen well at conventional field strengths. However, in certain cases there are technical challenges that must be addressed in order to obtain the theoretical increase in SNR. Radio frequency (RF) coils are a critical link to exploit this higher SNR.[1-3]

Proper design of a RF coil plays a very important role in obtaining high-resolution small animal magnetic resonance imaging. The RF field homogeneity and the coil filling factor directly affect the SNR and therefore limit the resolution. High quality (Q) factor is also important to maximize SNR and resolution. The higher Q, the higher SNR could be obtained.[4-6]

RF coil, one of the main elements of MRI, is a kind of antenna playing a role in causing the phenomenon of resonance directly and receiving a signal. RF coil utilizing LC [inductance (L), capacitance (C)] resonance phenomenon has been developed in various forms in accordance with its purpose and function so far. Resonance frequency is controlled by capacitors because it is very difficult to control inductor. In other words, resonance signals could be transmitted and received,[7, 8] only if the capacitor suitable for obtaining a desired frequency is used to coil.

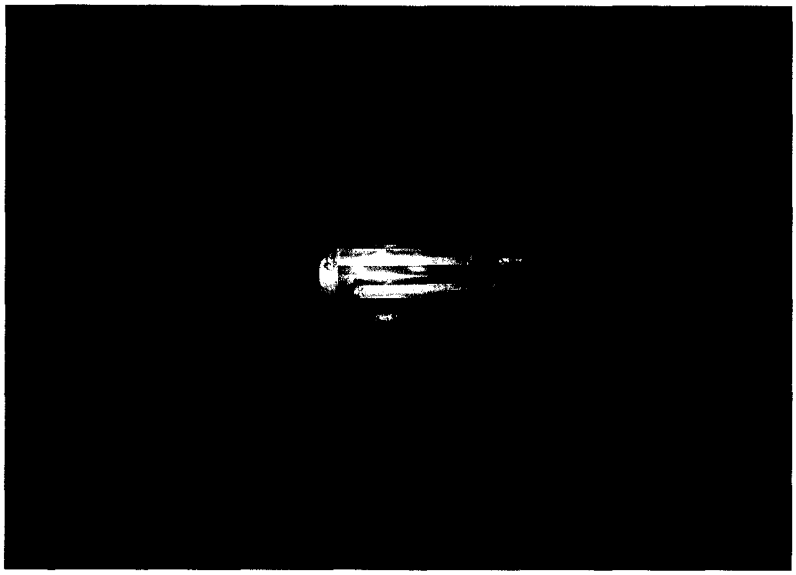
Birdcage RF coil is generally used as a RF coil that is used especially for the human head. Birdcage RF coils are preferred for use in MRI because of their excellent RF magnetic (B1) field homogeneity. Building these types of coils for applications at higher static magnetic field strengths (3T) is more difficult than for larger coils operating at lower frequencies (1~2T). This difficulty arises because the capacitance (as well as the inductance) of the circuit must be made quite small to ensure that the coil will resonate at the required frequency.[9] At these high frequencies, the impedance of all elements should be equivalent in order to provide the proper sinusoidal current distribution necessary to produce excellent B1 field homogeneity. In order to make a coil causing resonance at the desired frequency such as 127.73 MHz at 3T, L, and C should be considered main elements whose parameters are suitable for the frequency. Also, the final product of a RF coil can be manufactured with an L-C resonance circuit.

High RF field has been preferred among all MRI studies in improving SNR and spatial resolution. However, as increasingly magnetic field, susceptibility has become a prominent problem. With these various elements, the factor according to the size of an object in the RF coil has an important effect on resolution. If an object is much bigger or smaller in the RF coil, high-resolution images cannot be obtained due to inhomogeneity of the magnetic field, lower SNR and Q factor. Therefore, it is important to have the RF coil, keep the homogeneity and high Q factor in accordance with the object and operating at a given frequency.

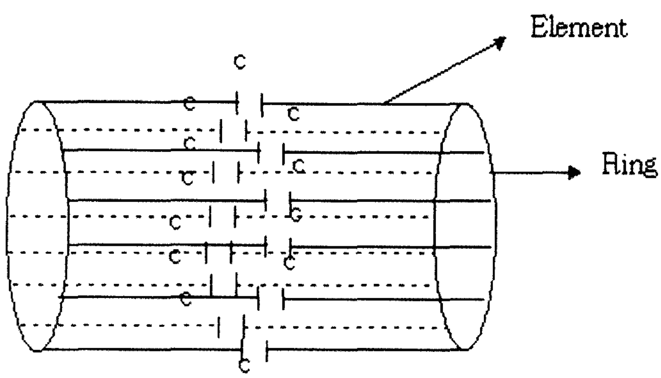
In this study, the low-pass filter form was applied to produce various sized birdcage resonators in accordance with the objects, and through analyzing the lumped element circuit, we tried to develop a RF coil with which high resolution images could be obtained by calculating the values of capacitor and inductor.

METHODS AND MATERIAL

All MRI experiments were performed on a Magnum 3T MRI scanner (Medinus Co, Seoul, Korea). Ahead of the substantial development, a birdcage resonator was made following the primary analysis by simulation (MRIEM). We designed and constructed a low-pass, 12-element transmit–receive birdcage coil for small animal imaging. We chose to use a 12-element configuration instead of 16 elements for the birdcage design to obtain higher Q, hence a better SNR (Fig. 1).



(a)



(b)

Fig. 1. (a) Manufactured birdcage resonator, (b) Illustration of birdcage resonator.

In order to transmit and receive RF signal, a copper tape was fixed on a cylindrical acryl and matched with each channel by using variable capacitors. A network analyzer (Hewlet-Packard, HP4195A) was used to measure the resonance frequency (f = 127.3 MHz), the reflection coefficient (S11), and the quality factor (Q) of the birdcage coil (Table 1). Following matching and tuning of the birdcage coil by network analyzer, the experimental data of return loss was measured when the coil unloaded, and loaded with two different sized NaCl solutions (Table 2).[10, 11]

Using the cylindrical acryl with a radius of 7.5 cm and a thickness of 5 mm like the structure seen in Fig. 1, the manufactured birdcage resonator was composed of 12 elements and used a copper tape with the following dimensions: thickness 0.05 mm, width 10 mm, and length 22 cm. The ring enclosed both ends of elements also used the identical coil type whose width was 10 mm. All the manufactured birdcage resonators were of this shape. An 8 cm orange, a 4 cm tangerine, and a rat (10 cm abdominal diameter) were used as phantoms for the experiment, and the sequence to obtain the image of the orange is described in the following paragraph.

T2-weighted MR image of the tangerine images were obtained using a fast spin echo pulse sequence: TR/TE = 3500/96 ms, Matrix size = 192×256, FOV = 67×90 mm, Thickness = 4 mm, and Ave = 3 (Fig. 3). T1weighted MR images of the orange were obtained using a spin echo pulse sequence (Fig. 4). The parameters were TR/TE = 500/17 ms, Matrix size = 256×256, Field of view (FOV) = 100×100 mm, Thickness = 6 mm, and Ave = 3.

Each diameter of the birdcage resonator and the length of elements were as follows. (1) diameter 13 cm and length of element 22cm; (2) diameter 15 cm and length of element 22 cm; (3) diameter 17 cm and length of element 25 cm.

An animal used for the experiment was fed in order to take its abdominal fat measurement as Otsuka Long-Evans Tokushima Fatty (OLETF) rat that breed at an animal laboratory in the Catholic Medical Center, and anesthetized for MR Imaging. Ketamin hydrochloride was used to anesthetize, and capacity was 80 mg/kgs. T1-weighted MR images of the OLETF rat were obtained using a spin echo pulse sequence: TR=500ms, TE=17ms, Matrix size = 192×256, FOV = 90×120 mm, Thickness = 4 mm, and Ave=2 (Fig. 5).

Table 1. Measurements of the SNR and Q factor in the birdcage resonator of diameter 15cm. The phantoms had a diameter of 4 cm tangerine (27%), 8 cm orange (53%), 9.23 cm NaCl solution (61%), and 11.84 cm NaCl solution (79%), respectively.

	Tangerine 4 cm	Orange 8 cm	9.23 cm	11.84 cm
SNR	150.7	212.8	220.4	201.3
Q	53.2	91.2	95.7	89.6

Table 2. Measurements of return loss in the birdcage resonator of diameter 15cm. The phantoms had a diameter of 11.84cm (79%), and 9.23cm (61%), respectively. The solutions were made with NaCl.

	None		11.84 cm		9.23 cm	
	S11	S22	S11	S22	S11	S22
Unload	-15.948	-16.592	—	—	—	—
Load	—	—	-8.0713	-7.5635	-11.295	-10.553

RESULTS

The seven of the resonance modes can be seen in the birdcage resonator consisting of manufactured 12 elements through analysis using the network analyzer. The first mode formed the most homogeneous B1 magnetic field among the seven modes that were tuned in to resonance frequency (127.73 MHz).

First, the T2-weighted MR image of a tangerine was obtained from the birdcage resonator in Fig. 3. The diameter of the birdcage resonator was 15 cm, and the ratio of the tangerine to the birdcage resonator accounted for approximately 27%. As seen on the obtained image, the artifact appeared on the edge of tangerine. The Q factor was 53.2, and the SNR was 150.7.[14]

Second, the T1-weighted MR image of an orange is shown in Fig. 4. The diameter of the birdcage resonator was 15 cm, and the ratio of the orange was approximately 53%. The artifact shown in the image of the orange disappeared on the edge of it, and a high-resolution image was obtained by a high SNR and Q parameter which was 212.8 and 91.2, respectively.

Measurements of the SNR and Q factor in the birdcage resonator using phantoms are listed in Table 1. In Table 1, the parameters are different in accordance with the size of phantoms. The low SNR and Q parameter of the tangerine cause the artifact to appear and the image of the parts of the edge to be unclear as seen from Fig. 3. On the other hand, orange and two of NaCl solution has high SNR and high Q parameter. Therefore high-resolution image of the orange and rat could be obtained.

Consequently, through this study, it was determined that the best quality of images and SNR can be obtained when the ratio of an object to the birdcage resonator is about 40~80%. The present study suggests that a size of the object within the RF coil could be very important for signal optimization at 3T MRI system. The parameters of the SNR and Q not only give clear anatomic information about abdominal cavity viscera, but also help in obtaining more exact data for estimating the ratio of rat (Fig. 5).

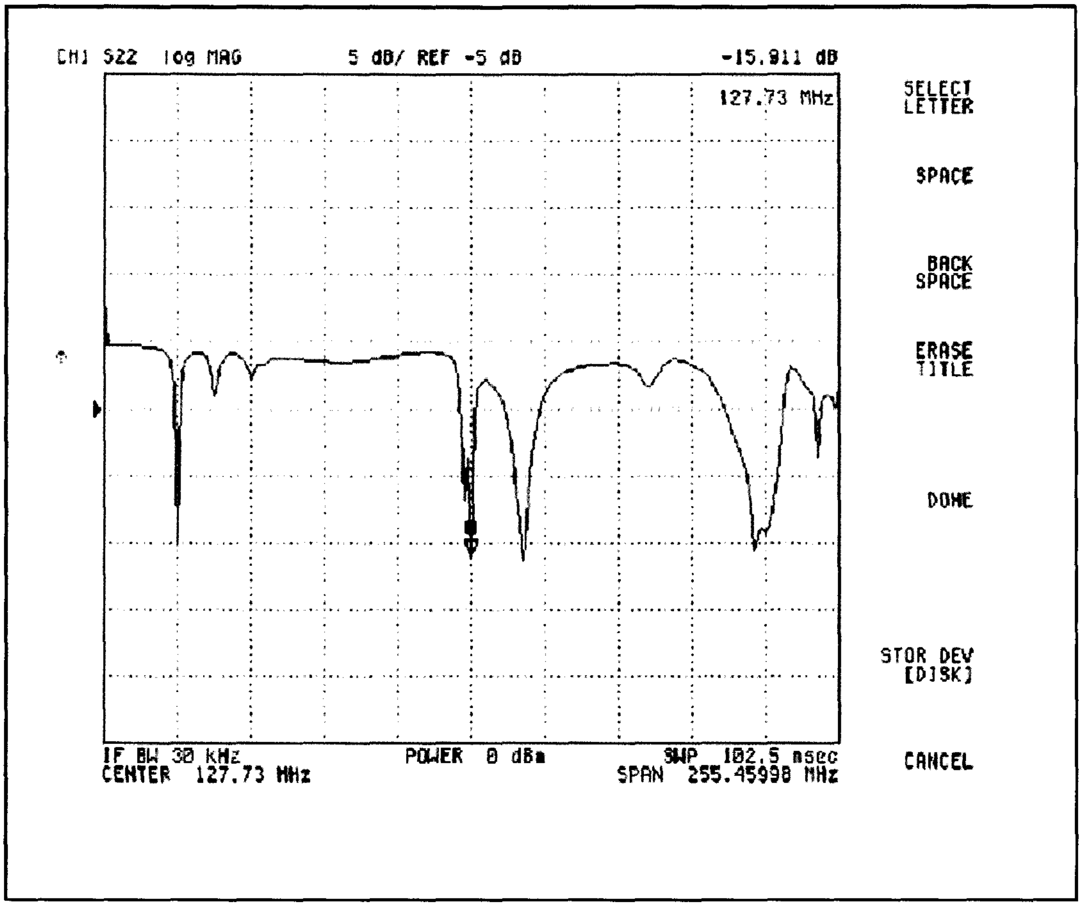
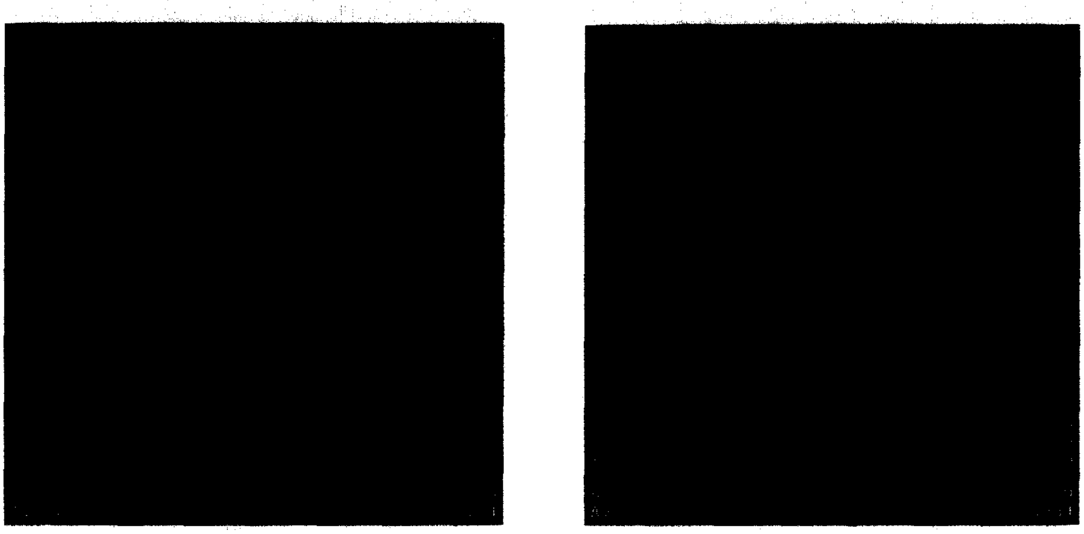
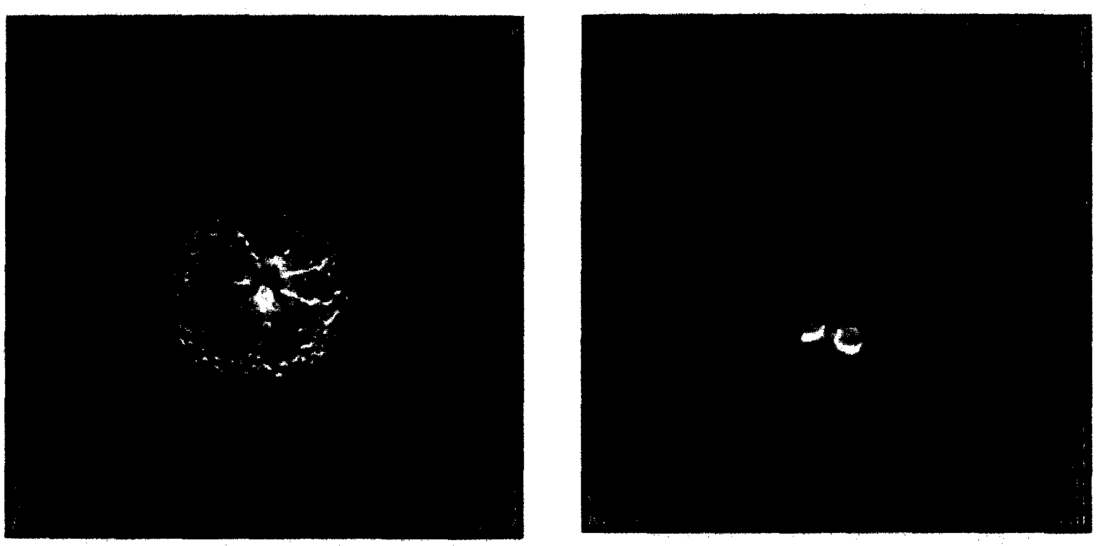


Fig. 2. Seven modes were demonstrated in unloaded and unmatched the RF coil.



(a) (b)

Fig. 3. Tangerine (diameter 4 cm), T2-weighted MR image, TR=4000 ms, TE=96 ms, Ave=3. (a) Artifact on the top and signal diminution on the edge in the image. (b) Artifact on the top and signal diminution on the left side in the image.



(a) (b)

Fig. 4. Orange (diameter 8 cm), T1-weighted MR image, TR=500 ms, TE=17 ms, Ave=3 (a) A slice of the orange's peel, (b) A slice of the orange with seed.

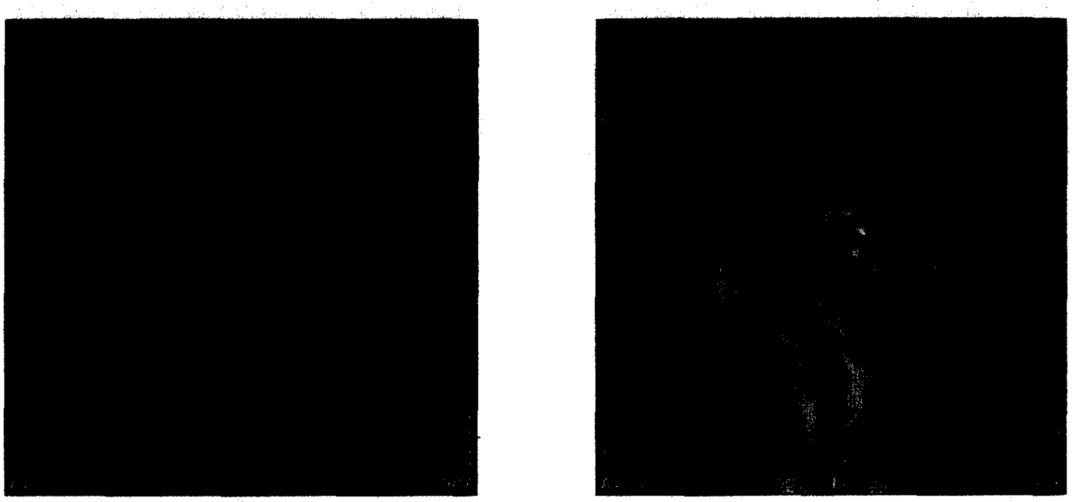
DISCUSSIONS

The non-invasive nature of MRI, and the excellent soft tissue contrast of the MR images, makes MRI an ideal tool for performing serial *in vivo* studies in animals. The RF coil design presented here was successfully used to demonstrate the potential clinical utility of these high field MRI systems for imaging of the small animal. By employing standard principles of RF coil design, we were able to create a very efficient coil. Consequently, this hardware combination produced images with excellent potential to be clinically useful for small animal imaging in future study protocols.[12, 13]

With careful engineering, certain coil designs like the birdcage can be utilized at 3T on a whole body system without degrading their performance. Prior to the substantial manufacturing, many parameters theoretically could be calculated through the use of simulations. It was identified that there were many differences between theoretically calculated parameters and results of the experiment performed over again after the birdcage resonator was produced. This was because many factors in the theoretical calculation had a greater effect on the real manufacturing than expected, and there were some differences inside the real magnet field after the experimental analysis.

The result of comparing images according to absorption region by the various birdcage resonators gave a clear proof that there were significant differences between the SNR and Q in accordance with the ratio of the object in the coil. Therefore, in making a birdcage resonator, many factors such as the coil's permittivity, circuit coupling, and isolation among channels should be sufficiently considered. When the object in the coil accounts for a definite ratio, high SNR and Q parameters can be calculated, and high-resolution images can be obtained.

Recently, MRI is growing as a new diagnosis modality in the area of animal clinics. In developing a new medicine and cure, the safety of the medicine should be examined before applying to people. At this point, using the animal image obtained from high resonance MRI with high SNR can be a big help for such studies.



(a) (b)

Fig. 5. OLETF rat, T1-weighted MR image, TR=500 ms, TE=17 ms, Ave=2 (a) Internal organs (liver, lung, paunch, etc.) can be seen. (b) Internal organs, the bladder, etc. can be seen.

However, despite the animals being smaller than the human body, the coil for the human body that was far bigger than an object was used. This caused noise in the background except for that the space where an object occupies, and had an effect on the quality of images. Thus, the development of various sizes of coils for animals is necessary to obtain high-resolution images of animals.

At present, the whole body scanner of high resolution has been used for the study of fMRI and central nervous system with its improved spatial resolution and image contrast degree. Also, as the result of this study, this research is considered to play a definite role in expanding area of veterinarian clinical diagnosis epochally.

Acknowledgement

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REFERENCES

1. Harpen MD. Equivalent circuit for birdcage resonators. *Magn Reson Med.*, 29, 263-268 (1993).
2. Harpen MD. Cylindrical coils near self-resonance. *Magn Reson Med.*,30, 489-493 (1993).
3. Wen H, Ghesnick AS, Balaban RS. The design and test of a new volume coil for high field imaging. *Magn Reson Med.*, 32, 492-498 (1994).
4. Jin J. Electromagnetic analysis and design in magnetic resonance imaging. 1st ed. CRC, press, 24, 243-252 (1999).
5. Leifer MC. Resonant modes of the birdcage coil. *J Magn Reson* ,124, 51-60 (1997).
6. Jin J, Shen G, Porkins T. On the field inhomogeneity of a birdcage coil. *Magn Reson Med.*,32, 418-422 (1994).
7. Leifer MC. Theory of the quadrature elliptic birdcage coil. Magn *Reson Med.*,38, 726-732 (1992).
8. Pascone RJ, Garcia BJ, Fitzgerald TM, Vullo T, Zipagan R, Cahill PT. Generalized electrical analysis of low-pass and high-pass birdcage resonators. *Magn Reson Imaging.*, 9, 395-408 (1991).
9. Bowtell RW, Peters A, Sharp JC, Mansfield P, Hsu EW, Aiken N, Horsman A, Blackband SJ. NMR microscopy of single neurons using spin echo and line narrowed 2DFT imaging. *Magn Reson Med.*, 33, 790-794 (1995).
10. Callaghan PT, Principles of Nuclear Magnetic Resonance Microscopy. Clarendon Press, Oxford, 1991
11. Pascone R, Vullo T, Farrelly J, Mancuso R, Cahill PT. Use of transmission line analysis for multi-tuning of birdcage resonators. *Magn Reson Imaging.*, 11, 705-715 (1993).
12. D.I. Hoult, R.E. Richards. Department of Biochemistry, University of Oxford. The Signal-to-Noise Ratio of The Nuclear Magnetic Resonance Experiment. *J. Magn Reson,* 24, 71-85 (1976).
13. Vaughan JT, Hetherington HP, Otu JO, Pan JW, Pohost GM. High frequency volume coils for clinical NMR imaging and spectroscopy. *Magn Reson Med.*, 32, 206-218 (1994).

14. Harpen MD. Radiative losses of a birdcage resonator. *Magn Reson Med.*, 29, 713-716 (1993).