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Slotted surface coil with reduced g-factor for SENSE imaging

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***Abstract*— A new coil design inspired on the slot-and-hole magnetron tube is proposed for SENSE imaging. To investigate its g-factor behaviour: an *SNR* formula was derived using the quasi-static approach, and combined with the ultimate g-factor formula to compute the ultimate-factor-g-vs-depth plots. A g-factor expression was derived for the circular coil using the same approach for comparison purposes. *SNR*-vs-depth profiles of an 4-slot coil showed an important improvement over the circular coil. The 4-slot coil g-factor can be up to 58.32% lower than that of a single circular-shaped coil. This improvement makes the slotted surface coil a good choice for SENSE imaging.**

I. INTRODUCTION

Parallel imaging (PI) is one of the most promising recent advances in MRI technology and has, similar to the introduction of multidetector helical scanning in CT, revolutionised MR imaging [1]. The speed of all conventional MRI methods has been limited by either gradient strength or their switching times. The basic idea in PI is to use some spatial information contained in the individual elements of a radiofrequency (RF) receiver coil array to increase imaging speed. PI was motivated by the wish to accelerate image acquisition without reducing the spatial resolution of the image.

PI schemes suffer from *SNR* loss when compred to the fully gradient-encoded acquired using the same array coil. This is due to: reduction in the temporal averaging of noise associated with the fact that fewer k-space points are used in the reconstruction, and the amplification of the noise. Then, a spatially-dependent source of noise can be appreciated, which can be quantified by the so-called geometry factor, *g*, and it is this geometry-associated loss that can de diminished through good coil array design.

PI places an additional demands upon the RF receive coils as not only do the coils need to be designed for optimal sensitivity but they also need to have individual coil sensitivity profiles which minimize the noise amplification caused by the reconstruction process. By adjusting the shape, size, and placement of individual coil elements in an array, significant reductions in the noise figure can be achieved. Conversely, many coils with excellent sensitivity have phase and amplitude characteristics that are non-optimal for PI particularly with low numbers of receive channels. Because of this, the design of PI array coils is a rapidly growing field and a large variety of interesting and novel designs have been presented over the past few years. Design of array coils for PI is challenging due to the need to maximize array sensitivity and minimize noise amplification or g factor of the coil.

A new coil design based on the cavity magnetron tube [2] was developed for parallel imaging. In this design, only the anode plate was used and configurated as a slot-and-hole structure, see Fig. 1.

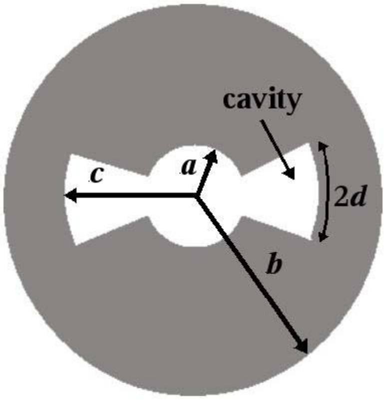

Fig. 1. Diagram of a slotted coil showing two cavities.

Experimental results showed that this coil design is able to generate a higher signal-to-noise ratio (*SNR*) that the popular circular-shaped coil [3]. These encouraging results motivated the calculation of an *SNR* to theoretically investigate the performance of this coil for other magnetic resonance imaging (MRI) and magnetic resonance spectroscopy (MRS) applications, like PI, phased-array imaging and in vivo proton MRS.

This is particularly important since allows to theoretically predict the performance of this coil design, replacing so the tedious method of trial-and-error scheme widely used. This method is particularly difficult to follow because of the complexity to find an analytically-derived expression for even simple geometries. However, it offers a reliable manner to study the performance of MRI coils for different MRI and MRS applications.

II. METHOD

The quasi-static approach proposed by Wang and collaborators [4] together with an approximation method based on the Legendre polynomials [5] were used to calculate a mathematical formula for the *SNR* of a surface coil with *n* slots as shown in Fig. 1. To include the sample losses the method to calculate the *SNR* of coils introduced by Schnell and co-workers [6] was also used to derivate the:

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SNR formula. Therefore, the general *SNR* expression is [5]

$$SNR_{mag}=\frac{\omega_0 V M \mu_0 n}{p\sqrt{8kT\Delta f P_B}}\left(\frac{1}{(b-a)\delta}\left(\frac{2\pi}{n}-2\phi\right)\left(\frac{a}{\sqrt{a^2+z^2}}-\frac{b}{\sqrt{b^2+z^2}}+\ln\left(\frac{b+\sqrt{b^2+z^2}}{a+\sqrt{a^2+z^2}}\right)\right)+\frac{2\phi}{(b-c)\delta}\left(\frac{c}{\sqrt{c^2+z^2}}-\frac{b}{\sqrt{b^2+z^2}}+\ln\left(\frac{b+\sqrt{b^2+z^2}}{c+\sqrt{c^2+z^2}}\right)\right)\right) \quad (1)$$

where *B(z)* is calculated in cylindrical coordinates and z is the depth, V, M, k, T, and Δf are defined in [4], and P_A, P_B, σ_A, σ_B, ω, δ, μ_0 and ε are defined in [6], δ is the coil thickness, $\tan(\phi) = d/c$, and S is the coil area.

To assess coil performance as a function of number of slots, and depth, z, an *SNR* expression of a 4-slot coil was derived from the general *SNR* function, eq. (1). The design parameters were: $a = 2$ cm, $b = 6$ cm and $c = 4$ cm.

The *SNR* formula for a 4-slot design is:

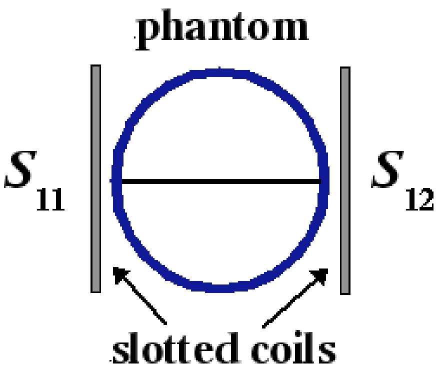

Fig. 2. Diagram of mirror symmetry.

$$SNR_{4\ slots}=212.84\left(\frac{0.024}{\sqrt{(0.02)^2+z^2}}+\frac{0.039}{\sqrt{(0.04)^2+z^2}}-\frac{0.12}{\sqrt{(0.06)^2+z^2}}-\ln\left(\frac{0.02+\sqrt{(0.02)^2+z^2}}{\left(0.04+\sqrt{(0.04)^2+z^2}\right)\left(0.06+\sqrt{(0.06)^2+z^2}\right)^2}\right)\right) \quad (2)$$

Additionally, a circular-shaped coil *SNR* with a 6 cm total radius was also obtained using the same approach as in [5] for comparison purposes.

The *SNR* formula of circular coil is:

$$SNR_{cir}=\frac{0.01}{\left((0.06)^2+z^2\right)^{3/2}} \quad (3)$$

To study the g factor of this new coil design, the Reykowsky's formula was used [7]:

$$g^{ultimate}=\frac{SNR^{full}}{SNR^{SENSE}}=\sqrt{1-\left|\frac{S_{12}^2}{S_{11}^2}\right|} \quad (4)$$

where S_{12} and S_{11} are the MR signals received by the coils as represented in Fig. 2.

Eqs. (2) and (4) were used to derive particular formulas for the g factor for the slotted coil, and Eqs. (2) and (4) were used for the circular coil for the mirror setup, as shown in Fig. 2. Then these g factor equations were used to theoretically compute:

a) *SNR-vs-depth profiles of both coils*

b) *g-factor-vs-fractional radius profiles of a 4 slot design*

c) *the ultimate g factor profiles for these two RF surface coils*

These computational simulations were done and used to compare coil performance and the g factor figure against the popular circular coil. All g factor profiles were calculated for mirror symmetry and using the methodology reported in [7]. MatLab (V. 6.1, The MathWorks, Natick, MA) programmes were specially written to calculate all profiles.

III. RESULTS

SNR-vs-depth profiles of a 4-slot coil and a circular-shaped coil with similar dimensions were computed and are shown in Fig. 3. The g profiles of the 4-slot surface coil forming a mirror symmetry (spherical phantom with a 6 cm radius) were computed with a reduction factor R =1, coil dimensions were determined as in the Method section. g-vs-z (depth) plots were then obtained and shown in Fig. 4. An improvement plot was theoretically estimated as well and shown in Fig. 5.

IV. DISCUSSION

It was possible to derive an *SNR* formula for a new coil design with 4 slots. From this particular results it can be inferred that the general SNR expression of eq. (1) can be used to calculate an *SNR* formula for any number of slots. This analytical model can then be used to guide to design new surface coil for other MRI applications. This is an important result since most of the MRI coil development is carried out with the trial-and-error approach. Consequently, any one interested to build his/her own coils can save a great deal of time and effort .

From the theoretical point of view (Fig. 3), there is a significant improvement in the coil *SNR* compared with the circular coil, even for point further away from the coil plane. These results are in good agreement with those reported in [7].

It can be appreciated from Fig. 5 that the factor g of the PERES coil shows an improvement of 58.32% over the circular coil. Simulation of the factor g of a coil is usually a very difficult task, however it offers a straightforward way to predict coil performance. This coil design is an example of an improved-*SNR* coil with a low factor g. The slotted coil design shows both an improvement of *SNR* and better performance than the circular coil for SENSE imaging. Finally, this coil design can be a good candidate for MRI applications where high *SNR* is required.

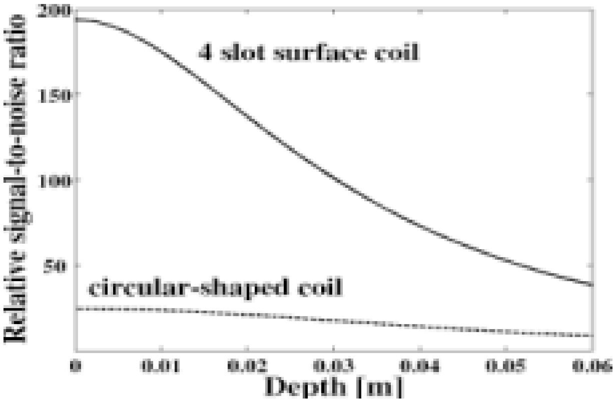

Fig. 3. The comparison graph shows a significant theoretical improvement of the 4-slot surface coil over the circular coil.

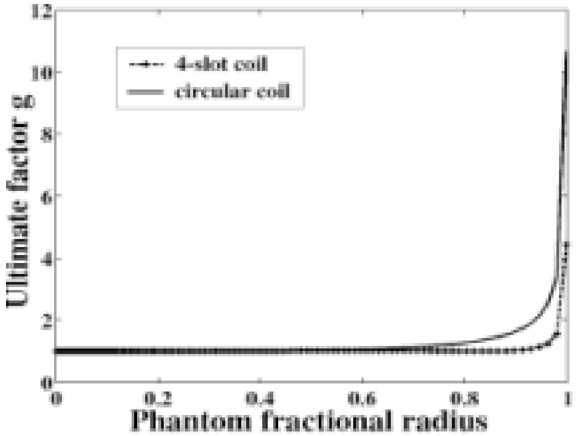

Fig. 4. The lower profiles of 4-slot coil show an important improvement over the circular coil.

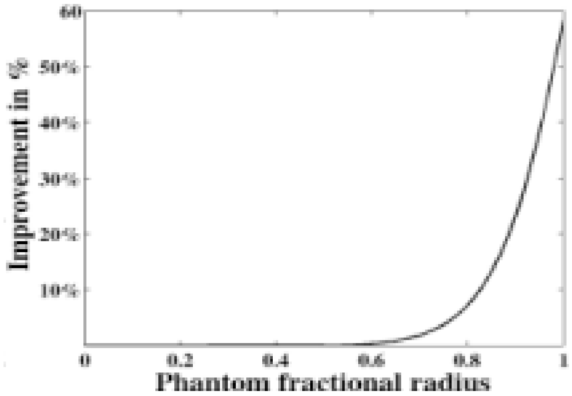

Fig. 5. Improvement profile shows the 58% upper limit.

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