NMR Signal Intensity And Receive Sensitivity

J. Wang[1], H. Kim[1], W. Mao[2], X. Zhang[3], W. Chen[3], M. B. Smith[2], and R. T. Constable[1]

[1]Department of Diagnostic Radiology, Yale School of Medicine, New Haven, Connecticut, United States, [2]Department of Radiology, The Pennsylvania State University, Hershey, Pennsylvania, United States, [3]Department of Radiology, University of Minnesota, Minneapolis, Minnesota, United States

INTRODUCTION

The principle of reciprocity has been suggested for its utility in determining receive sensitivity [1]. For high static field imaging two formalisms have been suggested for the receive sensitivity including a) $B_1^{(-)} = (B_x^*+iB_y^*)$ [2] and b) $B_1^{(-)} = (B_x+iB_y)$ [3-5]. It is crucial to clarify this problem for quantitative NMR and this issue has particular relevance for parallel image reconstruction where knowledge of the receive sensitivity is of utmost importance.

THEORY

Water phantoms and biological tissues can be approximated as a linear electromagnetic medium, and with such a medium the reciprocity principle of electromagnetic fields holds in NMR detection. We can write Eq. (1)

$$\iiint_v \left(\vec{B}_1 \cdot \vec{M}_2\right)dv = \iiint_v \left(-\vec{E}_2 \cdot \vec{J}_1\right)dv \qquad (1)$$

$$\varepsilon\hat{I} = \frac{\partial}{\partial t}\iiint_v \vec{E}_2 \cdot \vec{J}_1 dv = -\frac{\partial}{\partial t}\iiint_v \left(\vec{M}_2 \cdot \vec{B}_{receive}\right)dv \qquad (2)$$

When the receive coil is regarded as a battery, its electromotive force ε is defined as the energy per unit charge that is converted reversibly from the magnetic energy. In accordance with Eq. (1), the ε per unit current is given by Eq. (2). In Eq. (2), $B_{receive}$ is the field at the location of M_2, which is generated by unit current I in the receive coil or in the 'pseudo-transmit coil' which has the same configuration and current density distribution as the receive coil. If $B_{receive}$ is uniform throughout the load, then the magnetization of the loaded object M = $\iiint M_2 dv$. Eq. (2) reduces to Eq. (3) which is the same as Hoult's formula [3].

$$\varepsilon\hat{I} = -\frac{\partial}{\partial t}\iiint_v \left(\vec{M}_2 \cdot \vec{B}_{receive}\right)dv = -\frac{\partial}{\partial t}\left(\vec{M} \cdot \vec{B}_{receive}\right) \qquad (3)$$

$$\varepsilon = -i\omega_0 M_0 \frac{B_{transmit}^{left}}{B_{transmit}} \cdot B_{receive}^{right} \cdot \sin\left(\int_0^{t_p} \gamma B_{transmit}^{left} dt\right) \qquad (4)$$

Eq. (4) can be derived from Bloch equation and Eq. (3). $B_{transmit}^{left} = B_{transmit} \cdot \exp(-i\omega_0 t)$ is a left-handed circularly polarized component of the transmit field. $B_{receive}^{right} = B_{receive} \cdot \exp(i\omega_0 t)$ is a circularly polarized component of the receive RF field which rotates in opposite direction to the precessing magnetization .

METHODS

A simulated image was compared with the experimental image of a 20 mM NaCl phantom, acquired at 7 T, in order to evaluate our proposed theory. The details for both the experiment and the simulation are shown in ref.6. The image of a water phantom was also obtained on a Siemens 3 T Trio with a transmitter/receiver body coil, to quantitatively evaluate the difference between the transmit field and reception sensitivity. The spherical water phantom (17 cm diameter) was filled with distilled water and $NiSO_4.6H_2O$ (4.8mM). Multi-slice images of the phantom were acquired using a conventional GE sequence with excitation flip angles of 30, 60, and 120^o to estimate the transmit field and the receive sensitivity. The other imaging parameters were TR/TE 2500/20 ms, FOV 200 x 200 mm^2, matrix 128 x 128, slice number 30, slice thickness 3 mm, distance between 3 mm.

RESULTS AND DISCUSSIONS

An image simulated using Eq. (4) at 300 MHz exhibits close agreement with the distribution of signal intensity of the image acquired at 7 T, as shown in Fig. 1. Subtle differences between the distributions of the simulated image in Fig. 1**a** and the experimental image in Fig.1**b** may be due to a number of limitations in the exactness in which the experiment was modeled. Figure 2 shows the magnitude of the simulated field maps B_1^{left} (**a**), B_1^{right} (**b**) and their percent difference (**c**) for a phantom with a linear birdcage coil at the Larmor frequencies of 10, 20 64, and 128 MHz. Their difference here is significant when the size of the object is larger than one-tenth of the wavelength in the object, therefore, B_1^{left} and B_1^{right} cannot replace each other in these cases. Furthermore, Figure 3 shows the measured transmit field (**a**) and receive sensitivity (**b**) of a water phantom. The signal-to-noise ratio of the measured image at the flip angle of 30^o is around 100. The error estimated B_1^{left} and B_1^{right} should be around 2%. The difference between B_1^{left} and B_1^{right} in Fig. 3**c** is about 10% (bright and dark region), and this difference is significant.

Some authors have suggested that the receive sensitivity is proportional to $B_1^{(-)} = (B_x^*+iB_y^*)$ [2], and others $B_1^{(-)} = (B_x+iB_y)$ [3-5]. If Bx and B_y are complex, both $B_1^{(-)}$'s should be elliptically polarized fields. Strictly speaking, they are different from the circularly polarized components ($B_{receive}^{right}$). In some specific cases, $B_1^{(-)} = (B_x^*+iB_y^*)$ or $B_1^{(-)} = (B_x+iB_y)$ can be approximated by $B_{receive}^{right}$. However, the difference between elliptically polarized components ($B_1^{(-)}$) and the circularly polarized component ($B_{receive}^{right}$) can potentially lead to large errors, especially at the high field strength. In order to exactly simulate the transmit field, receive sensitivity, and MR signal intensity, the measured elliptically polarized RF field should be decomposed into two circularly polarized component ($B_{receive}^{right}$) to quantify the transmit field and receive sensitivity in NMR experiments using Eq. (4).

CONCLUSIONS

(1) The expression for the signal intensity in NMR is derived from the reciprocity principle in NMR reception. (2) A simulated image based on the proposed method is in a good agreement with the experimental images. (3) The simulated B_1^{left} and B_1^{right} significantly differ from each other when the size of the phantom is larger than one-tenth of the wavelength in the phantom, and (4) The experimental results at 3T prove the source of these differences.

ACKNOWLEDGEMENTS: Support from NIH NS40497, NS38467, EB00473, EB00513 and EB00454 is gratefully acknowledged.

REFERENCE:

1. Hoult DI, Richards RE. J. Magn. Reson. 1976;**24**:71.
2. Hoult DI. *Concepts Magn Reson*. 2000; **12**: 173-187.
3. Ibrahim TS. Magn Reson Med. 2005;**54**:677.
4. Sled JG, Pike GB. *IEEE Trans Med Imaging* 1998 ;**17**:653.
5. Glover GH et al. *J Magn Reson*. 1985;**64**:255.
6. Wang J et al. Magn Reson Med. 2002;**48**:362.

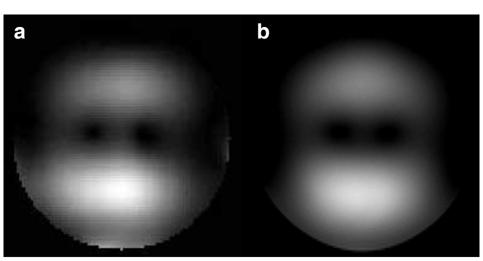

Fig 1. A simulated image (**a**) with the proposed formula, and experimental image (**b**) acquired using a GE sequence at 7 T.

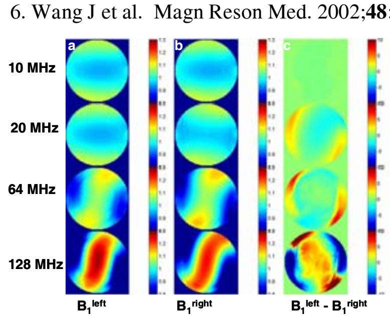

Fig 2. The simulated B_1^{left} (**a**), B_1^{right} (**b**) and their difference (**c**) with a linear birdcage coil at 10, 20, 64, and 128 MHz .

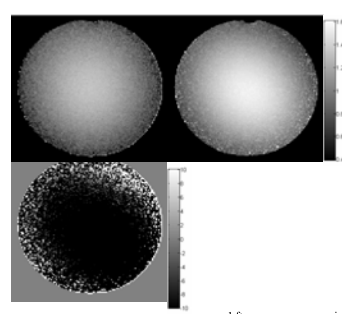

Fig.3. The measured $B_{transmit}^{lrft}$ (**a**), $B_{receive}^{right}$ (**b**), and the differences (**c**) for the water phantom at 3 T