TAILORED RF PULSE 를 이용한 NMR 에서의 뇌 기능 영상법

노용만[1], 조장희[2], R. S. Mennon[3], K. Ugurbil[3]

1. 대전대학교 전산과, 2. 한국과학기술원 정보및 통신공학과, 3. 미네소타대학 자기공명 연구 센타

NMR Functional brain Imaging with the Tailored RF Pulse

Y. M. Ro[1], Z. H. Cho[2], R. S. Mennon[3], K. Ugurbil[3]

1. Dept. of Computer Sciences, Taejon University, 2. Dept. of Information and Communication, KAIST, 3. Center of Magnetic Resonance Research, University of Minnesota

ABSTRACT

The experimental results of visual stimulation with the tailored RF pulse are reported. Tailored RF pulse is used for the susceptibility effect imaging. Around 25 % signal change of visual cortex area is detected during photic stimulation. Interestingly, with the tailored RF pulse, the signal intensity of visual cortex is deceased during photic stimulation. It is, however, increased with normal T_2 weighted imaging. The comparison between normal T_2 weighted imaging and the tailored RF pulse imaging are performed with 4T NMR system and the results with human volunteer are also presented.

INTRODUCTION

It is well known that oxygenation state of blood determines its magnetic properties; i.e., deoxyhemoglobin is paramagnetic while oxyhemoglobin is diamagnetic [1]. Since water in normal tissues has generally diamagnetic property the proton surrounded by the paramagnetic materials, e.g., deoxyhemoglobin is affected by susceptibility difference [2].

The susceptibility difference produces the field variation in the voxel at blood interface and leads to signal loss in gradient echo imaging. This signal loss phenomenon is now utilized as susceptibility-dependent contrast, i.e., T_2* contrast [3]. Namely, the paramagnetic deoxyhemoglobin in venous blood causes a magnetic field variation due to the differences in magnetic susceptibility between the oxygen-defficient blood and the surrounding tissues [3]. In this case, paramagnetic deoxyhemoglobin naturally plays a role as an endogeneous contrast agent according to the susceptibility effect.

Recently, several authors have published the function brain mapping papers by the use of the susceptibility effect in gradient echo imaging. Signal intensity change in human visual cortex have been found by photic stimulation [4,5,6]. The function image in motor cortex is also obtained by with a sequence of self-phased thumb movement [7]. Consequently there is evidence that the increase of blood oxygenation relates with the neuronal activity and thereby the neuronal activation can be observed in magnetic resonance imaging by the use of the susceptibility effect imaging.

For the susceptibility effect imaging, the tailored RF pulse was introduced in order to be more sensitive to the susceptibility effect. A venous blood imaging due to the susceptibility effect was obtained [8]. The tailored RF pulse designed for the susceptibility effect imaging made the signal coming from normal tissues be suppressed while the signals from paramagnetic bloods-tissues interfaces be enhanced.

In this paper, we applied the tailored RF pulse technique to the functional brain imaging. By the property that the susceptibility-affected signal is enhanced while the signal without susceptibility effect is suppressed, in functional brain imaging, the signal around visual cortex is decreased during photic stimulation in different way in normal T_2* imaging (whatever is gradient echo planar imaging or gradient echo imaging).

THE TAILORED RF PULSE AND SIGNAL INTENSITY DUE TO SUSCEPTIBILITY EFFECT

The tailored RF pulse here is called a RF pulse which produces a phase distribution with a selected rectangular slice. For the susceptibility effect imaging, the phase distribution within the selected slice is designed so that the intravoxel spins in the normal tissues which has no field variations cancel each other while the spins in susceptibility affected tissues such as venous blood-tissue interface become coherent. Therefore, by applying the tailored RF pulse, the signal affected by the susceptibility effect are enhanced and thereby one can obtain the susceptibility effect only imaging.

In general, the intravoxel signal intensity with the phase information generated by the tailored RF pulse can be written as [8];

$$S = \left| 2\pi M z_o \,\mathrm{sinc}\left(\frac{P_{sus}}{2\pi} z_o\right) * \mathcal{F}^{-1}\left[\exp\left[i\,\theta_{RF}(z)\right] \right] \right| \qquad [1]$$

where * represents the convolution operator. The intravoxel signal intensity with a tailored RF pulse appears the convolution of two functions. The first is the sinc distribution which represents the signal intensity distribution of voxel with no RF generated phase distribution and the second is Fourier transformed phase term of the voxel generated by the tailored RF pulse. This mathematical expression of signal intensity shows that the intravoxel signal intensity affected by the susceptibility effect can be controlled by the RF-generated phase distribution within the voxel. For the susceptibility effect imaging, a saw-tooth-like phase distribution is suitable [8]. Since the phase is distributed from 0 to 2π with the form of saw-tooth, the intravoxel spins in normal tissues cancel thereby no signal. On the contrary, the spins affected by the susceptibility effect produces signal because of the phase term induced by the susceptibility.

Therefore, with a tailored RF pulse which produces the saw-tooth phase distribution within the voxel, a susceptibility effect image can be obtained. Figure 1 shows the intravoxel signal intensity distribution as a function of susceptibility induced phase gradient (P_{sus}) with the tailored RF pulse producing the saw-tooth phase distribution.

EXPERIMENTS AND DISCUSSIONS

As mentioned earlier, the image contrast with the tailored RF pulse is different from normal T_2* imaging. As shown in Fig. 1, the signal intensity increases with increasing susceptibility gradient, i.e., increasing the susceptibility effect. In normal gradient echo imaging, the signal intensity is normally decreased with increasing the susceptibility effect. Therefore signal loss phenomenon due to the susceptibility effect in normal T_2* imaging now will be changed to the signal enhancement phenomenon by applying the tailored RF pulse, i.e., one can obtain the susceptibility image in which only susceptibility-affected area produces the signal while other areas are all suppressed. With this property of the tailored RF pulse, we have performed the functional brain imaging with visual stimulation.

Experiments were performed with 4T whole body imaging system with active shield-gradient coil [Sisco/Simens]. A curved surface RF coil was used for limited region and good SNR. First, we obtained the high resolution T_1 weighted image from a FISP sequence with 256 phase encoding steps. In the T_1 weighted image, the grey matter is dark while the white matter signal is enhanced. With the T_1 contrast, the visual cortex area which is believed to be located in the grey matter is easily defined.

Gradient echo imaging were performed with the two average. Echo time was 35 msec for allowing the sufficient susceptibility effect and repetition time was 60 msec with slice thickness of 10 mm. In the T_2* weighted image with 256 phase encodings, the susceptibility contrast can be seen in the area of venous blood-tissue interfaces, e.g., interfaces around venous internal sinus. In the vicinity of the visual cortex, one can also see dark signal as a susceptibility contrast (a box is outlined).

The tailored RF pulse with the same experimental conditions was applied. In the tailored RF pulse imaging, the image contrast is completely different from the case in the normal T_2* imaging. The venous blood interfaces are enhanced due to the susceptibility and the other normal tissues are suppressed. One can also see that the signal in the box region becomes no more dark.

We performed visual stimulation experiments with above experimental conditions. Visual activation was performed by photic stimulation with LED checker board manufactured by Grass Instrument (Quency, MA). 24 images sets are obtained. The first 10 images were obtained without photic stimulation for the control condition. Thereafter, by the use of flash checker board, photic stimulation was provided during the data acquisition between 11-th and 14-th images. Last 10 images were obtained again without photic stimulation for the baseline. This visual experiments were performed consecutively with normal T_2* imaging and the tailored RF pulse imaging.

Figure 2 (a) shows the time course of the signal change around visual cortex (box region) with visual stimulation in normal T_2* weighted imaging. As shown, one can see an increasing signal during photic stimulation. With turning off stimulation, the signal is again decreased and returns to the baseline. It is believed that the oxygenation state of visual cortex is changed during photic stimulation. The signal change was about 30 % in T_2* weighted imaging.

Same experiments were performed with the tailored RF pulse. In case of the tailored RF pulse imaging, the signal change responded in different way, i.e., the signal around visual cortex is decreased during photic stimulation. Figure 2 (b) shows the time course of signal change around visual cortex with the tailored RF pulse. This represents oxygenation dependent susceptibility effect is changed during stimulation. The signal change in case of the tailored RF pulse imaging was around 25 %. The reason of decreasing signal change is that the tailored RF pulse is designed with assumption that susceptibility-induced phase is linear within the selected slice. Even though the linear phase assumption causes decreasing signal change about photic activation, the susceptibility effect can be apparently observed. The experimental results also show that, during the stimulation, the tailored RF pulse made the visual cortex signal in oxy-state be suppressed because of less susceptibility effect.

Therefore, the tendency of signal change in response to the photic activation is different whether normal T_2* imaging or the tailored RF pulse imaging is employed. Experimental results show an increase in blood oxygenation during photic stimulation. Since the increase in cerebral blood volume is much greater than the oxygen consumption. Deoxyhemoglobin decreases in the region and thereby the signal intensity increases in normal T_2* weighted imaging. In the tailored RF pulse imaging, however, the decrease of deoxyhemoglobin, i.e., the decrease of susceptibility effect results in decreasing signal. The results of functional imaging obtained with the tailored RF pulse is well consistent with that in normal gradient echo imaging.

REFERENCES

1.L. Pauling and C. Coryell, *Proc. Natl. Acad. Sci.* **22**,159(1936).

2. K. R. Thulbom, J. C. Waterton, P. M. Matthews and G. K. Radda, *Biochim Biochem Acta* **714**, 265 (1982).

3.S. Ogawa and T. Lee, *Magn. Reson. Med.* **16**, 68 (1990).

4. S. Ogawa et al, *Proc. Natl. Acad. Sci. USA* **89**, 5951 (1992).

5.K.K.Kwong et al, *Proc. Natl. Acad. Sci. USA* **89**, 5675(1992).

6. R. Mennon, S. Ogawa, S. G. Kim, D. W. Tank and K. Ugurbil

7. S. G. Kim

8. Z. H. Cho and Y. M. Ro, *Magn. Reson. Med.* **23**, 197 (1992).

9. A. Villringer, B. R. Rosen, J. W. Bellivean, J. L. Ackerman, R. B. Lauffer, R. B. Buxton, Y. Chao, V. J. Wedeen, and J. Brady, *Magn. Reson. Med.* **6**, 164 (1988).

10. B. R. Rosen, J. W. Belliveau, J. M. Vevea and T. J. Brady, *Magn. Reson. Med.* **14**, 249 (1991).

11.J.C.Gore and S.Majumdar, *Magn. Reson. Med.*14, 242(1990).

12.P.T. Fox and M.E. Paichle, *Proc. Natl. Acad. Sci.USA* **83** 1140(1986).

13. C. R. Fiscl et al, *Magn. Reson. Med.* **17**, 336 (1991).

14. R. A. Brooks, A. Brunetti, J. R. Alger, and G. D. Chiro, *Magn. Reson. Med.* **12**, 241 (1989).

15. K. M. Brindle, F. F. Brown, I. D. Campbell, C. Grathwohl, and P. W. Kuchel, *Biochem. J.* **180**, 37, (1979)

FIGURE CAPTIONS

Figure 1. Signal intensity distributions as a function of susceptibility phase gradient, P_{sus} when a tailored RF pulse producing a saw tooth-like phase distribution are applied. As is seen, the signal intensity increases with increasing phase gradient value while the signal intensity of no susceptibility effect (P_{sus}=0) is suppressed.

Figure 2. (a) Time course of signal change around visual cortex with photic stimulation in normal T_2* imaging. (b) Same as Fig. 2 (a) but experiments were performed with the tailored RF pulse. As seen, the signal change responded in different way of T_2* imaging.

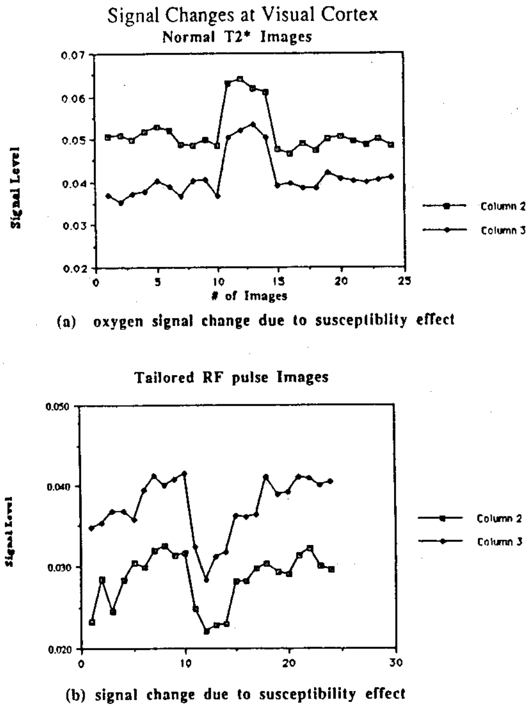

Figure 2.

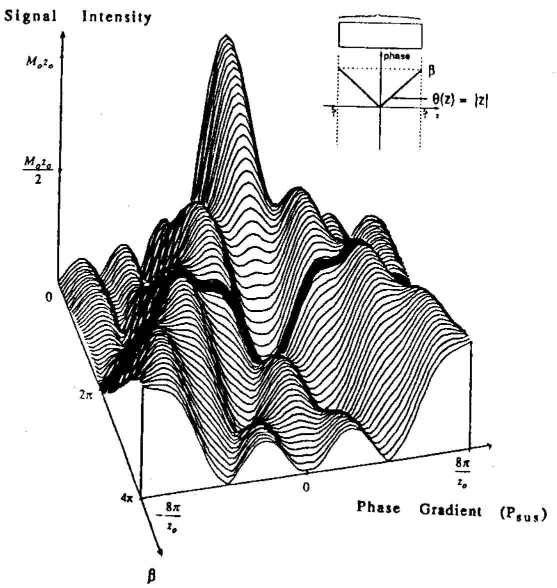

Figure 1.