1990年度 大韓醫用生體工學 春季 學術大會 論文集 90/5

Flow Restored SSFP Sequence in NMR Imaging

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Abstract

By designing the gradient pulses to be velocity compensated during one pulse cycle in SSFP (steady state free precession) imaging, the flowing spins can be maintained in the steady state. In the new SSFP sequence the flow signal which might be lost in conventional SSFP imaging sequences can be restored owing to the signal contribution from the preceding pulse cycles. By using the proposed SSFP sequence substantial restoration of the flow signal has been observed for the CSF (cerebro spinal fluid) of the human head.

I. Introduction

In SSFP imaging the stationary spins maintain the steady state. The importance of the steady state is that the signal of the preceding pulse cycles contributes to the signal of the current pulse cycle. In SSFP, therefore, more signal can be obtained than in spoiled fast imaging. However, the flowing spins violate the steady state condition because the phase of the flowing spins varies according to time in the presence of the imaging gradients. Consequently, the flowing spins can not maintain the steady state and act as in the spoiled fast imaging. In other words, the flow signal from the preceding pulse cycles does not contribute to the current signal, which results in the appreciable signal loss of the flowing spins in SSFP imaging. In this paper, the signal loss of the flowing spins in SSFP imaging is restored by compensating the phase shift of the flowing spins during a pulse cycle. This should be differentiated from the velocity compensated gradient echo pulse sequence where the imaging gradients are designed to be velocity compensated only for the data acquisition not for the one pulse cycle.

II. Methods

When an RF pulse with a flip angle α and duration τ is applied to the spins with magnetization $M(t)$ as shown in Fig. 1, the magnetization after the RF pulse is expressed as

$$F(t+\tau) = F(t)\cos^2\frac{\alpha}{2} + F^*(t)\sin^2\frac{\alpha}{2} - iM_z(t)\sin\alpha \tag{1}$$

$$M_z(t+\tau) = M_z(t)\cos\alpha - i\frac{1}{2}\left[F(t) - F^*(t)\right]\sin\alpha \tag{2}$$

where F denotes the transverse component of the magnetization, i.e., $F=M_x+iM_y$ and the super script * denotes the complex conjugate [1]. What is interesting in Eq. (1) is the fact that the transverse component $F(t)$ of the previous signal contributes to the current signal $F(t+\tau)$ in addition to the previous longitudinal component. On the other hand, in spoiled fast imaging, the previous transverse component is made zero due to the phase dispersion within a voxel and only the longitudinal component of the previous cycle contributes to the current signal, i.e.,

$$F(t+\tau)_{\mathrm{spoil}} = -iM_z(t)\sin\alpha. \tag{3}$$

Consequently, the steady state condition is important to obtain the maximum signal especially for the spins with long T_2 coefficients.

The above effects are reflected in the following formations of the signal intensities [2]:

for the steady state signal,

$$\begin{aligned}
&M_y = M_0\sin\alpha(1-E_1)\frac{C-E_2(B-A)}{AC}\\
&E_1=\exp(-T_R/T_1),\ E_2=\exp(-T_R/T_2)\\
&A=\sqrt{B^2-C^2}\\
&B=1-E_1\cos\alpha-E_2{}^2(E_1-\cos\alpha)\\
&C=E_2(1-E_1)(1+\cos\alpha)
\end{aligned} \tag{4}$$

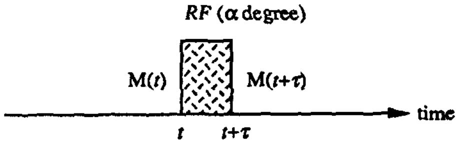

Fig. 1 An RF pulse with a flip angle α and a duration τ is applied at t.

and for the spoiled signal,

$$M_y = M_0 \sin\alpha(1-E_1)/(1-E_1\cos\alpha)\,. \qquad (5)$$

The relation (5) corresponds to the steady state relation (6) for the spin with $T_2=0$ which is same as the flowing spins in the steady state sequence.

The flowing spins experience the phase shift in the presence of the gradient fields, i.e.,

$$\phi_v(T_R) = \gamma \int_0^{T_R} G(t)\,v(t)\,t\;dt \qquad (6)$$

where $\phi_v(T_R)$ is the phase shift during one T_R or one pulse cycle, γ is the gyromagnetic ratio, $v(t)$ is the velocity vector of the flowing spins, and $G(t)$ is the gradient vector. Since the phase shift varies for each pulse cycle due to the different initial position of the flowing spins, the flowing spins can not satisfy the steady state condition. Consequently, the signal of the flowing spins depart from the steady state relation (4) and will approach the spoiled relation (5) as the velocity induced phase shift becomes large. The signals for the two cases are plotted in Fig. 2 for the spins with $T_1/T_2=1500/250$ msec. It is noticeable that the steady state generates much greater signal than the spoiled case. In other words, the flow signals are severely lost in SSFP imaging. To recover the signal loss of the flowing spins it is needed to compensate the phase shift in Eq. (6). For this purpose the readout gradient in SSFP imaging is modified to the back-to-back bipolar waveform which is known to be velocity compensated. The new pulse sequence for the FID component signal is shown in Fig. 3 where the readout gradients of the conventional SSFP sequence are shown together for the comparison. The echo component imaging sequence will be designed in the same manner by reversing the time order. In SSFP imaging the suppression of one of the FID or echo components is needed to avoid the phase interference artifacts [3] and the slice selection gradient in the new pulse sequence performs the role. But the slice selection gradient can be designed to satisfy the relation (6) as well as to perform the suppression by using the gradients shown in Fig. 4.

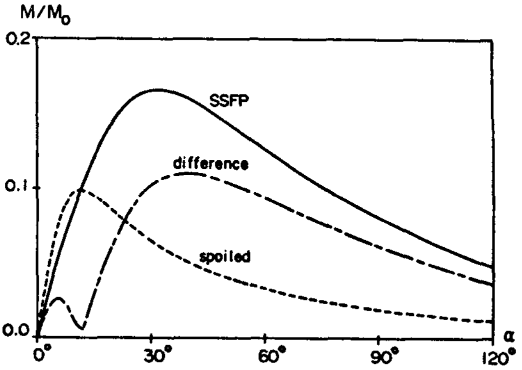

Fig. 2 Signal intensity profiles for the steady state (solid curve) and spoiled (dotted curve) sequences. The intensity difference of them is drawn as a dot-and-dash curve.

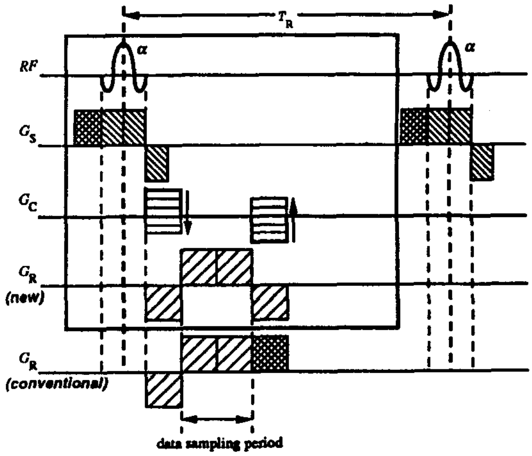

Fig. 3 Pulse diagram of the flow restored SSFP sequence.

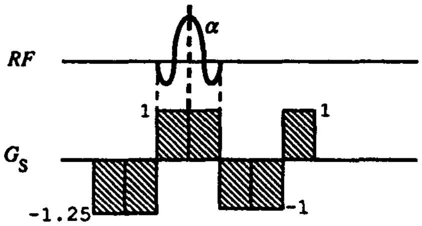

Fig. 4 Velocity compensated slice selection gradients for flow restored SSFP imaging.

III. Experimental Results

The flow restored SSFP pulse sequence of Fig. 3 was experimentally compared with the conventional SSFP pulse sequence with respect to the signal restoration of the flowing spins. By using KAIS 2.0 Tesla whole body imaging system, the sagittal section of the head was obtained with T_R=33 msec as shown in Fig. 5 where the images in the upper and lower rows correspond to the FID and echo component images, respectively. The direction of the readout gradient was oriented along the longer axis of the body. The effects of the proposed sequence are well shown in the magnitude difference images (c) and (d) where the CSF in the ventricles are well shown. Here only the readout gradients are designed based on the proposing rationale, but the modification of the slice selection gradient as in Fig. 4 will further improve the restoration of the flow signal by the same effects.

IV. Conclusions

The proposed SSFP sequence significantly restores the signal from the flowing spins by maintaining the steady state for the flowing spins. This technique can be widely applied to all kinds of flow imaging such as angiography, heart CINE imaging, and CSF imaging to obtain more signal from the flowing spins.

References

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(a) FID (compensated) (b) FID (uncompensated) (c) FID (difference)

(d) Echo (compensated) (e) Echo (uncompensated) (f) Echo (difference)

Fig. 5 Images obtained from the sagittal section of a human head.