Quadrature-Multiplexed rf Excitation for Information Doubling in NMR Imaging

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A quadrature multiplexed pulse sequence to double the data information in a given acquisition time is proposed for NMR tomography. This technique takes advantage of the Hermitian property of the Fourier transform operation in NMR imaging. The proposed technique uses two rf pulses with 90° phase difference simultaneously applied for the excitation of the spins in two different slices. The method results in truly simultaneous data acquisition coming from two different anatomical slices which can be separated into the real and imaginary parts of the image domain. This technique, therefore, also allows us either to reduce the experiment time by half or double the number of slices in the same examination time, depending on the applied imaging scheme. As a preliminary study, simultaneous dual-slice imaging of a human head using a conventional single-slice imaging scheme was performed.

INTRODUCTION

The inherent limitation imposed upon NMR imaging is the imaging speed, or data acquisition time, mainly due to the spin–lattice relaxation time $T_1$ and low signal-to-noise ratio (SNR) (1, 2). The latter has been greatly enhanced with increased magnetic field strength, i.e., use of superconducting magnet of a few tesla (3). The former, however, still exists due to a certain amount of repetition time for the $T_1$ relaxation and the number of views (projection type) or encoding steps (Fourier imaging) required for high-resolution images (4). To partly overcome the imaging time requirement, time-multiplexed multislice, or slice by slice, technique has been used to obtain more slices within a basic imaging time by using the $T_1$ relaxation waiting time for the other slices' excitation (5).

As another approach to overcoming the imaging time requirement, we propose a technique with which two-slice information can be simultaneously obtained by use of quadrature excitation, i.e., simultaneous excitation of two slices with 90° phase difference by using a rf pulse pair which consists of both real and imaginary components. After receipt of the composite echo signal, by Fourier decomposition and appropriate signal processing, two slice images can be obtained simultaneously. This technique can also be combined with the time-multiplexed technique for multislice imaging.
Theory of Proposed Quadrature-Multiplexing Technique

Let us consider conventional two-dimensional (2D) Fourier imaging with slice selection and the echo signal which can be obtained by quadrature-sensitive detection as

$$S(t_x, t_y) = \int \int dx dy \rho(x, y) \exp \{i \gamma (x G_x t_x + y G_y t_y)\}$$  \[1\]

where $\rho(x, y)$ is the spin-density distribution function, $\gamma$, $G_x$, and $G_y$ are gyromagnetic ratio, $x$- and $y$-directional field gradients, respectively, and $t_x$ and $t_y$ are illustrated in Fig. 1. In this case, the image can be obtained by 2D Fourier transform of the obtained echo signals as given in Eq. [1]. The resultant image, in principle, has only real value because it represents the spin-density distribution of the corresponding nucleus. From the pulse sequence point of view, implementation of Eq. [1] is usually carried out by excitation of single-band rf pulses in 90–180° sequence. Now let us consider a rf excitation which consists of a quadrature pair so that two different slices are excited with 90° phase difference from each other. Practically, this can be done by adding two selective complex rf pulse waveforms representing two different slice frequency bands before single sideband (SSB) modulation. In this case, 90° phase difference can be made simply by exchanging the real and imaginary parts of one of the rf pulse waveforms before adding them. The resultant echo signal measured with this quadrature-multiplexed selective excitation along the $z$ axis can be expressed as

$$S_Q(t_x, t_y) = \int \int dx dy \{\rho_1(x, y) + i \rho_2(x, y)\} \exp \{i \gamma (x G_x t_x + y G_y t_y)\}$$  \[2\]

where subscripts 1 and 2 indicate the slices at $z = z_1$ and $z = z_2$, respectively. After 2D Fourier transform of Eq. [2], the resultant image function $f_Q(\omega_x, \omega_y)$ would be a complex function which is given by

![Fig. 1. Radiofrequency and gradient pulse sequence of the proposed quadrature-multiplexing technique for simultaneous dual-slice imaging.](image-url)
where $\mathcal{F}_2[\cdot]$ is the 2D Fourier transform operator, $\omega_x = \gamma G_x \cdot x$, $\omega_y = \gamma G_y \cdot y$, and $f_{Q_1}(\omega_x, \omega_y)$ and $f_{Q_2}(\omega_x, \omega_y)$ are the real and imaginary parts of the Fourier transformed result, respectively. From Eq. [3] and basic Fourier transform properties, it can easily be shown that the spin-density images corresponding to slices at $z = z_1$ and $z = z_2$ are related as

$$P_1(x, y) = f_{Q_1}(\omega_x, \omega_y) = \text{Re}[f_Q(\omega_x, \omega_y)]$$
$$P_2(x, y) = f_{Q_2}(\omega_x, \omega_y) = \text{Im}[f_Q(\omega_x, \omega_y)]$$

where $\text{Re}[\cdot]$ and $\text{Im}[\cdot]$ represent real and imaginary parts of complex value, respectively.

In practical imaging application, this quadrature-multiplexing technique can be used together with time-multiplexed multislice, or slice-by-slice, imaging or the regional volume selection imaging scheme (5, 6). This proposed technique, therefore, can either double the number of slices for a given imaging time or reduce the imaging time by half for a given number of slices.

**EXPERIMENTAL RESULTS AND DISCUSSION**

In practical NMR imaging, phase errors due to electronics and the eddy current effect of gradient pulses are observed and often create undesirable effects such as creation of nonzero imaginary values in the image domain. This effect is normally observed in conventional imaging (either single-slice or time-multiplexed multislice imaging) and a correction scheme is usually applied (7). The echo signal obtained in practical experiments can be expressed as

$$S(t_x, t_y) = S(t_x - \beta, t_y) \exp(i\alpha)$$

where $\tilde{S}(t_x, t_y)$ and $S(t_x, t_y)$ represent the echo signals with and without phase errors, and $\alpha$ and $\beta$ are the phase errors associated with zeroth and first-order phase delay, respectively. In this case, higher order phase error terms are not considered because these terms are negligible in comparison with zeroth and first-order terms. The effect of these phase errors in the image domain can be expressed as

$$f(\omega_x, \omega_y) = f(\omega_x, \omega_y) \exp(i(\alpha - \beta \omega_x)).$$

These phase errors, however, usually can be measured by an additional experiment and their compensation can be carried out with measured phase error terms (7). In addition to these phase error terms, the echo signal is weighted with $T_2$ relaxation as $S(t_x, t_y) \exp(-t/T_2)$. In principle, this $T_2$ term will introduce the nonzero imaginary part in the resultant image even in conventional single-slice imaging. However, it is found that an echo signal which is weighted by $\exp(-t/T_2)$ shows no measurable imaginary part compared with the real value. It is considered that the main reason for this negligible $T_2$ effect is that data acquisition time, $T_{da}$, is shorter than $T_2$ relaxation time.
Fig. 2. Human head image obtained with conventional single-slice Fourier imaging with phase correction. (a) and (b) show the real and imaginary parts of the image, respectively. The average image intensity ratio of (a) and (b) is about 50/1.
FIG. 3. Human head image obtained at another slice with the same scheme as in Fig. 2 except for a 90° phase difference in rf pulse excitation. Also, (a) and (b) represent the real and imaginary parts.
FIG. 4. Two simultaneously obtained head images with the proposed quadrature-multiplexing technique. (a) represents the real part while (b) represents the imaginary part. The two images are separated by 3 cm.
As the primary implementation of the proposed scheme, dual-slice imaging has been done using the human head. Figure 2 shows the real and imaginary parts of an image obtained using a conventional single-slice imaging scheme. As expected, the imaginary part has almost negligible information which can be used for another slice image. To show the feasibility of the proposed scheme, a single-slice image in another location is shown in Fig. 3 using exactly the same imaging method as in Fig. 2 except that the rf excitation pulses have a 90° phase difference. Figures 3a and b show the real and imaginary parts of the image without and with information, respectively. Finally, Fig. 4 shows the real and imaginary part images by the suggested quadrature-multiplexed pulse scheme with rf pulses combined with the ones in Fig. 2 and Fig. 3. It is noted that the dual images, (a) and (b), which correspond to Fig. 2a and Fig. 3b, can be obtained simultaneously with proper phase correction.\(^2\)

In conclusion, a new quadrature technique applicable to either shortening the imaging time by half or effectively doubling the number of image slices is proposed and experimentally proved. This method is effectively applicable to the existing time-multiplexed multislice technique to obtain \(2N\) slice images in conjunction with the already developed time-multiplexing \(N\) slice imaging. Care should be taken, however, to eliminate the phase errors as described because a simple magnitude technique is not applicable to phase correction in this case. It is also noted that this method is very sensitive to object motion which introduces phase distortion.

REFERENCES


\(^2\) As implied, phase error correction is essential for the quadrature-multiplexing technique.