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The Effect of High Performance Gradients on Fast Gradient Echo Imaging

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Abstract

The effect of gradient system performance on segmented k -space gradient echo imaging is presented. Three cases were investigated. First, an ideal system that has infinite slew rates and unlimited maximum gradient strengths was considered. Second, a “high speed” imaging system (2.3 (G/cm), 23 (G/cm)/ms) was considered. These two cases were compared with a “conventional” imaging system (1(G/cm), 1.67 (G/cm)/ms). It was found that substantial increases in SNR can be achieved ($\approx 45\%$) by using high speed versus a conventional gradient system, for a TR of 6 ms. For trapezoidal gradient waveforms, there exists an optimum maximum gradient strength for a given slew rate, and any increase in gradient strength above this optimum will not be utilized by an optimized sequence. These studies have shown that increasing TR without decreasing the bandwidth is not a good way to increase SNR for constant scan time.

Keywords

optimization; MRI; SNR; gradient coils

INTRODUCTION

It has been shown recently that very high quality cine cardiac studies can be obtained with standard MRI hardware. Two philosophies have been employed in these studies. Interleaved “spiral scans” (1,2) use high tip angles to collect k -space data over a pin-wheel trajectory in a short period. Similarly, interleaved echo planar imaging (EPI) techniques have been employed for rapid sampling of k -space (3,4). Segmented k -space gradient echo (GRE) methods with very short TR values ($TR < 7$ ms) have also been developed which scan a single line of k -space after each low tip angle RF pulse, but groups of lines are collected in each heartbeat as a single movie frame (5,6). Critical to the success of either approach is the suspension of patient breathing while scanning. Two major sources of image artifact were eliminated with these imaging methods: motion artifact from patient breathing, and flow artifact from the ventricular blood.

Two imaging parameters deserve particular attention in these protocols: the time resolution and the signal-to-noise ratio (SNR). High time resolution is required to freeze physiologic motion of the heart and breath-hold acquisition times challenge the SNR capabilities of the instrument. Both types of acquisition will benefit from the increased time resolution and SNR derived from using a high performance gradient system. In this paper, the dependence of the SNR on the gradient system performance in rapid GRE imaging has been investigated. Since performance has a nonlinear relationship with cost, it is important to estimate the benefits of

improved gradient performance to establish the optimum operating point for clinical systems. This analysis has focused on cardiac imaging, but the same analysis can be applied to functional imaging, diffusion imaging, velocity imaging and other methods that demand high gradient performance.

Specifically, the performance of short TR GRE cardiac imaging for use with segmented k -space techniques has been analyzed. This method has a number of advantages: the SNR is insensitive to field inhomogeneities, there is insignificant T_2^* decay during readout, it has low first moments on all gradient waveforms, a simple image reconstruction is used, and there is great flexibility between time resolution and total scan time trade-offs. The major disadvantage of segmented k -space techniques is that single heartbeat acquisitions will have lower time resolution than EPI or spiral techniques.

The effects of gradient performance on SNR are compared for a conventional gradient system maximum gradient strength ($G_{max} = 1 \text{ G/cm}$), slew rate ($dG/dt = 1.67 \text{ G/cm/ms}$), a high speed gradient system ($G_{max} = 2.3 \text{ G/cm}$, $dG/dt = 23 \text{ G/cm/ms}$), and a no-limitations case ($G_{max} = \infty$, $dG/dt = \infty$). Such a comparison quantifies the improvement in image quality with increased gradient performance, and its approach to the theoretical maximum.

The following sections contain the equations that describe the SNR behavior of rapid gradient echo imaging, and their implications for rapid gradient echo imaging techniques.

SNR of Rapid Gradient Echo Imaging

For a given magnetic field strength and receiver/transmit coil geometry, the amplitude of an MR signal can be expressed as (7):

$$S_{\text{tot}} \propto N_{\text{avg}} \Delta x \Delta y \Delta z S \quad [1]$$

where N_{avg} is the number of averages, Δx and Δy are the x and y voxel dimensions, Δz is the slice thickness, and S is the “relative signal” that accounts for the transient behavior of magnetization seen during the approach to steady-state of fast imaging techniques such as SPGR and GRASS (8-10). S is a function of TR , TE , T_1 , T_2 , T_2^* , tip angle (α), and RF repetition number.

With field strengths greater than 0.3T, the dominant source of noise originates from the sample, rather than the standard deviation of the receive coil resistive noise (11),

$$N \propto \sqrt{\frac{BWN_{\text{avg}}}{N_y}} \quad [2]$$

where BW is the voxel bandwidth (12) in the readout direction, and N_y is the number of phase encoding steps. The $\sqrt{N_y}^{-1}$ term represents the root mean square deviation (RMSD) noise contribution in the phase encoding direction. Defining SNR as the ratio of the signal amplitude, S , to the standard deviation of the noise (RMSD) (13), Eq. [1] is divided by Eq. [2],

$$\text{SNR} \propto \sqrt{N_{\text{avg}}} \Delta x \Delta y \Delta z S \sqrt{\frac{N_y}{BW}} \quad [3]$$

The voxel bandwidth in the readout direction is

$$BW = \frac{1}{N_x T} \quad [4]$$

where T is the time between samples and N_x is the number of samples acquired during readout.

We define the “efficiency” of a pulse sequence (14) as,

$$\eta = \frac{N_x T}{TR} \quad [5]$$

representing the fraction of TR that is devoted to sampling the signal. Thus, Eq. [4] becomes

$$BW = \frac{1}{\eta TR} \quad [6]$$

Substituting Eq. [6] into Eq. [3]

$$SNR \propto \sqrt{N_{avg}} \Delta x \Delta y \Delta z S \sqrt{N_y \eta TR} \quad [7]$$

The total scan time of an experiment is

$$T_s = N_{avg} N_y TR \quad [8]$$

Thus, the SNR per voxel becomes

$$SNR \propto S \Delta x \Delta y \Delta z \sqrt{\eta} \sqrt{T_s} \quad [9]$$

Equation 9 states that the SNR per pixel of an **MR** image is proportional to the relative signal, S , the voxel volume ($\Delta V = \Delta x \Delta y \Delta z$), root efficiency ($\sqrt{\eta}$), and root total scan time ($\sqrt{T_s}$). This is equivalent to the result derived by Parker and Gullberg (15).

SNR with Constant Bandwidth for SPGR

The relative signal, S , depends on the type of gradient echo pulse sequence. With a gradient recalled acquisition in steady-state (GRASS), S is most easily solved numerically (16,17). For a spoiled GRASS (SPGR) sequence, an analytical solution is given by (18),

$$S = \frac{(1 - e^{(-TR/T_1)}) e^{(-TR/T_2^*)} \sin \alpha}{1 - \cos \alpha e^{(-TR/T_1)}}. \quad [10]$$

To maximize S , and therefore SNR, the Ernst angle (19) should be used when imaging at steady-state,

$$\alpha_{Ernst} = \arccos(e^{(-TR/T_1)}) \quad [11]$$

Substituting Eq. [11] into Eq. [10] and simplifying,

$$S = \frac{(1 - e^{(-TR/T_1)}) e^{(-TR/T_2^*)}}{\sqrt{1 - e^{(-2TR/T_1)}}} \quad [12]$$

which implies from Eq. [9],

$$SNR \propto \Delta x \Delta y \Delta z \sqrt{\eta} \sqrt{T_s} \frac{(1 - e^{(-TR/T_1)}) e^{(-TR/T_2^*)}}{\sqrt{1 - e^{(-2TR/T_1)}}} \quad [13]$$

If $TR \ll T_1$, the Taylor approximation of an exponential is

$$e^{-(TR/T_1)} \approx 1 - \frac{TR}{T_1} \quad [14]$$

Substituting this approximation and Eq. [5] into Eq. [13]

$$SNR \propto \Delta x \Delta y \Delta z \sqrt{\frac{N_x T}{TR}} \sqrt{T_s} \frac{\frac{TR}{T_1} e^{(-TR/T_2^*)}}{\sqrt{\frac{2TR}{T_1}}} \quad [15]$$

which simplifies to

$$\text{SNR} \propto \Delta x \Delta y \Delta z \sqrt{N_x T} \sqrt{T_s} \frac{e^{(-TE/T_2^*)}}{\sqrt{2T_1}} \quad [16]$$

Equation 16 implies that the SNR per pixel for constant scan time is *independent* of TR when the readout sample bandwidth is fixed, $TR \ll T_1$, and α equals the Ernst angle. This equation demonstrates that for SPGR any increase in signal by T_1 relaxation due to an increase in TR , is exactly offset by the reduction in averaging to maintain a constant scan time. Therefore, for constant scan time, nothing is gained by adding dead time to an SPGR sequence to allow for longitudinal magnetization recovery, unless another slice can be imaged during that dead-time.

Pulse Sequences

A standard fast gradient echo sequence shown in Fig. 1 has been previously described for a GE 1.5T Signa clinical scanner (version 4.7) (6) with conventional gradient hardware. Features of this pulse sequence include: asymmetrical sinc, fractional echo, GRASS and SPGR modes, (spoiling achieved through phase cycling (g)), and overlapping slice ramp and phase encoding rewinder gradients. The minimum $TR \approx 6$ ms, and minimum $TE \approx 2$ ms, with conventional gradient hardware. The readout bandwidth can be chosen as ± 16 kHz or ± 32 kHz. This pulse sequence was used for both simulations and experiments.

METHODS

Simulations

A Bloch equation simulation computer program was written to calculate the expected relative signal, S . The effects of T_1 , T_2 , T_2^* , α , TR , TE , and RF repetition number are included in these simulations. The simulations assumed that the phase encoding pulse is properly rephased and that a 2π phase shift exists across each pixel at the completion of the readout gradient. The slice selection pulse of the pulse sequence (asymmetrical sinc with apodizing Hamming window and trapezoidal gradient) was simulated to generate the actual slice profile. The RF phase spoiling method (9) used in this pulse sequence was accounted for in the SPGR simulations. For steady-state simulations, (large number of RF pulses, with $nTR \gg 5T_1$), S was solved analytically for SPGR (Eq. [10]), and numerically for GRASS (16,17). Timing calculations of each pulse sequence were used to account for the effect of efficiency on SNR. The optimum α was used to maximize S . The dependence of SNR on TR was calculated by increasing the readout acquisition time ($N_x T$) from its minimum allowable value (determined by the maximum readout gradient strength), such that SNR was a parametric function of $N_x T$. The readout gradient G_x was decreased commensurate with increases in $N_x T$ to maintain constant spatial resolution. For each value of $N_x T$, the TR is calculated based on the pulse sequence shown in Fig. 1. Increasing $N_x T$ increases TR and decreases the sample bandwidth ($1/N_x T$). Once a minimum bandwidth $BW_{\min}$ has been reached, the algorithm fixed sample bandwidth at $BW_{\min}$ and incremented TR by adding dead time. $BW_{\min}$ is set by the user, to prevent artifacts from inhomogeneous fields and chemical shift. For example, $BW_{\min} = 225$ (Hz/pixel) reduces chemical shift between fat and water to one pixel, at 1.5T. SNR was subsequently calculated from Eq. [9].

Simulations with the nonselective pulse are useful because they are independent of a particular slice profile. In addition, calculation of S at steady-state removes the dependence on the transient portion of the MR signal, making SNR estimates independent of the number of RF repetitions used ($N_{\text{avg}} \cdot N_y$). When experimentally verifying SNR predictions, however, the approach to steady-state, as well as slice selection must be considered.

The computer program also calculated the effect of switching time and gradient strength on efficiency (η). TR was calculated for the pulse sequence diagrammed in Fig. 1 for particular imaging parameters (Δx , Δy , Δz , field of view (FOV), etc).

Readout sampling time is calculated from the sample bandwidth and η is the ratio of readout sampling time to TR (Eq. [5]).

Experimental Protocol

Experiments were performed to validate the simulations. A stationary phantom ($T_1 = 685$ ms and $T_2 = 73$ ms at 1.5T) made from agarose (1.5 wt%) and CuSO_4 (1.25 mM) was used to emulate the relaxation characteristics of the myocardium. The agarose was contained within a 25-ml scintillation vial, approximately 25 mm in diameter.

Profiles in the readout direction were measured during the approach to steady-state for GRASS and SPGR at different bandwidths. At each bandwidth, dead time was added to TR , and the approach to steady-state measured. The Ernst angle was used for SPGR, and $\alpha = 20^\circ$ for GRASS. The dependence of the SNR as a function of α for GRASS has a broad maximum (14,17), and simulations show that the optimum α as a function of TR varies little from 20° at $TR < 50$ ms, $T_1 = 685$ ms and $T_2 = 73$ ms (data not shown). The phase encoding gradient was disabled and data were collected over 256 repetitions. The voxel volume was held constant by maintaining constant Δx , Δy , and Δz . Imaging parameters were chosen to be: $\text{FOV}_x = \text{FOV}_y = 24$ cm, $\Delta z = 0.5$ cm, and echo fraction (ζ) = 0.62. Echo fraction is the ratio of the distance traversed in k -space during readout over the maximum k -space dimension (14), such that $\zeta = 1$ for a symmetrical echo, and 0.5 for a free induction decay. Although SNR is proportional to $\sqrt{\zeta}$, fractional echoes can significantly reduce TE and TR , compensating for this loss in SNR, through increased efficiency by decreasing the duration of the readout prephaser. Echo fraction, therefore, should only be reduced until the readout prephaser is no longer a determining factor of the dead time.

RESULTS

Experimental Results

Approach to Steady State—Figure 2 shows the signal evolution (normalized and noise corrected (13)), S , for SPGR and GRASS as a function of RF repetition number. Symbols are experimental data and solid lines are calculated from the Bloch equation simulations. Close agreement existed between the experimental and calculated signal levels for both the steady-state and transition regions.

SNR Experimental Results—The mean signal values of the imaginary and real signal components were calculated and found to be zero in the region of the profile outside the phantom, indicating that this region was artifact free. The variance, σ^2 , was calculated from the complex profile data in this region from all 256 excitations. The total signal power of the profiles from the last 50 excitations was calculated and averaged together, because the signal level had reached steady-state (Fig. 2). Figures 3a and 3b show the SNR behavior for SPGR and GRASS for constant image bandwidths of ± 16 kHz and ± 32 kHz ($BW_{\min} = 125$ (Hz/pixel), 250 (Hz/pixel), respectively). All data were normalized by $\sqrt{T_s}$ to calculate SNR for constant scan time, and scaled such that the signal from a 90° pulse had a value of 100. Actual SNR values before normalization ranged from 20 to 30. Also shown in these graphs are simulations (solid lines) that account for slice selection profiles, the approach to steady-state, and pulse sequence efficiency. The close agreement between the experimental SNR measurements and calculated predictions validates the SNR theory developed in the SNR of Rapid Gradient Echo Imaging section.

SNR Steady-State Simulation Results

Once an understanding of the SNR behavior for gradient echo sequences was established and experimentally validated, additional simulations were performed to evaluate the effect of gradient performance.

Figures 4a and 4b plot the relative SNR against TR for GRASS with conventional and high speed gradient hardware, respectively. The steady-state simulations assume constant scan time and constant spatial resolution (Δx , Δy , Δz). The effect of fixing the bandwidth at a value of $BW_{\min}$ and increasing TR with dead time, is also seen in these figures, for various values of $BW_{\min}$ (50, 100, 200, 400, 800 Hz/pixel). The imaging parameters used in these simulations include: FOV = 24 cm, $N_x = 160$, $N_y = 128$, $\zeta = 0.62$, $\Delta z = 1$ cm, $T_1 = 875$ ms, and $T_2 = 60$ ms. $G_{\max} = 1$ G/cm, $dG/dt = 1.67$ G/cm/ms for the conventional gradients, and $G_{\max} = 2.3$ G/cm, $dG/dt = 23$ ((G/cm)/ms) for the high speed gradients. Finally, the no-limitations responses ($G_{\max} = \infty$, $dG/dt = \infty$, $\eta = 1$) are shown in these plots, representing the maximum possible SNR response. Figures 5a and 5b are equivalent simulations for SPGR.

The minimum TR point in each curve occurs when the readout gradient is at its maximum strength. It can be seen from these plots that significant improvement in SNR, as well as reduced minimum TR , can be achieved with high performance gradients. For example, at $TR = 6$ ms, there is a 48% increase in SNR with the high speed gradients for both GRASS and SPGR. This increase in SNR is due to increased pulse sequence efficiency (η) when using high speed gradients. The details of efficiency optimization for different components of gradient echo sequences are now investigated.

Efficiency Optimization

The dead time of the phase encoding, slice selection, and readout prephaser lobes are the major contributors to dead time of a gradient echo pulse sequence. Minimization of the time required to execute these waveforms improves efficiency and reduces the minimum TR ($TR_{\min}$) and minimum TE ($TE_{\min}$).

Phase Encoding and Slice Selection Dead Time—The dead time required to execute the phase encoding lobe (and rewinder) with the largest area is (Fig. 1),

$$T_{pe} = \begin{cases} \frac{1}{\gamma \Delta y G_{\max}} + \frac{G_{\max}}{dG/dt} & \text{if } G_{\max} < \sqrt{\frac{dG}{dt} \frac{dG}{\gamma \Delta y}} \text{ (trapezoid)} \\ \frac{2}{\sqrt{\gamma \Delta y \frac{dG}{dt}}} & \text{if } G_{\max} > \sqrt{\frac{dG}{dt} \frac{dG}{\gamma \Delta y}} \text{ (triangle)} \end{cases} \quad [17]$$

where dG/dt is the gradient slew rate and $G_{\max}$ is the maximum available gradient strength available. The first case of Eq. [17] is the time required to play a trapezoidal phase encoding gradient, and the second case is the time required to play a triangular phase encoding lobe. The triangular lobe is independent of $G_{\max}$, so that no gains are made by increasing the maximum available gradient strength. The maximum available gradient strength and slew rate are properly “matched” when the phase encoding lobe is at the transition between a trapezoidal and triangular gradient waveform. This “optimal” maximum available gradient strength is given as,

$$G_{\text{opt}} = \sqrt{\frac{dG}{dt} \frac{dG}{\gamma \Delta y}} \quad [18]$$

Figure 6a is a contour plot of the phase encoding dead time behavior as a function of maximum available gradient strength and slew rate (Eq. [17]) for a 1.9 mm Δy voxel dimension (FOV = 24 cm, $N_y = 128$). There is a “corner” point in the contour that represents the transition point

from trapezoidal to triangular phase encoding lobes, given by Eq. [18], and plotted in Fig. 6b for three Δy values.

It is not possible to reduce phase encoding dead time with higher maximum available gradient levels than G_{opt} for a particular (dG/dt) ($G_{max} > G_{opt}$).

In addition to the phase encoding lobe, the slice selection gradient can be optimized in a similar manner. For a trapezoidal slice selection gradient, the dead time for slice selection is

$$T_{ss} = \begin{cases} 2 \frac{G}{\frac{dG}{dt}} + \frac{Z_c}{\gamma \Delta z G} + 2 \sqrt{\frac{f Z_c}{\gamma \Delta z \frac{dG}{dt}} + \frac{G^2}{2 \frac{dG}{dt}}} & \text{if } G_{max} > \sqrt{\frac{f \frac{dG}{dt} Z_c}{\gamma \Delta y} + \frac{G^2}{2}} \\ 2 \frac{G}{\frac{dG}{dt}} + \frac{Z_c}{\gamma \Delta z G} + \frac{f Z_c}{\gamma \Delta z G} + \frac{f Z_c}{\gamma \Delta z G_{max}} & \text{if } G_{max} < \sqrt{\frac{f \frac{dG}{dt} Z_c}{\gamma \Delta y} + \frac{G^2}{2}} \end{cases} \quad [19]$$

where G is the gradient strength of the plateau during RF irradiation ($G \leq G_{max}$), Z_c is the number of zero crossings of the sinc, and f is the fraction of the plateau that needs to be refocused in the slice refocusing lobe. For a symmetrical sinc RF waveform, $f = 1/2$, although the pulse sequence used in this study has an asymmetrical sinc, with $Z_c = 3$ and $f = 1/3$. For a given slew rate, there exists an optimum value of G , since ramp times increase as G increases, and there is therefore a trade-off between a short RF pulse with a high gradient and the total ramp and rephasing time required. Although an analytical expression can be derived for the optimum slice selection gradient, G , it is a complicated expression and does not add insight into this problem. Ideally, the gradient strength should be sufficiently high to achieve this optimum plateau gradient strength. For minimum slice selection time, G_{max} should also be high enough to allow for a triangular slice refocusing lobe. Figure 7 is a contour plot of slice selection dead time as a function of G_{max} and slew rate. This plot was generated by increasing G_{max} for a given slew rate. When the optimum plateau gradient strength was reached, the plateau gradient strength was fixed, and the maximum available gradient strength for the refocusing lobe was increased further. A “corner” point can be seen for the isocontours, where additional increases in the maximum available gradient strength do not continue to reduce slice selection dead time. This point occurs at the transition between a trapezoidal and triangular refocusing lobe. It was found for typical slice thicknesses (1–20 mm), and slew rates and maximum available gradient strengths shown in Fig. 7, that the optimum plateau gradient strength was always less than G_{max} necessary for a triangular refocusing lobe, for this pulse sequence.

The methods described above can also be applied to the readout prephaser. The time required for the readout prephaser, however, is usually smaller than the time required for phase encoding or slice selection with the use of fractional echoes.

When these three gradient lobes (slice selection, phase encoding, and readout prephaser) are considered in the context of the final pulse sequence, it becomes very difficult to describe sequence dead time analytically. Regardless, the above analysis has value in understanding the overall optimization problem.

Overall Effect of Maximum Gradient Strength and Slew Rate on Efficiency—The effects of slew rate and maximum available gradient strength on efficiency of a complete sequence are summarized in the contour plot found in Fig. 8a. As discussed in the Phase Encoding and Slice Selection Dead Time section, the slice gradient strength is not increased beyond its optimum value, so the efficiencies shown are the best possible for that combination of gradient strength and slew rate. The gradient strengths for all other gradients were set to maximum, for optimum efficiency. Again, there exists a “corner” point in each of the efficiency isocontours. This point occurs when the gradient lobes that determine the dead time of the sequence, make the transition from trapezoidal to triangular lobes. Figure 8b shows the optimum maximum gradient strength as a function of increasing slew rate, for three Δz -FOV

pairs. A small “kink” in curves 2b and 3b is seen at low slew rates. This occurs because the readout prephasing lobe has a longer duration than either the phase encoding or the slice rephasing lobes with a small field of view at low slew rates. The readout prephasing lobe duration can be reduced with a lower echo fraction, ζ . It is assumed that the gradients on each axis are identical and have the same maximum available gradient strength and slew rate.

Efficiency Comparison of Conventional and High Speed Gradient Sets—A

comparison of the efficiency performance of the conventional gradient hardware ($G_{\max} = 1 \text{ G/cm}$, $dG/dt = 1.67 \text{ G/cm/ms}$) and high speed gradient hardware ($G_{\max} = 2.3 \text{ G/cm}$, $dG/dt = 23 \text{ G/cm/ms}$) was made. Two sets of imaging parameters were chosen to compare relative efficiencies of both the conventional and high speed gradient sets. Figure 9a plots η with higher resolution imaging parameters ($\Delta z = 0.5 \text{ cm}$, $\text{FOV} = 12 \text{ cm}$, $N_y = 128$ and $\zeta = 0.62$). Similarly, Fig. 9b plots η with lower resolution imaging parameters ($\Delta z = 1 \text{ cm}$, $\text{FOV} = 24 \text{ cm}$, $N_y = 128$ and $\zeta = 0.62$).

With the higher resolution imaging protocol, $TR_{\min} = 3.3 \text{ ms}$ using the high speed gradients and 8.5 ms with the conventional gradients¹ (Fig. 9a). $TR_{\min} = 2.3 \text{ ms}$ and 5.2 ms for the high speed and conventional gradients, respectively, when imaging with the lower resolution protocol. Although the improvement in efficiency with the high speed gradients is small at $TR > 20 \text{ ms}$, there are substantial gains in efficiency at $TR < 10 \text{ ms}$. As seen in Fig. 9a there is a 111% increase in efficiency at $TR = 8.5 \text{ ms}$ from conventional to high speed gradients, and in Fig. 9b there is a 167% increase in efficiency at $TR = 5.2 \text{ ms}$.

DISCUSSION

Until recently gradient performance features such as switching times and maximum amplitudes had little effect on SNR considerations because the switching times were short with respect to TR and TE . In rapid breath-hold imaging, these factors now play a significant role in determining the time resolution and SNR. While single heartbeat imaging is possible, (20-22) multiple heartbeat acquisitions can be used to increase the SNR by increasing the data acquisition time and collecting the data with lower bandwidth. However, rapid gradient switching is needed to play out the multiple gradient echo acquisitions.

A Bloch equation simulation of the rapid GRE acquisition, including the transition to steady-state, has been written and validated with experiments. Using this simulation, the effects of the slew rate and maximum available gradient strength on SNR were analyzed.

It has been shown in this work that increasing TR without decreasing the bandwidth is not a good way to increase SNR for constant scan time. The increase in steady-state signal from the increased T_1 recovery is almost exactly cancelled by a decrease in averaging.

In addition, reduced dead time (improved efficiency) without commensurate increases in sampling time and decreases in bandwidth does little to improve SNR. Therefore, an imaging system can only take full advantage of high performance gradients if its receiver bandwidth is easily adjusted.

It has also been shown for trapezoidal phase encoding and slice selection gradient pulses, and an entire gradient echo sequence that there exists an optimum maximum gradient strength for a given slew rate. Any increase in the maximum gradient strength above this value will not be utilized by an optimized sequence.

¹Bandwidth at $TR_{\min}$ is $\approx \pm 50 \text{ kHz}$ using conventional gradients and $\approx \pm 120 \text{ kHz}$ with high speed gradients.

Comparison of Figs. 6b and 7b with Fig. 8b for FOV = 24 cm, $N_y = 128$, and $\Delta z = 10$ mm shows that the slice selection gradient pulses were more important in determining the overall pulse sequence efficiency than the phase encoding pulses, for the pulse sequence and spatial resolution used in this analysis. Figures 6b and 7b show that optimal maximum gradient strengths were higher for the phase encoding pulse than the slice selection pulse. This suggests that techniques that reduce the dependence of pulse sequence efficiency on the slice selection gradient pulse will allow the pulse sequence designer to take advantage of higher maximum gradient strengths for a given slew rate. Some potential techniques are variable-rate selective excitation (VERSE) (23) or self-refocussing slice selection through symmetrical weighting of k -space (24). The asymmetrical sinc RF pulse used in this study helped alleviate the domination of slice selection on gradient matching.

It was also found that significant improvements in SNR will be achieved by faster switching times for TR values under 10 ms. For the gradient values associated with conventional hardware, using a TR of 6 ms implies operating at 39% efficiency when the sequence has been optimized for a 24-cm FOV/1 cm Δz imaging protocol (Fig. 9b). If high speed imaging gradients are used, the efficiency increases to 82% corresponding to an increase of 45% in SNR. This increase in SNR was achieved by decreasing the bandwidth, as seen by comparing minimum bandwidths, $BW_{\min}$, between Figs. 4a and 4b or Figs. 5a and 5b.

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FIG. 1.

The gradient echo pulse sequence used in this study. Features of this sequence include an asymmetrical sinc, fractional echo, GRASS and SPGR modes, and overlapping slice ramp and rewinder. Minimum $TR \approx 6$ ms and $TE \approx 2$ ms, for typical imaging parameters, with conventional gradient hardware.

FIG. 2. Signal, S as a function of RF repetition number for SPGR ($\alpha_{\text{Emst}} = 10.0^\circ$) and GRASS ($\alpha = 20^\circ$) at 1.5T. $TR = 10.5$ ms, $TE = 3.6$ ms, $T_1 = 683$ ms, $T_2 = 73$ ms. Symbols are experimental data and solid lines are Bloch equation simulations. $S = 1$ corresponds to the maximum possible signal.

FIG. 3. SNR (normalized by the square root of T_s , versus TR for (a) GRASS and (b) SPGR, at ± 32 kHz and ± 16 kHz. Symbols are experimental data and solid lines are Bloch equation simulations. Both simulated and experimental data were normalized to a 90° pulse, whose SNR was taken as 100.

FIG. 4.

SNR (normalized by the square root of T_2) versus TR for GRASS for (a) conventional hardware and (b) high speed gradient hardware. Also shown are the SNR responses with no hardware limitations ($\eta = 1$). Data were normalized to a 90° pulse, whose SNR was taken as 100. The “branch” points occur at TR values where the BW (Hz/pixel) first reaches $BW_{\min}$ (Hz/pixel)

FIG. 5. SNR (normalized by the square root of T_s) versus TR for SPGR for (a) conventional hardware and (b) high speed gradient hardware. Also shown are the SNR responses with no hardware limitations ($\eta = 1$). Data were normalized to a 90° pulse, whose SNR was taken as 100. The “branch” points occur at TR values where the BW (Hz/pixel) first reaches BW_{min} (Hz/pixel).

FIG. 6.

(a) Phase encoding pulse duration time (ms) as a function of maximum available gradient strength and slew rate. $\Delta y = 1.9$ mm (FOV = 24 cm, $N_y = 128$). The dashed line is the optimum gradient strength. (b) Optimum gradient strength for phase encoding versus slew rate for $\Delta y = 1$ mm, 1.9 mm, 4 mm. The triangle and square are the operating points of the conventional high speed gradients, respectively.

FIG. 7.

(a) Contour mapping of the slice selection dead time against maximum available gradient strength and slew rate, for $\Delta z = 5$ mm. The gradient strength is not increased past its optimum value. The dashed line is the optimal gradient strength for a given slew rate. (b) Optimum gradient strength versus slew rate for slice selection. $\Delta z = 2, 5$, and 10 mm. The triangle and square are the operating points of the conventional high speed gradients, respectively.

FIG. 8.

(a) Contour mapping of the optimum efficiency against maximum available gradient strength and slew rate. The slice gradient strength during the plateau is not increased past its optimum value. $\Delta z = 10$ mm, FOV = 24 cm, $N_y = 128$, $N_x = 160$, and bandwidth = ± 32 kHz. (b) Optimum gradient strength versus slew rate. $\Delta z = 5$ mm and FOV = 12 cm for curve 1b, $\Delta z = 10$ mm and FOV = 24 cm for curve 2b, $\Delta z = 15$ mm and FOV = 36 cm for curve 3b. $N_y = 128$, $N_x = 160$, and bandwidth = ± 32 kHz for all three curves. The triangle and square are the operating points of the conventional and high speed gradients, respectively.

FIG. 9.

Efficiency versus TR with conventional and high performance gradient hardware for (a) higher resolution imaging protocol ($FOV = 12$ cm, $\Delta z = 5$ mm, $N_y = 128$, and $\zeta = 0.62$) and for (b) lower resolution imaging protocol ($FOV = 24$ cm, $\Delta z = 10$ mm, $N_y = 128$, and $\zeta = 0.62$).