Spiral Scan Peripheral Nerve Stimulation

Kevin F. King, PhD,* and Daniel J. Schaefer, PhD

Time-varying magnetic fields induce electric fields that can cause physiological stimulation. Stimulation has been empirically characterized as a function of $dB/dt$ and duration based on experiments using trapezoidal and sinusoidal gradient waveforms with constant ramp time, amplitude, and direction. For two-dimensional (2D) spiral scans, the readout gradient waveforms are frequency- and amplitude-modulated sinusoids on two orthogonal axes in quadrature. The readout gradient waveform therefore rotates with amplitude and angular velocity that are generally not constant. It does not automatically follow that spiral stimulation thresholds can be predicted using available stimulation models. We scanned 18 normal volunteers with a 2D spiral scan and measured global thresholds for axial, sagittal, and coronal planes. We concluded that the stimulation model evaluated accurately predicts slew rate-limited spiral mean stimulation thresholds, if the effective ramp time is chosen to be the half-period at the end of the spiral readout. J. Magn. Reson. Imaging 2000;12: 164–170. © 2000 Wiley-Liss, Inc.

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IN MRI, TIME-VARYING magnetic fields ($dB/dt$) are used to determine spatial locations of precessing nuclei. Electric fields induced by $dB/dt$ can cause nerve stimulation in patients (1–11). At a sufficiently high level, gradient-induced electric fields can induce ventricular fibrillation (12–15). To avoid potential hazards, safety standards ensure that such electric fields are far below levels that can stimulate the heart (16,17). An indicator of induced electric fields is peripheral nerve stimulation (PNS). PNS is not considered life threatening, but at a sufficiently high level it can result in involuntary muscle movement and can be very unpleasant or painful, even though far below the cardiac stimulation threshold. Electric fields induced by switching gradients must therefore be limited to minimize patient discomfort.

PNS has been extensively studied with trapezoidal and sinusoidal gradient waveforms. These studies have typically used a train of periodic waveforms played on one or more gradient axes. Even though stimulation is directly caused by electric fields, empirical models and experiments focus on $dB/dt$ as a stimulation measurement. Most experimental data, plus the results of a semiempirical model of nerve stimulation by Reilly (1) can be fit (18) using the formula

$$
\left(\frac{dB}{dt}\right)_{\text{threshold}} = 54(T/\text{sec}) \left[1 + \frac{132 \text{ ms}}{\tau(\mu\text{sec})}\right]. \quad (1)
$$

Equation [1] (called the stimulation model in this paper) has been found to predict population mean threshold $dB/dt$ levels for PNS caused by periodic trains of identical trapezoids or sinusoids. In Eq. [1], $\tau$ is the total ramp time, eg, the time to ramp from zero to the plateau for a unipolar trapezoidal waveform, or the time to ramp from the negative plateau to the positive plateau for a bipolar trapezoidal waveform such as an echoplanar (EPI) readout. Equation [1] also applies to sinusoidal waveforms if $\tau$ is taken to mean the peak-to-peak waveform slewing time, ie, the time from the valley to the crest of a sinusoid (half-period). [However, note that Harvey and Katznelson (19) use $\tau$ equal to $1/\pi$ times the sinusoidal period.]

For the complicated gradient waveforms used in MRI, extending the results of currently available data and models to ensure avoiding PNS is problematic. For the most part, the gradient waveforms typically used in imaging are not the same ones used in experiments or computer models of nerve stimulation, nor is it a simple matter to use more complicated waveforms as the basis of such studies.

Spiral scans (20,21) have been increasing in popularity for fast imaging applications. Extending gradient switching safety requirements to spirals is necessary as its use becomes more widespread. The readout gradient waveforms for spirals (22) are frequency- and amplitude-modulated sinusoids applied on two gradient axes in quadrature (Fig. 1). In general, the vector representing the readout gradient rotates with time-dependent amplitude and angular frequency. It is not clear to what extent previous models of PNS can be applied to spiral imaging gradient waveforms.

We studied PNS by scanning normal volunteers with a two-dimensional (2D) spiral scan protocol that was chosen to give a relatively low threshold of PNS based on the assumption that the stimulation model is valid. In preliminary work (23), we found that PNS thresholds are in reasonable agreement with the stimulation model for a slew rate-limited spiral k-space trajectory, pro-
used a spiral that reached \( G = G_0 \) near the end of the readout and had \( S \approx S_0 \) during the entire trajectory. The instantaneous frequency is \( \omega = \dot{\theta} \), resulting in an instantaneous half-period \( \tau = \pi/\omega \). Numerical solution of the equations of motion for such an Archimedean spiral (Eq. [8] in Appendix A) shows that \( \tau \) is initially large, decreases briefly, and then increases throughout the rest of the readout (Fig. 2). Since the threshold predicted by Eq. [1] decreases with increasing \( \tau \), the lowest threshold should occur either near the beginning or near the end of the spiral readout. The exact duration of the large value of \( \tau \) near the beginning of the readout depends on the scan parameters but is typically only a few hundred \( \mu \text{sec} \) at most. Since the nerve stimulation time constant used in Eq. [1] is 132 \( \mu \text{sec} \), it seems reasonable that stimulation for comparable or shorter time durations would not be significant. Therefore, in developing a spiral protocol with the lowest threshold, we used the value of \( \tau \) at the end of the readout. During the test, we kept \( (dB/dt)_{\text{threshold}} \) in Eq. [1] roughly constant at this chosen threshold by using a prescription where \( \tau \) did not vary much as a function of \( S_0 \) (see the discussion at the end of Appendix A). We then changed the actual \( dB/dt \) by varying the spiral slew rate \( S_0 \). The complete protocol is \( M = 2, D = 14 \) cm, readout bandwidth \( \pm 125 \) kHz, readout time 32 msec (8000 points/interleave), gradient echo, TR/TE 100/3.2 msec, flip angle 0. Waveforms are shown in Fig. 1. Justification for the scan parameters is given in Appendix A.

Figure 2. \( \tau \) (msec) as a function of time during the spiral readout. The scan prescription is the one used for PNS testing for a slew rate \( S_0 = 120 \) T/m/sec. a: The first 0.128 msec of the readout, shown on an expanded scale. b: The complete 32 msec.
**Scanning Protocol**

A 1.5-T commercial scanner (GE Medical Systems, Milwaukee, WI) with a cardiac-optimized gradient coil (field of view 40 cm, maximum amplitude 40 mT/m) and an experimental spiral pulse sequence were used for data collection. Gradient amplifier hardware limited slew rates to a maximum of 180 T/m/sec. Eighteen normal volunteers (17 males, 1 female) were scanned. Informed consent was obtained from each volunteer after the nature of the procedure had been fully explained. Volunteer parameters included (mean ± standard deviation) 83.9 ± 11.3 kg weight and 1.77 ± 0.05 m height. Volunteers were placed in the scanner supine, feet first, with arms and legs in any comfortable, unclasped position. The umbilicus of each volunteer was initially placed at isocenter. Spiral slew rates from $S_0 = 80$ T/m/sec to $S_b = 180$ T/m/sec were tested. At threshold, the electrical stimulation sensation is just perceptible.

The subject was exposed to increasingly high gradient slew rates starting from 80 T/m/sec (subthreshold intensity for all volunteers) until stimulation was reported and then to lower slew rates until stimulation was no longer reported. By increasing slew rates above perception threshold levels, subjects were clearly able to distinguish between gradient-induced stimulation and other distracting stimuli such as table vibration. The volunteer was then moved in 2-cm increments superior of isocenter. Positions up to 32 cm superior of isocenter were examined. Volunteers reported the quality and location of each stimulation. All stimulation data were measured in terms of gradient slew rates. The minimum stimulation slew rate for all positions (global threshold) was tabulated. Global thresholds were found for axial, sagittal, and coronal planes. The means and standard deviations of the global thresholds were calculated for the entire group of 18 volunteers for each of the three scan planes. When stimulation thresholds exceeded the 180-T/m/sec hardware limit, logistic regression was applied to provide estimates of the mean and standard deviation.

**Validity of the Stimulation Model for Spirals**

Accuracy of the stimulation model for spiral waveforms was tested by comparing the spiral PNS data with measurements using a trapezoidal waveform for which the stimulation model is accepted to be valid (9). The trapezoids had a different $\tau$ than the spirals. To allow a comparison, the trapezoidal PNS mean thresholds were adjusted by multiplying by the scale factor

$$
\left(1 + \frac{132 \mu\text{sec}}{\tau_{\text{spiral}}}ight) / \left(1 + \frac{132 \mu\text{sec}}{\tau_{\text{trapezoid}}}ight).
$$

(4)

The trapezoid experiment used $\tau_{\text{trapezoid}} = 368 \mu\text{sec}$. For the spiral protocol used, $\tau_{\text{spiral}}$ is somewhat dependent on the slew rate. Numerical solution of Eq. [8] shows that $\tau_{\text{spiral}}$ ranges from approximately 830 to 1000 $\mu\text{sec}$ for the chosen protocol over the slew rate range we used. This variation in $\tau$ gives less than 3% variation in the scale factor computed using Eq. [4]. We used $\tau_{\text{spiral}} = 1000$ $\mu\text{sec}$, appropriate for the worst case, for the comparison. Agreement between spiral and trapezoidal thresholds indicates consistency of the scale factor in Eq. [4], and by extension, consistency of the stimulation model between spirals and trapezoids. Because of data scaling and logistic regression, the validity of a Student’s $t$-test to compare spiral and trapezoidal means is questionable. However, results of $t$-tests are given in the Results section. One object of the study was to obtain a practical method for estimating mean stimulation thresholds for spiral scans.

To determine whether the stimulation model agreed with our measured PNS thresholds, we estimated the $dB/dt$ actually induced by the gradient waveforms. The maximum instantaneous $dB/dt$ resulting from the spiral readout gradients for an axial plane is (Appendix B):

$$\left(\frac{dB}{dt}\right)_{\text{actual}} = SL.\quad (5)$$

where $S$ is the spiral slew rate and $L$ is the distance of the stimulation point from isocenter. We compared Eqs. [1] and [5] for axial planes to determine whether our measured spiral PNS thresholds agreed with the thresholds predicted by the stimulation model. This required estimating the distance $L$ of the stimulation point. Ideally $L$ would be estimated by measuring the stimulus distance from isocenter. This was not practical in our experiment because of time constraints and the obstruction caused by the volunteer. We also observed that the stimulus was perceived to be diffusely located in many instances, thus further increasing the difficulty in estimating $L$. Instead we used field maps of the gradient coil to estimate the worst-case value of $L$ corresponding to the largest $dB/dt$ found within the patient bore. The field maps were produced using a Biot-Savart calculation, given the wire pattern and current for the coil. The maps were used to calculate (9):

$$dB/dt = \sqrt{(dB_x/dt)^2 + (dB_y/dt)^2 + (dB_z/dt)^2}$$

for an input current that would produce a slew rate of 150 T/m/sec on each axis separately. Due to gradient nonlinearity, the physical distance of the maximum $dB/dt$ point is not the same as the effective distance $L$. The effective distance $L$ is chosen to give the actual maximum $dB/dt$ for the nominal slew rate used. Based on the field maps, at a slew rate of 150 T/m/sec, the maximum $dB/dt$ found anywhere within the patient bore was 80 T/sec for $x$, $y$, or $z$ axes separately. This gave a worst-case effective distance $L = 0.53$ m. The actual distance of the maximum $dB/dt$ point is quite
RESULTS AND DISCUSSION

The means and standard deviations of the spiral scan thresholds \((n = 18)\) for axial, sagittal, and coronal scan planes are shown in Table 1. The adjusted trapezoidal mean thresholds \((n = 13)\) are also shown in Table 1. Because of the concerns about data scaling and logistic regression discussed earlier, it is of questionable validity to use a Student’s \(t\)-test to determine whether differences between spiral and trapezoidal means are significant. However, if \(t\)-tests are performed in spite of these considerations, the \(P\) values found are 0.17 for the axial plane, 0.11 for the sagittal plane, and 0.19 for the coronal plane. The two data sets may have statistically significant differences. Note that the axial means differ by 6.4\%, the sagittal means differ by 8.0\%, and the coronal means differ by 0.8\%. Since these differences are close to the 10 T/m/sec resolution of the experiment, the means are comparable. Thus it appears that stimulation thresholds for spiral waveforms may be predicted from those of trapezoidal waveforms based on the longest \(\tau\) used in the spiral protocol.

To compare the \(dB/dt\) thresholds predicted by the stimulation model with the measured thresholds, we compared Eqs. [1] and [5] using data for an axial plane. For the comparison, we used \(\tau = 900\) \(\mu\)sec in Eq. [1]. This is the value of \(\tau\) that results at the end of the spiral readout when \(S = 110\) T/m/sec (mean for an axial plane) is used for the slew rate. We also used \(S = 110 \pm 23\) T/m/sec and \(L = 0.53\) m in Eq. [5]. The resulting stimulation model and actual \(dB/dt\) thresholds are 61.9 T/sec and 58.3 T/sec, respectively. The agreement between the stimulation model and the experimental data is quite reasonable.

Alternatively, we can estimate the mean threshold slew rate from the stimulation model by equating Eqs. [1] and [5] and solving for \(S\). For the experimental protocol, \(\tau\) ranges from 830 to 1000 \(\mu\)sec, giving a mean threshold slew rate ranging from \(S = 118\) T/m/sec to \(S = 115\) T/m/sec with \(L = 0.53\) m. This is in reasonable agreement with the measured axial plane threshold \(S = 110 \pm 23\) T/m/sec.

From these comparisons we conclude that, within the accuracy of our experiment, the stimulation model predicts mean peripheral nerve stimulation thresholds caused by spiral scan imaging gradients for the constant slew rate spiral case, if the effective ramp time is chosen to be the half-period of the longest sinusoid at the end of the spiral readout.

The spiral scan parameters for the experiment do not correspond to any useful clinical application. It is of interest to estimate the mean thresholds for more clinically realistic parameters. Since the stimulation model seems to be valid, we can estimate the threshold slew rates (at least for an axial plane) as we did above for the experimental protocol.

One typical case is a high-resolution scan (21) with 16 interleaves, 24 cm field of view, readout bandwidth \(\pm 125\) kHz, and readout time 16 msec (4096 points per interleave). The Nyquist limit for avoiding aliasing restricts the maximum readout gradient amplitude to \(G_o = 24.5\) mT/m. This is not a constant slew rate spiral and is more difficult to analyze than our experimental protocol because \(dB/dt\) exceeds \([dB/dt]_{\text{threshold}}\) during part of the readout for some starting slew rates. Figure 3 shows \(dB/dt\) and \([dB/dt]_{\text{threshold}}\) as a function of time during the spiral readout for \(S_o = 80\) T/m/sec and \(S_o = 180\) T/m/sec. Note that \(dB/dt > [dB/dt]_{\text{threshold}}\) during part of the readout for \(S_o = 180\) T/m/sec. The most conservative estimate of the mean threshold is the one corresponding to \(\tau \to \infty\) in Eq. [1], which guarantees \(dB/dt < [dB/dt]_{\text{threshold}}\) during the entire readout. This threshold is \(S_o = 102\) T/m/sec for \(L = 0.53\) m. A less conservative, and probably more realistic, threshold results if we ignore the short portion near the beginning of the readout with large \(\tau\). For any scan prescription that has \(\beta > 1\) by the time \(G = G_o\), we can estimate the axial plane mean threshold starting slew rate \(S_o\). This estimate is based on combining Eqs. [1], [5], and [7] to get

\[
S_o L = 54(T/sec) \left[ 1 + \frac{(132\mu\sec)S_o}{\pi G_o} \right].
\]  

Equation [6] gives an \(S_o\) that results in \(dB/dt = [dB/dt]_{\text{threshold}}\) at the point where \(G = G_o\). Since \(G\) remains
constant and $S$ decreases subsequent to this point. Both $dB/dt$ and $(dB/dt)_{\text{threshold}}$ therefore subsequently decrease as well. For our system parameters, the factor $L = 0.53 \text{ m}$ multiplying $S_0$ on the left side of Eq. [6] is larger than the factor $(54 \text{ T/sec})(132 \mu\text{sec})/(\pi G_0) = 0.057 \text{ m}$ multiplying $S_0$ on the right side of Eq. [6] as long as $G_0 > 4 \text{ mT/m}$. For $G_0 < 4 \text{ mT/m}$, Eq. [6] predicts $dB/dt < (dB/dt)_{\text{threshold}}$ when $G = G_0$ for all $S_0$. Therefore the actual $dB/dt$ decreases faster than $(dB/dt)_{\text{threshold}}$ as the slew rate decreases. Therefore if $dB/dt = (dB/dt)_{\text{threshold}}$ at the point where $G = G_0$, then $dB/dt < (dB/dt)_{\text{threshold}}$ subsequent to this point. Solving for $S_0$ with $L = 0.53 \text{ m}$ and $G_0 = 24.5 \text{ mT/m}$ gives $S_0 = 123 \text{ T/m/sec}$. Figure 4 shows $dB/dt$ and $(dB/dt)_{\text{threshold}}$ for $S_0 = 123 \text{ T/m/sec}$. Note that $(dB/dt)_{\text{threshold}}$ is exceeded for about 10 $\mu\text{sec}$ near the beginning of the readout. Volunteer studies are needed to determine whether any of the above estimates are appropriate for the mean threshold for this case and similar cases that are not slew rate limited for the entire readout.

Another typical case is a low-resolution localizer (24) with 4 interleaves, 24 $\mu\text{sec}$ field of view, readout bandwidth $\pm 62.5 \text{ kHz}$, and 8 msec readout (1024 points per interleave). This is also not a constant slew rate spiral, even for $S_0$ as low as 80 mT/m/sec. The Nyquist limit for $G_0$ is 12.2 mT/m. Solving Eq. [6] for $S_0$ with $L = 0.53 \text{ m}$ and $G_0 = 12.2 \text{ mT/m}$ gives a mean threshold slew rate $S_0 = 157 \text{ T/m/sec}$.

These results suggest that the slew rate needs to be limited for typical spiral applications to avoid excessive PNS. Much more work is required to actually determine appropriate limits for clinical protocols, however. The stimulation distance $L$ used for these estimates is based on the point in our coil with the highest $dB/dt$. The actual $L$ is determined by patient positioning and physiological factors that are not well understood. A lower $L$ may be more appropriate for some cases, resulting in a higher predicted threshold and allowing a higher starting slew rate $S_0$.

In our experiments we noted that, at low PNS levels, training was required for volunteers to distinguish PNS from table vibration and other distracting stimuli. Previous studies have shown that mean discomfort levels from gradient stimulation are approximately 50% above mean perception thresholds (11). Thus responses to gradient stimuli appear to rise faster than a linear rate. By increasing slew rates above perception thresholds, our subjects were clearly able to distinguish between table vibration and gradient-induced stimulation. However, it seems plausible that in typical clinical scanning, PNS may not be reported because patients will be less apt to notice PNS if they are not specifically sensitized to it.

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**APPENDIX A: SPIRAL SCAN IMAGING PARAMETERS**

We start with the assumption that the mean stimulation threshold for spirals is predicted by the stimulation model (Eq. [1]). There are two criteria we consider for developing the spiral pulse sequence: (a) the threshold for stimulation; and (b) the level of stimulation actually created. If the threshold is above the stimulation level actually created, no PNS results. The stimulation level is proportional to the slew rate $S$. For spiral waveforms, $S$ equals the starting slew rate $S_0$ as the gradient amplitude $G$ builds from zero to its final value $G_0$. After $G$ reaches $G_0$, $S$ decreases. For maximum stimulation, we want $S$ to remain constant during the entire readout.

The stimulation threshold depends on the half-period $\tau$. For the most useful spiral protocols, the number of interleaves is small enough, and the readout time long enough, that the k-space polar angle $\theta$ obeys $\theta \gg 1$ by the end of the spiral readout. Using the spiral equations of motion (Eq. [8]), it is straightforward to show that when $\theta \gg 1$, 

$$\tau = \pi \left( \frac{G}{S} \right).$$  

(7)

To get the lowest PNS threshold, we want $\tau$ as large as possible at the end of the readout, which means making $G$ as large as possible according to Eq. [7]. However if $G$ reaches $G_0$ before the end of the readout, the slew rate begins to drop. Therefore, to get the minimum PNS threshold and the maximum $dB/dt$, we want $G = G_0$ at the end of the readout, and we want $G_0$ as large as possible (40 mT/m on the system we used). For the
experiment we varied the slew rate $S_p$ from 80 to 180 T/m/sec. With $G_0 = 40$ mT/m, Eq. [7] estimates $\tau$ ranging from 1571 to 698 $\mu$s, and Eq. [1] predicts a dB/dt mean threshold ranging from 58.5 to 64.2 T/sec over this range. Since this is a fairly narrow range for dB/dt, we decided to simplify the experiment by using exactly the same spiral scan parameters instead of trying to use the lowest threshold for each slew rate. This resulted in approximately the same dB/dt mean threshold for all slew rates.

This means either allowing $G$ to reach $G_0$ slightly before the end of the readout (high slew rate case) or allowing the readout to end before $G_0$ is reached (low slew rate case). The resulting prescription can be obtained by the following derivation. We chose to try for a $\tau$ somewhat midway between the estimates found above corresponding to minimum threshold, i.e., about 1000 $\mu$s.

For a constant slew rate Archimedean spiral, $\theta$ obeys the differential equation (22):

$$\dot{\theta} = \frac{\alpha^2(1 + \theta^2) - \theta^4(2 + \theta^2)^{1/2} - \theta^2}{1 + \theta^4}, \hspace{1cm} (8)$$

where a dot denotes the time derivative, where $\alpha$ is given by

$$\alpha = \frac{\gamma DS_p}{M}, \hspace{1cm} (9)$$

and where $M$ is the number of interleaves and $D$ is the field of view. Explicit numerical solution of this differential equation shows that $\dot{\theta} \approx 0$ after no more than a few hundred microseconds for useful clinical prescriptions. Using $\dot{\theta} \approx 0$ and $\theta \gg 1$ in Eq. [8] gives

$$\dot{\theta}^2 \theta = \alpha. \hspace{1cm} (10)$$

Solving Eq. [10] gives

$$t = \frac{2\theta^{1/2}}{3\sqrt{\alpha}}. \hspace{1cm} (11)$$

The gradient amplitude $G$ is given by

$$G = \left(\frac{M}{\gamma D}\right)^{\frac{1}{2}} \sqrt{1 + \theta^2}. \hspace{1cm} (12)$$

With the approximation $\theta \gg 1$, Eq. [12] becomes

$$G = \left(\frac{M}{\gamma D}\right)^{\frac{1}{2}} \theta \dot{\theta}. \hspace{1cm} (13)$$


$$G^2 = \left(\frac{M}{\gamma D}\right)^2 \alpha \left(\frac{3\sqrt{\alpha t}}{2}\right)^{2/3}. \hspace{1cm} (14)$$

Setting $G = G_0$ at the end of the readout, using Eq. [9] for $\alpha$, and setting $t = T_r$ where $T_r$ is the total readout time, gives

$$G_0^2 = \frac{3MTS_p^2}{2\gamma D}. \hspace{1cm} (15)$$

Using Eq. [7], Eq. [15] becomes

$$\left(\frac{\tau}{\pi}\right)^3 = \frac{3MT}{2\gamma DS_p}. \hspace{1cm} (16)$$

The parameters in Eq. [16] can be chosen to meet the target $\tau$ at the chosen slew rate. We chose $\tau = 1000$ $\mu$s at $S_p = 80$ T/m/sec. Note that this value of $\tau$ is different from the estimate based on Eq. [7] for this slew rate (1571 $\mu$s) because the latter assumed $G_0 = 40$ mT/m, whereas we have abandoned that assumption in order to use the same protocol and mean threshold dB/dt for each slew rate $S_p$. To maximize the probability of PNS, we want to apply the stimulus for as long as possible, i.e., we want the largest possible $T_r$. For the data acquisition architecture on our system, the number of readout points before decimation plus the number of digital filter taps is limited to 8192 or less for a single receiver. We used 8000 undecimated readout points with 5 digital filter taps to avoid data acquisition crashes. The a/d sample time on our system is 4 $\mu$s.

The number of undecimated readout points is $T_r/(4$ $\mu$s), resulting in the requirement $T_r = 8000 \times 4$ $\mu$s = 32 msec. Any combination of readout bandwidth and number of readout points that satisfy $T_r = 32$ msec is acceptable. We chose a $\pm 125$ kHz bandwidth, resulting in 8000 readout points and no decimation. The other parameters in Eq. [16], $M$ and $D$, can be chosen arbitrarily. Software limitations on our scanner force $M$ to be an even number. We chose $M = 2$. This fixes $D$ at about 14 cm for $S_p = 80$ T/m/sec.

The complete spiral prescription is as follows: 2 interleaves, 8000 readout points, 14 cm field of view, readout bandwidth $\pm 125$ kHz, TE 3.2 msec (minimum), TR 100 msec, flip angle zero, 1.5 mm slice, 1.0 mm skip, 121 slices, and one repetition. To allow sufficient time for manually moving the table over the range of positions tested, we needed at least 2 minutes of continuous scanning. The slice width and spacing were chosen to increase the scan duration. To increase the total acquisition time further, to more than 2 minutes, we used 8 dummy acquisitions per slice. This meant that the first nine spiral arms of the scan were identical and the tenth arm was rotated by 180°. We do not believe this had any significant impact on the results because the slew rate vector rotates continuously during the scan, and its starting angle is probably irrelevant. The radiofrequency (RF) power output was set to zero by setting the flip angle to zero to avoid any RF heating. The 100 msec TR was the minimum allowed by the gradient driver heating limitations. Numerical solution of Eq. [8] shows that $\tau$ actually varies from 830 to 1000 $\mu$s over the range $S_p = 80$ T/m/sec to $S_p = 180$ T/m/sec. From Eq. [1], the resulting range of
\( \frac{dB}{dt} \) thresholds is 62.5–61.1 T/sec, relatively constant, as desired.

**APPENDIX B: SPIRAL SCAN \( \frac{dB}{dt} \)**

We will calculate \( \frac{dB}{dt} \) during the readout for spiral scans with an axial plane. To be exact, the quantity we are calculating is

\[
\frac{\partial B}{\partial t} = \sqrt{\left( \frac{\partial B_x}{\partial t} \right)^2 + \left( \frac{\partial B_y}{\partial t} \right)^2 + \left( \frac{\partial B_z}{\partial t} \right)^2}. \tag{17}
\]

where bold denotes a vector. Even though the useful component of the magnetic gradient field is oriented in the \( z \) direction, it is important to include the \( B_x \) and \( B_y \) terms. For this calculation, we will assume all fields are spatially linear. This assumption is not true for distances far enough from isocenter, but we will ignore the resulting error. Assuming spatial linearity, the magnetic field components are given by (25)

\[
B_x = -\frac{1}{2} G_x x + G_x z, \tag{18}
\]

\[
B_y = -\frac{1}{2} G_y y + G_y z, \tag{19}
\]

\[
B_z = B_0 + G_x x + G_y y + G_z z, \tag{20}
\]

where \( B_0 \) is the main magnetic field (assumed to be time independent). During the readout, \( S_r = 0 \) with an axial plane. Defining \( S_x = \partial B_x / \partial t \), etc., setting \( S_r = 0 \), and substituting Eqs. [18] through [20] into Eq. [17] gives

\[
\frac{\partial B}{\partial t} = [(S \cdot r)^2 + |S|^2 z^2]^{1/2}, \tag{21}
\]

where the \( \cdot \) denotes the dot product. For spiral gradient waveforms, \( S \) rotates in the scan plane. Therefore \( \partial B / \partial t \) oscillates and reaches a maximum when \( S \) and \( r \) are aligned. Therefore

\[
\left| \frac{\partial B}{\partial t} \right| \leq S(\rho^2 + z^2)^{1/2} = SL, \tag{22}
\]

where \( S = |S| \), \( \rho = \sqrt{x^2 + y^2} \), and \( L = \sqrt{x^2 + y^2 + z^2} \)

\[
= \sqrt{\rho^2 + z^2}
\]

is the total distance of the stimulation point from isocenter.

**REFERENCES**


