Effect of Multislice Interference on Image Contrast in T2- and T1-Weighted MR Images

Walter Kucharczyk[1]
Adrian P. Crawley[2]
W. M. Kelly[3]
R. Mark Henkelman[2]

Multislice imaging markedly degrades the contrast of T2-weighted MR images as the separation between slices is reduced. Image contrast was measured clinically at 1.5 T and experimentally at 0.15 T as a function of interslice gap width and shown to be in agreement with calculations based on known relaxation times and excitation profiles. Thus, the cause of T2 contrast degradation in multislice sequences is demonstrated. Contrast in T1-weighted sequences is shown to be minimally affected or even slightly enhanced. Selective excitation pulses with better spatial definition will diminish these contrast changes. Since perfect slice profiles can never be achieved, the clinical implications of these findings are discussed for MR imaging.

The choice of slice gaps is an important operator-selected parameter in reducing contrast degradation in T2-weighted sequences.

It is desirable with any tomographic technique to be able to acquire contiguous slices so as not to exclude substantial amounts of tissue from the imaged volume. Unfortunately, the acquisition of contiguous slices in multislice MR imaging can lead to substantial degradation of image contrast and signal due to interslice interference, particularly on T2-weighted sequences with long TRs and long TEs [1–3]. Figure 1 illustrates this contrast degradation by comparing a long TR/long TE single-slice image with an image of the same location from a contiguous multislice acquisition with the same parameters. In the multislice image, the signal-to-noise ratio (SNR) is clearly decreased and the contrast is degraded.

Selective excitation pulses with better slice definition minimize this contrast degradation. A number of alternative and significantly improved excitation pulses have been described [4–9]. However, from a fundamental point of view, slice profiles must always have finite transition regions; that is, they can never be perfectly rectangular. The goal of contiguous and nonoverlapping slices therefore remains an unachievable ideal. Partial-volume effects also depend on the slice profile, and can lead to contrast degradation [10]. Partial volumes affect both single-slice and multislice images, and therefore are not considered in this article.

It is the purpose of this article to explain the origin of the contrast degradation in T2-weighted sequences and to show how it arises from slice interference. Quantitative agreement between experimental measurements and detailed calculations demonstrate the validity of the explanation. It is further shown that the same mechanism that leads to contrast degradation in T2-weighted sequences has less effect on contrast in short TR/short TE (T1-weighted) sequences. Finally, the implications of these findings for clinical MR are discussed.

Subjects and Methods

Clinical Study

A single adult volunteer was studied. Imaging was performed on a 1.5-T GE Signa MR system. Slice selection was accomplished with sinc excitation pulses including one negative
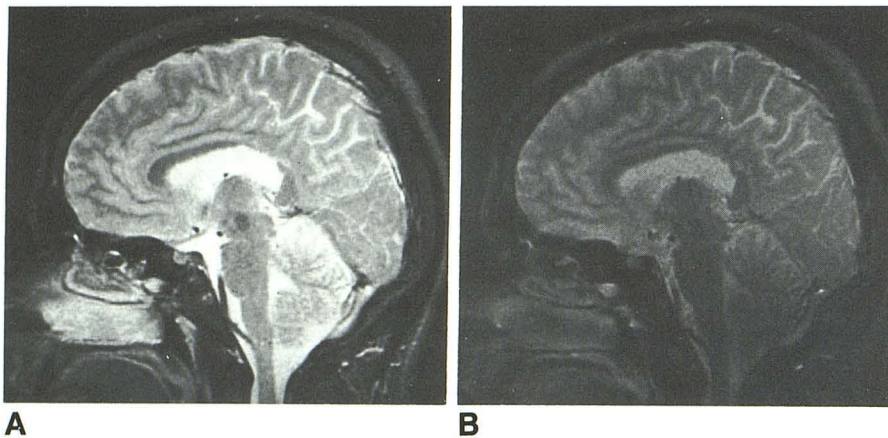
Fig. 1.—T2-weighted cardiac-gated images, 2000/70, 5-mm slice thickness. Single slice (A) and central slice from a series of seven contiguous slices (B). Both images have the same window and level settings.

side lobe on each side and filtered with a Hanning filter. The width of the 180° pulse was twice that of the 90° pulse. Multiple T2-weighted 2000/70/2 (TR/TE/excitations) imaging sequences were performed by using a 128 × 256 matrix and a 20-cm field of view. Slice thickness was maintained at 5 mm full-width-at-half-maximum throughout. A single-slice location was obtained through the basal ganglia followed by successive multislice imaging sequences altering only the gap width (100%, 50%, 20%, 10%, and 0% of slice thickness) with each acquisition. Regions of interest were defined in the frontal white matter, the caudate head, and the frontal horn. Signals from these regions of interest were plotted as a function of gap width. SNRs and contrast-to-noise ratios (CNRs) were calculated and graphed. T1-weighted images (600/20/2) were obtained in an identical fashion.

Phantom Study

The quantitative demonstration that contrast degradation is caused by multislice interference could be done at any field strength. A 0.15-T resistive imager was chosen because the slice definition had been well characterized [11]. Even though the gaussian selective pulses [11] gave somewhat inferior slice definition than that obtained in the clinical studies, similar slice interference effects are evident in each imager.

A phantom consisting of eight vials of different concentrations of aqueous manganese chloride solution was imaged with a 0.15-T resistive imager. The concentrations of manganese chloride and their associated T1 and T2 relaxation times measured at the same field strength with a spectrometer are given in Table 1. Imaging was performed by using T2-weighted 1000/60 and T1-weighted 300/28 sequences.

A slice thickness of 1 cm full-width-at-half-maximum was used throughout. Single-slice and multislice images were recorded; a variety of slice spacings was used, ranging from 0.7 cm (significant slice overlap) through to 2 cm (corresponding to 1-cm gaps). The multislice sequence acquired five slices, but in all cases only the center slice was evaluated. The RF excitation pulses were gaussian in shape, truncated at ±2 SD. The 90° pulse had a duration of 4 msec and the 180° pulse had a duration of only 2 msec, yielding a broader inversion profile than the 90° pulse slice excitation profile. All slices were acquired within a single TR. The order of acquisition was such that first all odd-numbered slices were acquired in order, then all even-numbered slices.

TABLE 1: Relaxation Times of Different Vials of Manganese Chloride

Concentration of Manganese Chloride (μM)	Relaxation Time (msec)	
	T1	T2
50	938	458
100	545	246
200	318	131
300	226	91
400	185	67
500	148	54
600	127	45
800	94	34

Note.—Relaxation times were measured at 0.15 T and have an accuracy of ±2% for T1 and ±5% for T2.

Results

Clinical Study

Figures 2A–2F show marked degradation of SNR and CNR on T2-weighted images as the interslice spacing was reduced from 100% to 0%. Quantitative measures of SNR and CNR are shown in Figure 3 (a and b). CNR is defined conventionally as signal difference divided by mean signal divided by noise. The greatest reduction in signal was in tissue with the largest T1: CSF, followed by gray matter; the least reduction was in signal from white matter. From the perspective of diagnostic interpretation arising from visual perception, the CNR is the most important. For each pair of tissues of interest, there is a 60–75% reduction in the CNR in reducing from a 100% gap to a 0% gap. The degradation is sufficiently severe that the caudate nuclei cannot be discriminated as distinct structures.

The T1-weighted images are shown in Figures 2G–2L, and the quantitative results are presented in Figure 3 (c and d). Decreasing the interslice gap had much less effect on T1-weighted images. There is a decrease in SNR for each of the

tissues but negligible change in the CNR, with satisfactory contrast between gray or white matter and CSF maintained at even a 0% gap. In these T1-weighted sequences there is negligible contrast between gray and white matter, since the increased recovery of magnetization from the shorter T1 of white matter is largely offset by the reduced mobile proton density evident in the white matter. Although it is difficult to demonstrate quantitatively, the ability to differentiate the caudate nuclei visually is lost with contiguous slices.

Phantom Study

Figure 4 shows a pair of T2-weighted images taken with a single-slice sequence (Fig. 4A) and a five-slice sequence with contiguous slices (Fig. 4B). As was shown in Figure 1, the contrast is degraded in the multislice sequence. The overall signal intensity is also reduced owing to slice interference.

Figure 5 shows plots of signal as a function of slice spacing for the T2- and T1-weighted sequences. The results correspond to five of the sample vials, which span appropriately the range of clinical T1 and T2 values obtained at this frequency. As the slice spacing decreases from 2.0 cm (well-separated slices) down to 0.7 cm (overlapping slices) the signal intensities decrease and move toward a single value showing that the contrast is degraded. As shown in Figure 5, a T1-weighted sequence shows a similar decrease in intensity but no degradation of contrast.

In the next section, a theoretical explanation of the contrast behavior caused by multislice interference is given. The results of the theoretical calculations are shown as solid lines in Figure 5, and are clearly in good agreement with the measured data points.

Discussion

Explanation of the Contrast Behavior

As has been stated by others [2, 3], the contrast changes observed in multislice images as the slices are brought closer together arise from slice interference. The effect on image contrast in T2- and T1-weighted sequences can be appreciated qualitatively in Figure 6.

Figure 6A shows a composite representation [12] of the recovery of longitudinal magnetization and transverse decay for two different samples in a single-slice T2-weighted sequence. During the 1000-msec TR interval, both samples attain almost full longitudinal recovery. However, because the T2 values are quite different, the signal of the short T2 sample decays away during the time elapsed for echo formation (60-msec TE). Thus, the contrast in this imaging sequence is primarily derived from tissue differences in T2, leading to the designation *T2 weighted*.

However, in multislice sequences, there may be loss of recovered longitudinal magnetization owing to interference from excitation pulses for adjacent slices applied during the TR recovery phase. This situation is illustrated in Figure 6A,

where partway through the recovery phase 25% of the longitudinal magnetization is lost on two occasions due to interference of the excitation pulses of the two adjacent slices. The long T1 sample is unable to recover full longitudinal magnetization during the TR interval. In fact, the partial interference from the adjacent slices effectively reduces the TR interval. Thus, during echo formation, the persistent long T2 sample begins with a reduced longitudinal magnetization and hence achieves a final signal intensity comparable to the short T2 sample. Qualitatively, this is the mechanism whereby interference between slices reduces the contrast in T2-weighted sequences.

Figure 6B shows a similar illustration for the T1-weighted sequence. In this sequence it is the short T1 sample that recovers most of its longitudinal magnetization during the short TR recovery phase. Since the TE time is comparatively shorter, the T2 decay of the short T2 sample has less time to develop, and hence the final contrast is still dominated by the T1 recovery. Thus, a short TR/short TE sequence is designated as *T1-weighted*, although in most practical examples the contrast is determined by a combination of both T1 and T2 as well as by effective proton density, as has been reported before [13]. When there is interference from adjacent slices during the recovery period, the total longitudinal recovery is diminished for both samples and the signal intensity at the time of the echo is decreased by an almost constant amount for both samples. Thus, the relative contrast for simple tissues is slightly increased in T1-weighted sequences owing to multislice interference.

The qualitative explanation of how interslice interference leads to degraded contrast on T2-weighted sequences and enhanced contrast T1-weighted sequences can be made quantitative by exact calculations performed with experimentally determined RF excitation profiles [11, 14]. Figure 7 shows the excitation profiles that have been measured for the 90° and 180° pulses used in the phantom experiment. The excitation profile is a plot of transverse magnetization as a function of distance through the slice. By plotting the profiles for contiguous slices, it can be seen that slices i − 1, i + 1, and i − 2 have excitation profiles that overlap with the ith slice. Thus, a complete calculation considers interference from a couple of adjacent slices on each side of the slice of interest. The calculation is performed as a function of distance perpendicular to the slices.

Figure 8A shows the resulting magnetization profiles for the T2-weighted sequence. The upper panels show the longitudinal magnetization that exists just before the excitation of the slice of interest. The lower panels show the transverse magnetization measured at the time of the echo. The left-hand panels are for the 100-μM manganese chloride solution and the right-hand panels are for the 400-μM solution. Different curves correspond to different slice spacings, and infinite slice spacing is included to show the profiles of the longitudinal magnetization when there is no slice interference. Thus, the W-shaped curve in the upper left panel of Figure 8A corresponds to the residual saturation of the longitudinal magnetization from the previous excitation of this slice. For the more
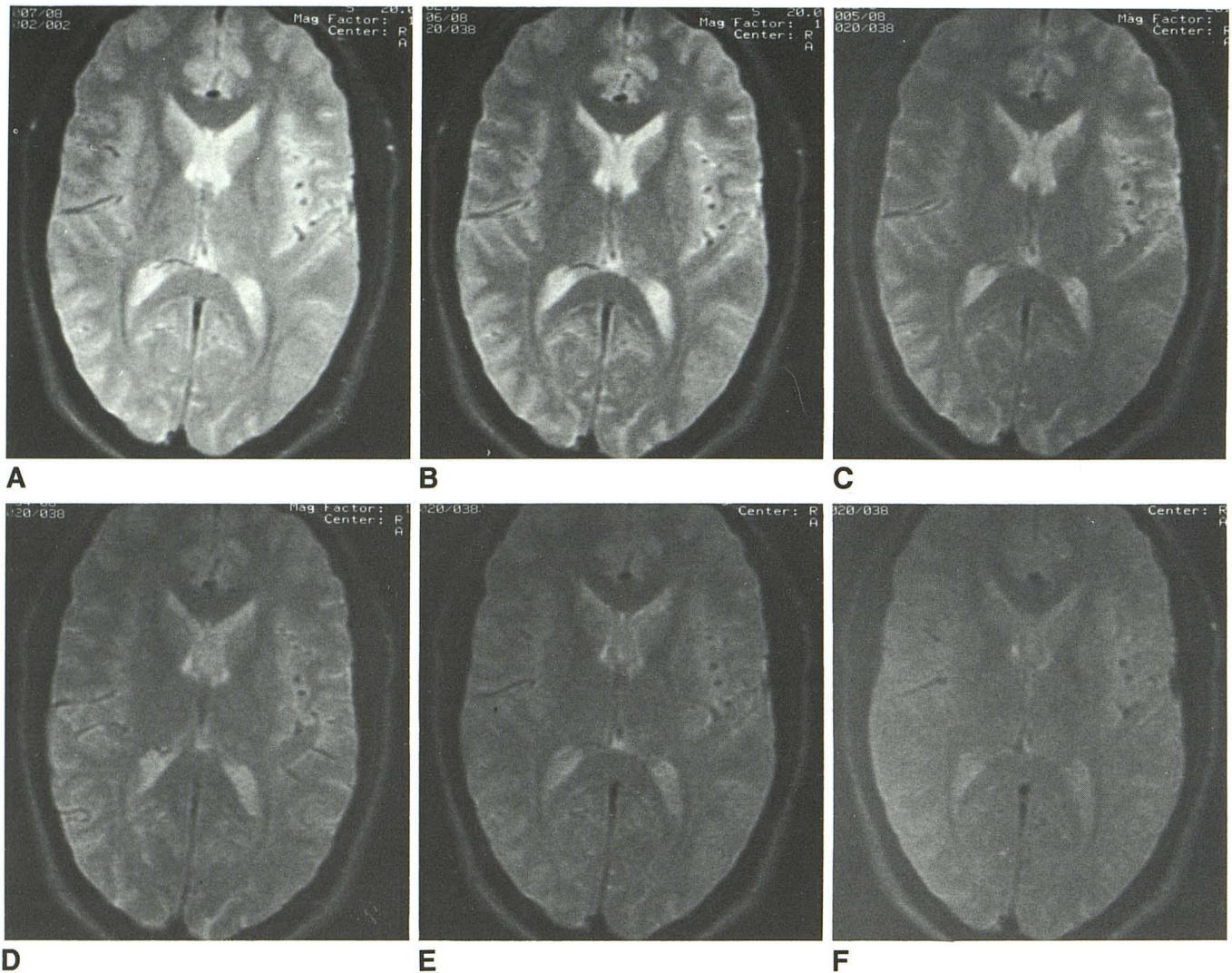
Fig. 2.—Multislice spin-echo images through basal ganglia. Window, level, and receiver attenuation are the same in each image.

A–F, T2-weighted images, 2000/70, show a progressive degradation of signal- and contrast-to-noise. *A* is single-slice acquisition for comparison. Interslice spacing: 100% (*B*), 50% (*C*), 20% (*D*), 10% (*E*), and 0% (*F*).

G–L (next page), T1-weighted images, 600/20, are less affected by decreasing the interslice gap. *G* is single-slice image. Interslice spacing: 100% (*H*), 50% (*I*), 20% (*J*), 10% (*K*), and 0% (*L*).

heavily saturated sample, the recovery from the previous excitation is complete, and so the infinite slice spacing occurs at full longitudinal magnetization. As the neighboring slices are moved closer, their interference begins to encroach on the longitudinal magnetization. This interference diminishes the intensity of the longitudinal magnetization that is available for excitation by the slice of interest (the ith slice). Also, for overlapping slices with a spacing of 0.7 cm, encroachment of the i − 2 slice from the left is evident in the longitudinal magnetization. This asymmetry arises from the fact that the i − 2 slice precedes the ith slice, but the i + 2 slice is subsequent to it.

The lower panels show the slice profiles that are extracted

from the longitudinal magnetization by the selective 90° and 180° pulses for the ith slice. The profiles show a comparatively uniform and approximately gaussian shape, with the differences in amplitude for a given sample determined by the available longitudinal magnetization. For very narrow slice spacings with overlap (0.7 cm), there is some shift of the peak position to the right owing to interference from the i − 2 slice. An integration over the transverse magnetization profiles in the lower panels is used to obtain the signal intensities and hence the theoretical curves shown in Figure 5.

Figure 8B shows a similar set of longitudinal and transverse magnetization profiles for the ith slice for the T1-weighted sequence. The explanation of these curves is completely
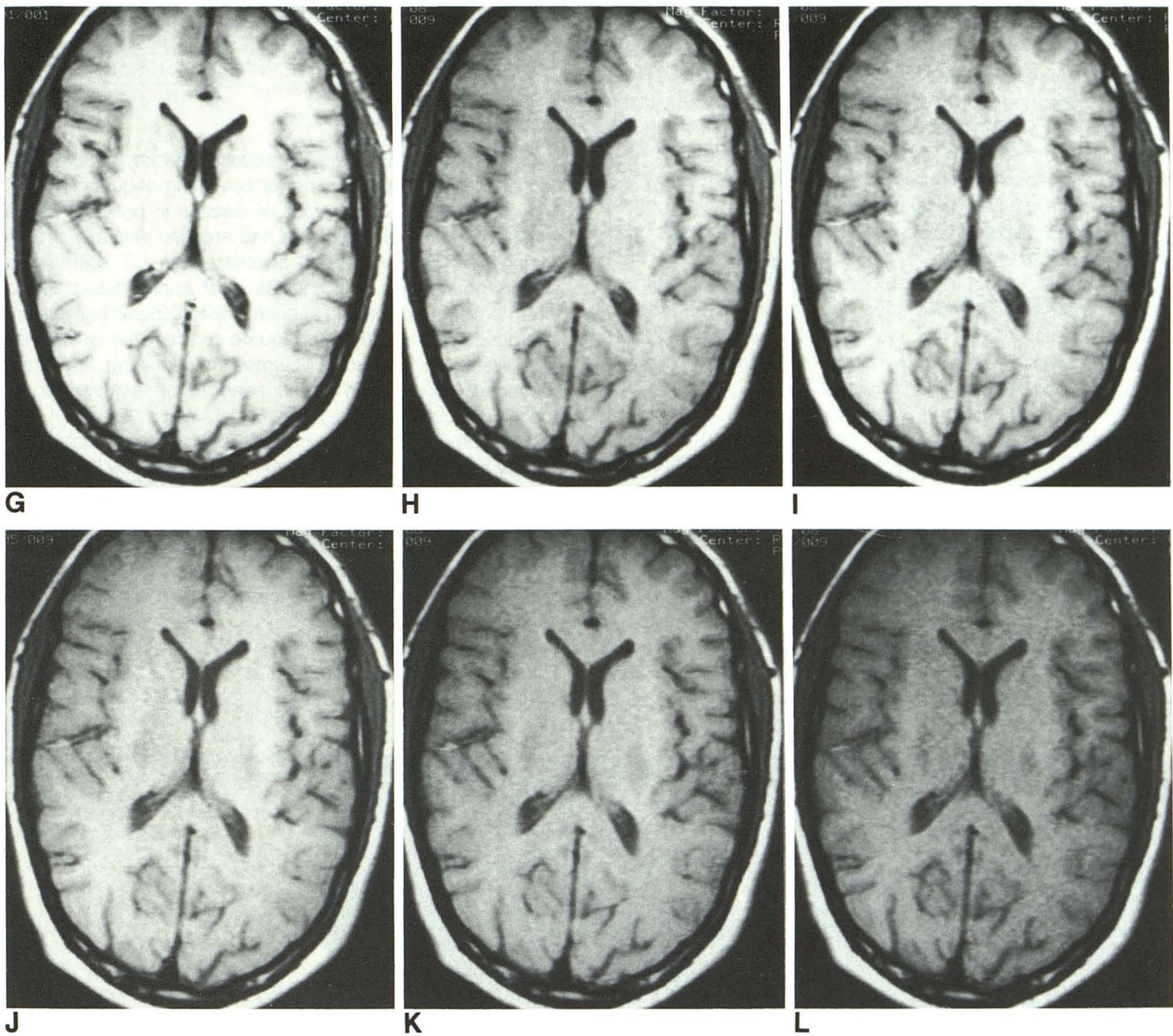
parallel to that given for Figure 8A. Theoretical curves derived from Figure 8B are shown in Figure 5. The calculated lines in Figure 5, which make use of the measured relaxation times of the various samples and the measured slice excitation profiles, show excellent agreement with the experimentally measured contrasts. Thus, it can be concluded that a complete picture of multislice interference effects on contrast has been achieved.

It is clear from the preceding analysis that better slice definition using more precisely defined selective excitation pulses [4–9] for both the 90° and 180° excitations will diminish the contrast degradation evident on T2-weighted sequences. It will also reduce any slight contrast enhancement on T1-weighted sequences as seen in Figure 5, but this will

be more than offset by the overall increase in signal obtained with diminished interference.

Clinical Implications

In clinical practice the effect of gaps on image quality is generally not evaluated with the same care that is given to choosing the appropriate TR and TE for the specific problem at hand. Yet the effect of interslice spacing can be significant. The manner and degree to which interslice spacing affects image quality, in particular CNR, is important in planning imaging protocols. This is best illustrated with several common clinical examples. These specifically pertain to neurora-
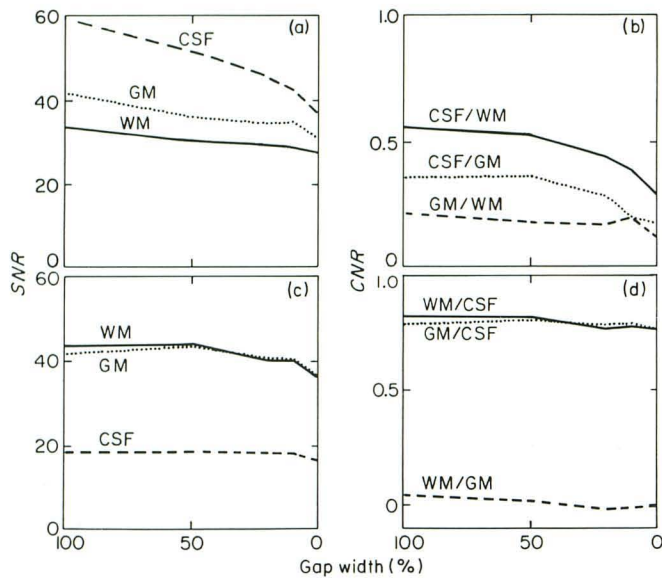
Fig. 3.—Quantitative presentation of signal- (SNR) and contrast-to-noise (CNR) ratios for tissues imaged in Figure 2. On T2-weighted sequences (a and b), both SNR and CNR decrease as gap width is reduced. For T1-weighted sequences, SNR (c) decreases with reduced gap, but CNR (d) shows little change. GM = gray matter; WM = white matter.

diology, but the principles can be applied to the imaging of other parts of the body as well.

T2-Weighted Images

T2-weighted images are commonly used for the examination of the brain, particularly as screening sequences [15]. They are a sensitive detector of disease in patients with a variety of neurologic problems and are also valuable in confirming or excluding lesions suspected on CT scans. The primary objective in selecting the most appropriate protocol for a T2-weighted imaging sequence is to achieve high lesion-to-brain contrast. Without adequate contrast the lesion may go undetected. Excluded volumes and imaging times are secondary considerations and need to be adjusted to fit specific clinical problems.

For example, to clarify a subtle but relatively large low-density area in the temporal lobe on CT, good MR contrast is required, but it is not necessary to cover every millimeter of tissue. Therefore, the scan could be obtained with large gaps (50% or 100%) to yield good contrast and without a repeated interleaving scan to fill in the gaps. Contiguous cuts could result in nondefinitive visualization (negating the pur-
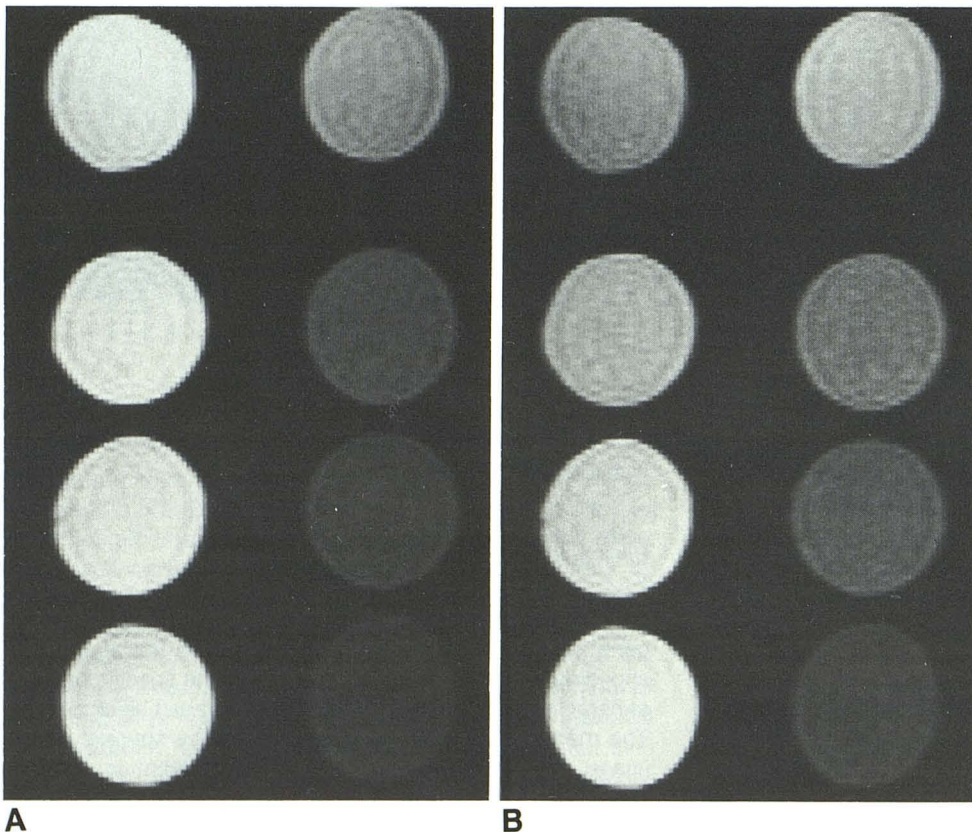

A   B

Fig. 4.—Images of a phantom, consisting of vials with differing concentrations of manganese chloride, at 1000/60. The concentrations of manganese chloride in the vials are (top to bottom, left column first): 50, 100, 200, 300, 400, 500, 600, and 800 μM, respectively.

A, Single-slice acquisition.

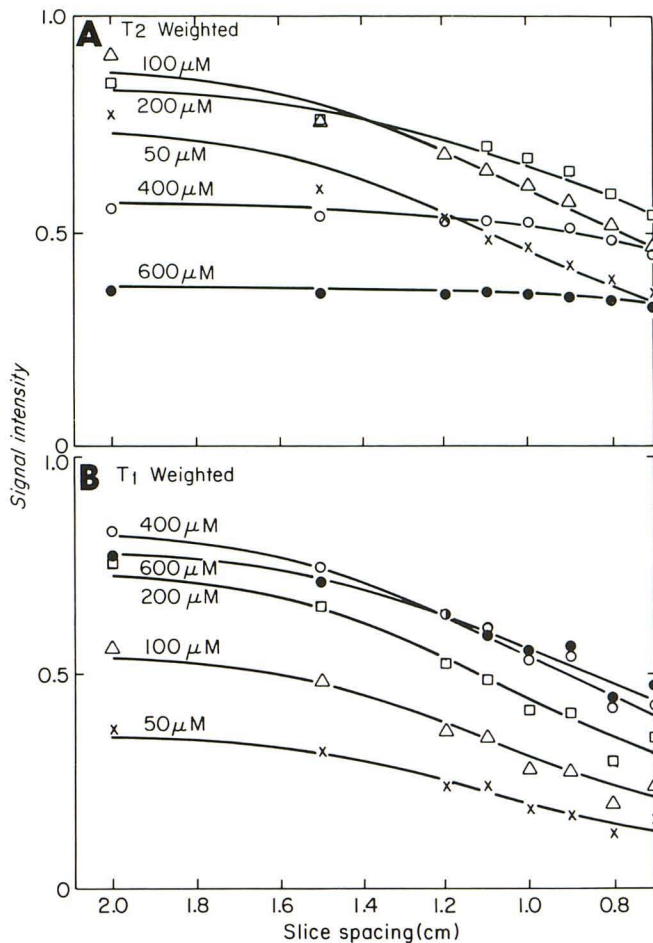B, The same slice from the center of a multislice acquisition consisting of five contiguous slices.

Fig. 5.—Signal intensity plotted for five sample vials as a function of slice spacing. *Data points* are experimental measurements; *Solid lines* show theoretical calculations.

A, T2-weighted sequence, 1000/60.
B, T1-weighted sequence, 300/28.

pose of the study), whereas a second interleaved scan would unnecessarily double imaging time. On the other hand, if the suspicious area were small, interleaving would be the best and possibly only way to image the area adequately and establish a diagnostic opinion despite the cost in imaging time.

If T2-weighted images are to be the primary method of investigation (that is, if CT had not been performed previously), it is most important to minimize the false-negative rate. It follows that good image contrast must be achieved and that no tissue, or little tissue, should be excluded from the imaged volume. Both these objectives can be achieved by using two interleaved sequences to maintain T2-weighted contrast and to cover the whole volume. One option is not to interleave but to insert a gap large enough to maintain good contrast but within clinically acceptable gap dimensions. We have chosen this latter option. We review an initial T2-weighted sequence performed with 5-mm-thick slices and a 50% gap. If no lesion is seen, the gaps are filled with a second identical, but shifted sequence. If the lesion is seen with the initial sequence, additional planes or different sequences are obtained if required.

The evaluation of the maturational state of the infant brain is another interesting application of these principles. The infant brain contains a substantially higher percentage of water than does the adult brain. With commonly used T2-weighted 2000/70–100 sequences, gray- white-matter discrimination is poor. It has been shown that improved contrast can be achieved by using much longer TRs (3500) and TEs (160) to compensate for the substantially longer T1 relaxation of the infant brain [16]. Similar results can be achieved by introducing larger gaps (e.g., 100%) at only a marginally longer TR of 2500 msec (Fig. 9). The large spacing is not anatomically significant because it is the general pattern that is of diagnostic interest. The contrast of other long T1 structures such as cysts can be similarly improved.
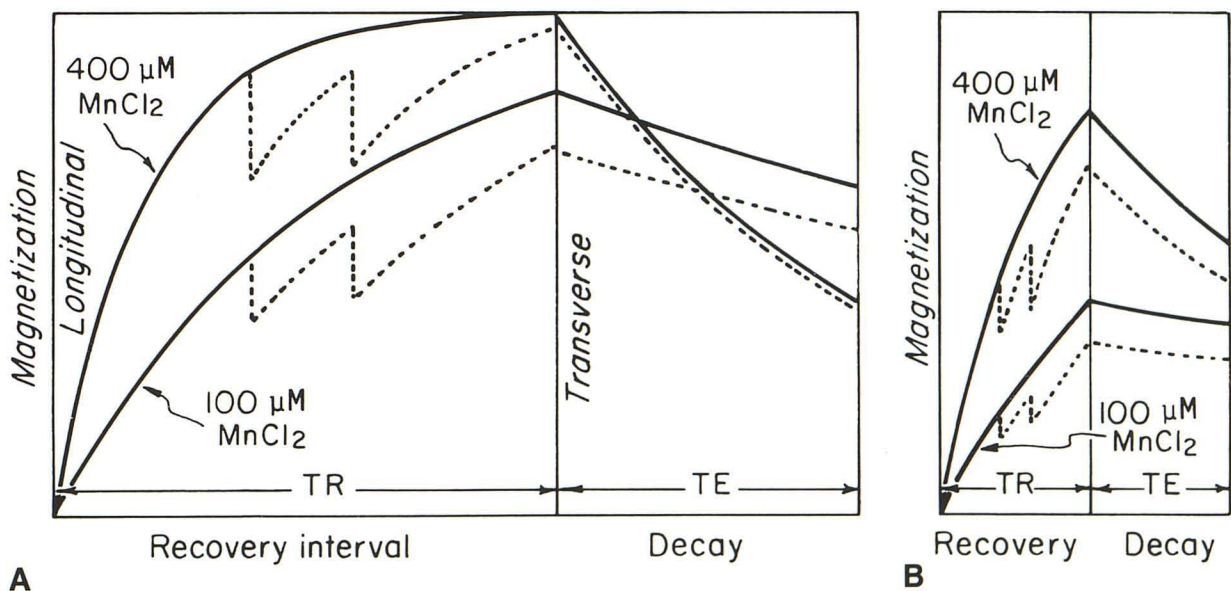

Fig. 6.—*A*, Evolution of magnetization as a function of time for two tissues. Recovery of longitudinal magnetization over a TR interval of 1000 msec is on the left. The decay of transverse magnetization after the 90° pulse is shown over an expanded time scale for TE=60 msec on the right. *Solid lines* represent the situation with no slice interference and *dotted lines* show the effect of the 25% reduction in longitudinal magnetization due to interference from adjacent slices. Diminished T2 contrast from slice interference is evident.

B, T1-weighted sequence, 300/28. *Solid lines* represent no slice interference; *dotted lines* correspond to a 25% reduction in the longitudinal magnetization due to interference from adjacent slices. Signal intensity is reduced with slice interference, but the contrast is minimally enhanced.

Slice number   i-2 i-l   i   i+l

Slice profiles

90° i-l

l80° i-l

90° i+l
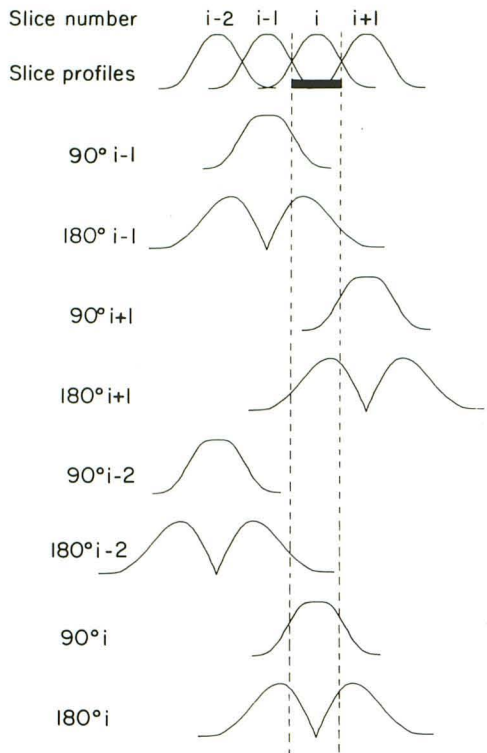
l80° i+l

90° i-2

l80° i-2

90° i

l80° i

Fig. 7.—Plot of 90° and 180° excitation profiles as a function of position perpendicular to the slices in a contiguous multislice sequence shows regions of interference on the ith (i) slice by slices i − 1, i + 1, and i − 2. Slice profiles were measured experimentally. Full-width-at-half-maximum is 1 cm and is represented by the bar for the ith slice. (Adapted from [11].)

T1-Weighted Images

Typical spin-echo T1-weighted images display the interface between brain and CSF spaces very well, but contrast within the brain is often poor unless inversion recovery is used. For this reason typical T1-weighted images are excellent for evaluating extraaxial disease (because these lesions border on CSF spaces) but poor for evaluating lesions intrinsic to the brain.

The detection and determination of the extent of acoustic neuromas is a good example of a common use of T1-weighted images. These tumors are often very small (requiring contiguous or near-contiguous images) and are located in the internal auditory canal or cerebellopontine angle surrounded by bone or CSF. Even though CNR for brain/CSF diminishes as gaps narrow, there remains high contrast even at zero gap width. Therefore, this particular area should be imaged with a thin-section contiguous slice typical of the T1-weighted sequence.

Conclusions

In conclusion, we have shown that contrast degradation in multislice T2-weighted images arises from slice interference. We have shown that detailed calculations of the interference effects account quantitatively for experimentally measured signal intensities. Explained simply, image contrast decreases to full intensity in a long TR sequence. Slice interference, therefore, introduces an intensity dependence on differential T1 relaxation that interferes with the desired T2-weighted contrast.
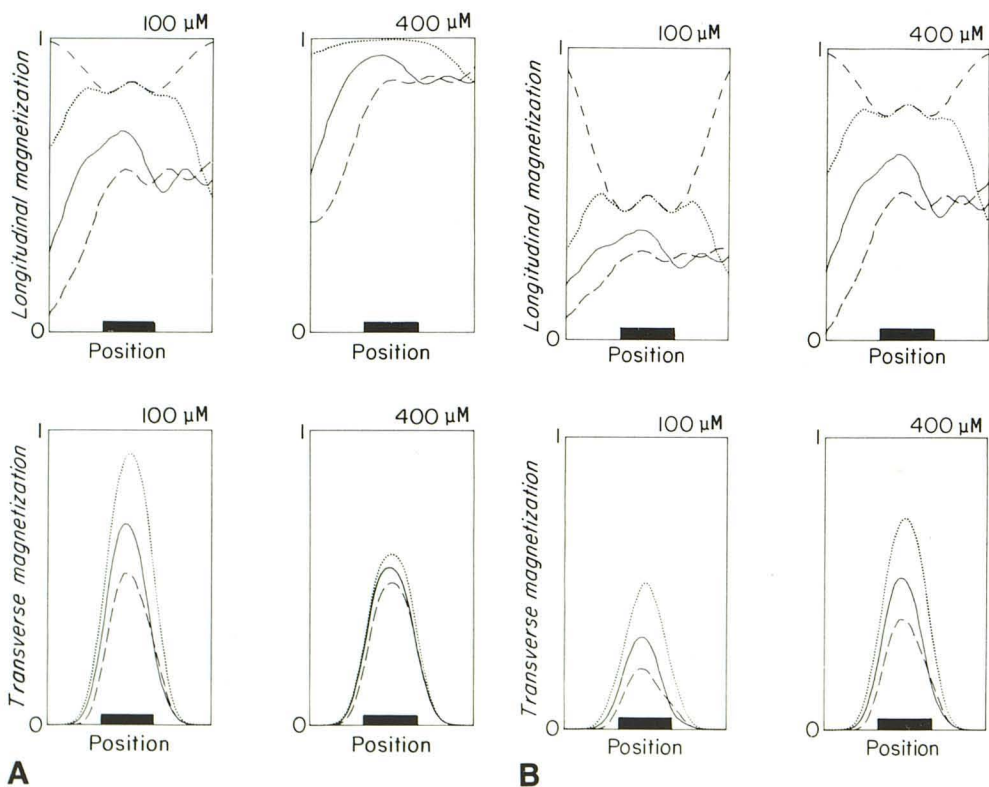
Fig. 8.—Longitudinal and transverse magnetization profiles. Upper panels show longitudinal magnetization as a function of distance perpendicular to the slices. Bars represent full-width-at-half-maximum of the slice. Different curves represent different slice spacings ranging from infinite (no slice interference) (short broken lines) down through 2 and 1 cm (contiguous slice spacing) to 0.7 cm (overlapping slices). Lower panels show transverse magnetization obtained at the time of echo after slice-selective 90° and 180° pulses.
A, T2-weighted sequence, 1000/60.
B, T1-weighted sequence, 300/28.

A

B

100 µM   400 µM   100 µM   400 µM

Longitudinal magnetization / Position

Transverse magnetization / Position

Fig. 9.—Multislice axial sections of brain of 3-month-old baby.

A, 100% gap between slices, 2500/160.

B, 20% gap, 3500/160. Despite 40% longer imaging time, signal-to-noise ratio and contrast are both inferior in B.

A   B
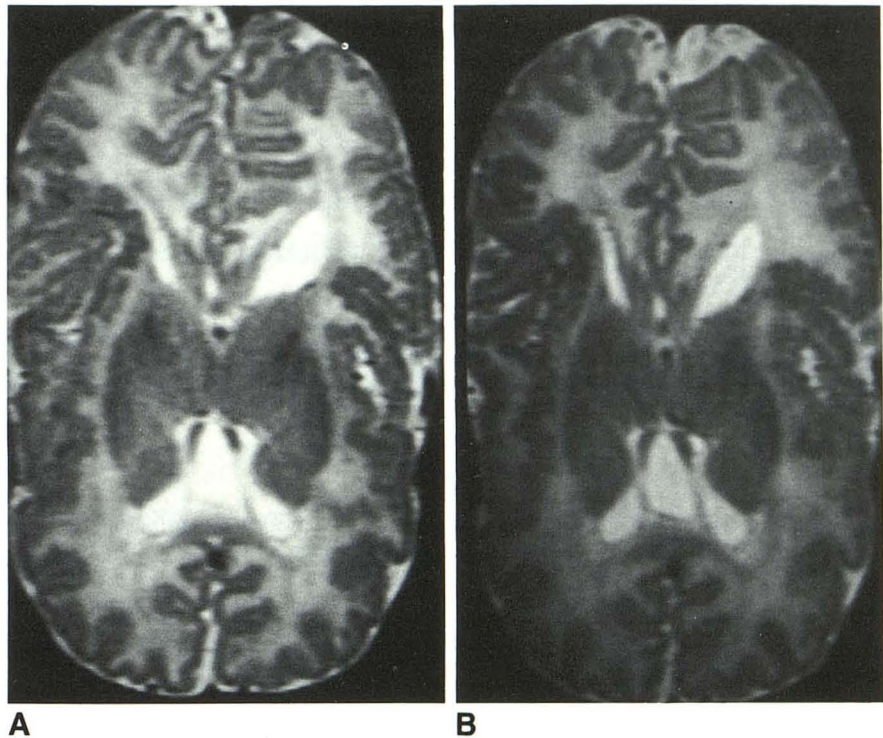
On T1-weighted sequences, the same mechanism can lead to a slight increase in contrast in phantom studies, although with an associated decrease in signal intensity and therefore a net reduction in CNR. In clinical studies, no contrast enhancement is observed for important neurologic tissues.

Changes in contrast due to slice interference can be reduced with more precisely defined selective pulses. Nonetheless, perfectly rectangular excitation profiles cannot be achieved with finite excitation times, and thus there will remain MR applications where it is preferable to perform multislice acquisitions with gaps equal to the slice thickness followed by a second acquisition to fill in the gaps.

ACKNOWLEDGMENTS

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