The Effect of Variation in Slice Thickness and Interslice Gap on MR Lesion Detection

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Lesion detection by MR imaging depends on the contrast-to-noise ratio of the voxels containing the lesion relative to those containing the background. When the lesion voxels are less than completely filled, the inherent contrast between lesion and background is modified by the filling factor. Lesion detection thus depends on lesion size, slice thickness, lesion position relative to slice, thickness of gap between slices, and inherent contrast between lesion and background.

Using computer simulation, the effect of variation in the slice thickness and the interslice gap on lesion detection is modeled as a function of lesion size, filling factor, and inherent contrast. Detection of small, low-contrast lesions is shown to be most sensitive to partial volume effects and to be greatest with thin slices. Detection of high-contrast lesions is shown to be limited primarily by the presence of a gap between slices. For patients with diffusely distributed disease—e.g., the small, low-contrast lesions of multiple sclerosis—lesion detection is greater for thin slices, even with a gap, than for thick, contiguous slices.

Lesion detection by MR imaging is primarily dependent on the contrast-to-noise ratio (C/N) of the lesion relative to the background [1, 2]. The intensity of each pixel in the lesion or the background represents the total signal returned from a given volume element or voxel. Thus, if a lesion fills an entire voxel, the contrast between lesion and background pixels is dependent solely on the inherent contrast of the lesion. If the lesion occupies less than 100% of the voxel, the lesion contrast is then dependent on both the inherent contrast of the lesion and the percentage of the voxel that is filled by the lesion, the so-called "filling factor." As the inherent contrast and filling factor decrease, the intensity of the voxel tends toward the intensity of the background, limiting lesion detection. These "partial volume effects" may be minimized by decreasing the slice thickness [3]. This maneuver will generally prolong the imaging time if contiguous slices are still obtained over the same imaging volume (all other factors remaining constant) [4]. To avoid a longer scan time, the slice thickness may be decreased while maintaining a constant slice-to-slice interval (the distance between the beginning of each slice), thus increasing the gap between slices. By decreasing slice thickness in this manner, partial volume effects are minimized, but at the expense of increasing the probability that a lesion will be located in the gap. This computational study was undertaken to evaluate how these two effects interact to affect the detection rate of lesions of different size and inherent contrast.

Theory

Pixel contrast (PC′) is defined as the product of the inherent contrast (IC) and the filling factor (FF′), the percentage of the slice filled by the lesion:

$$PC' = FF' \times IC \quad (1)$$

The minimum PC′ necessary to detect a lesion is defined as PC, the pixel contrast threshold

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for detection. The actual value of PC is unknown and depends on the signal-to-noise ratio (S/N) and on subjective interpretation, both of which will be assumed constant for this analysis. (While the signal-to-noise ratio will normally decrease for thinner slices with smaller voxels, this may not be perceptible at higher values of S/N—e.g, at higher fields—or it can be countered by increasing the number of excitations or by increasing the echo sampling time, which decreases the bandwidth, thereby partially offsetting the signal-to-noise decrease.) If PC is substituted for PC′ and equation 1 solved for FF′, it can be seen that for any given IC there is a minimum FF′ required for detection, which we will denote as the filling-factor threshold for detection (FF):

$$FF = PC/IC \quad (2)$$

Thus, lesion contrast can be expressed in terms of the minimum fraction of the voxel that needs to be filled for detection (FF). This is a very useful concept in our model, and we will use this convention to quantify lesion contrast. For example, an FF 40% lesion is one with inherent contrast such that at least 40% of a voxel must be filled before the lesion can be detected.

Using the above parameters and assumptions, a simple model was created. Considering all possible positions in or out of the imaging plane, the lesion is modeled as a line along the long axis of the voxel, perpendicular to the imaging plane (Fig. 1). The length of the line is equal to the diameter of the lesion. To determine the probability of detection, the lesion is moved (by the computer) through the interval INT from the beginning of one slice to the beginning of the next. This corresponds to moving from point X to point Y in Figure 1 and represents all possible positions of the lesion within the interval INT of slice thickness plus gap. As the lesion moves through this interval, detection occurs whenever the overlap between the lesion and the slice is greater than the size threshold for detection FF × ST (where ST is the slice thickness). The total distance over which detection occurs, divided by the distance over which detection was possible (the interval INT), is the probability of detection (P).

There are three possible situations for lesion detection. Either:

1. The lesion will *not* be detected at any point along the interval ($P_1 = 0$); or
2. The lesion will be detected at *all* points along the interval ($P_2 = 1$); or
3. The lesion will be detected only at *certain* points along the interval ($0 < P_3 < 1$).

The first situation, $P_1 = 0$, occurs when the lesion is unable to fill enough of the voxel for detection even at maximum overlap. In other words, there is no detection when the lesion size LS is smaller than the required size threshold for detection; that is:

$$\text{if } LS < FF \times ST,\ P_1 = 0 \quad (3)$$

The other extreme, $P_2 = 1$, occurs when a lesion always fills more than the size threshold at every point along the interval INT. The point of minimum overlap between the lesion and the slice occurs when the center of the lesion is equidistant from the center of each slice. Thus, if the lesion is still detected in this position of minimum overlap, it will *always* be detected ($P_2 = 1$). This occurs when the lesion spans the gap (INT–ST) and overlaps *each* slice by an amount greater than or equal to the size threshold FF × ST; that is:

$$\text{if } LS > (INT–ST) + 2(FF \times ST),\ P_2 = 1.0 \quad (4)$$

For lesions in between these two extremes, detection will occur only at positions where the overlap between the lesion and the slice is greater than or equal to the size threshold (FF × ST). As the lesion begins moving into the interval from point X to point Y in Figure 1, the overlap with slice A begins to decrease. The lesion will continue to be detected as long as the overlap with slice A is greater than or equal to FF × ST. The distance over which detection occurs is thus equal to the lesion size minus the size threshold:

$$LS - FF \times ST \quad (5)$$

As the lesion continues toward point Y and begins to overlap slice B, detection does not occur initially, because the overlap is not greater than the size threshold. Eventually, the slice B overlap equals FF × ST, and detection occurs over the distance from this point to point Y. This distance is equal to the slice thickness minus the required size threshold:

$$ST - FF \times ST \quad (6)$$

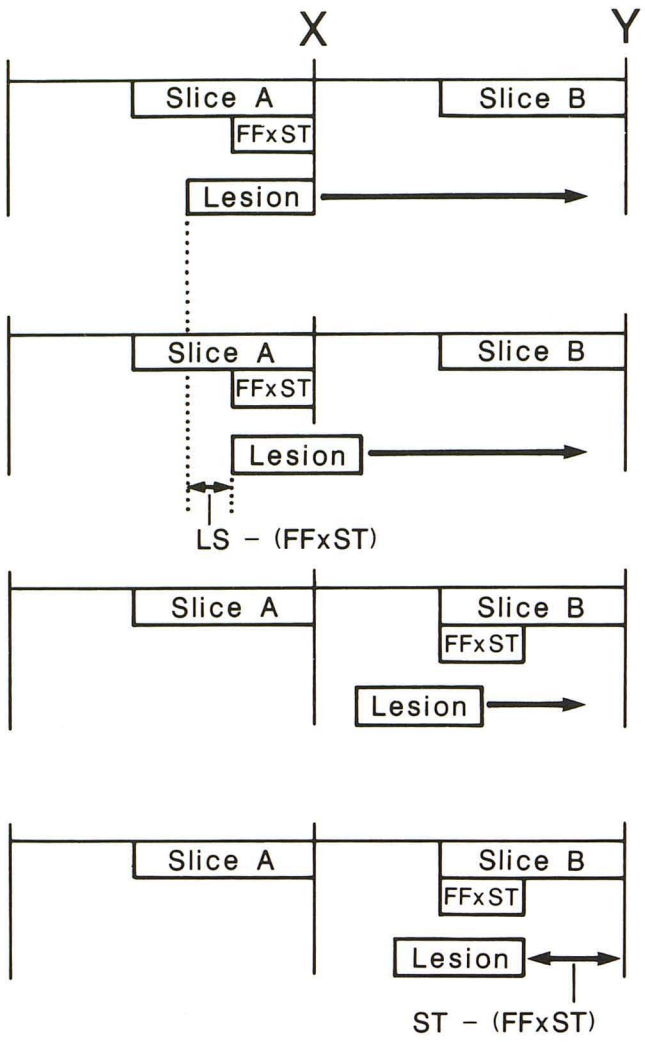

Fig. 1.—Computer simulation diagram. To simulate the variable position of a lesion (of size LS) relative to the slice thickness (ST) and interslice gap, the lesion is advanced by computer through the entire interval from the right edge of slice A to the right edge of slice B. This is interval INT in equations 4 and 7 in text. Detection occurs whenever the lesion overlaps either slice A or slice B at least by the amount FF × ST (where FF is the threshold filling factor for detection and ST is the slice thickness). Moving from left to right, detection occurs over the distance LS – (FF × ST) as the lesion overlaps slice A by FF × ST. Continuing to the right, detection does not occur again until there is a minimal overlap (by FF × ST) of slice B. Detection then occurs over the distance ST – (FF × ST) until the lesion has been moved to the right edge of slice B.

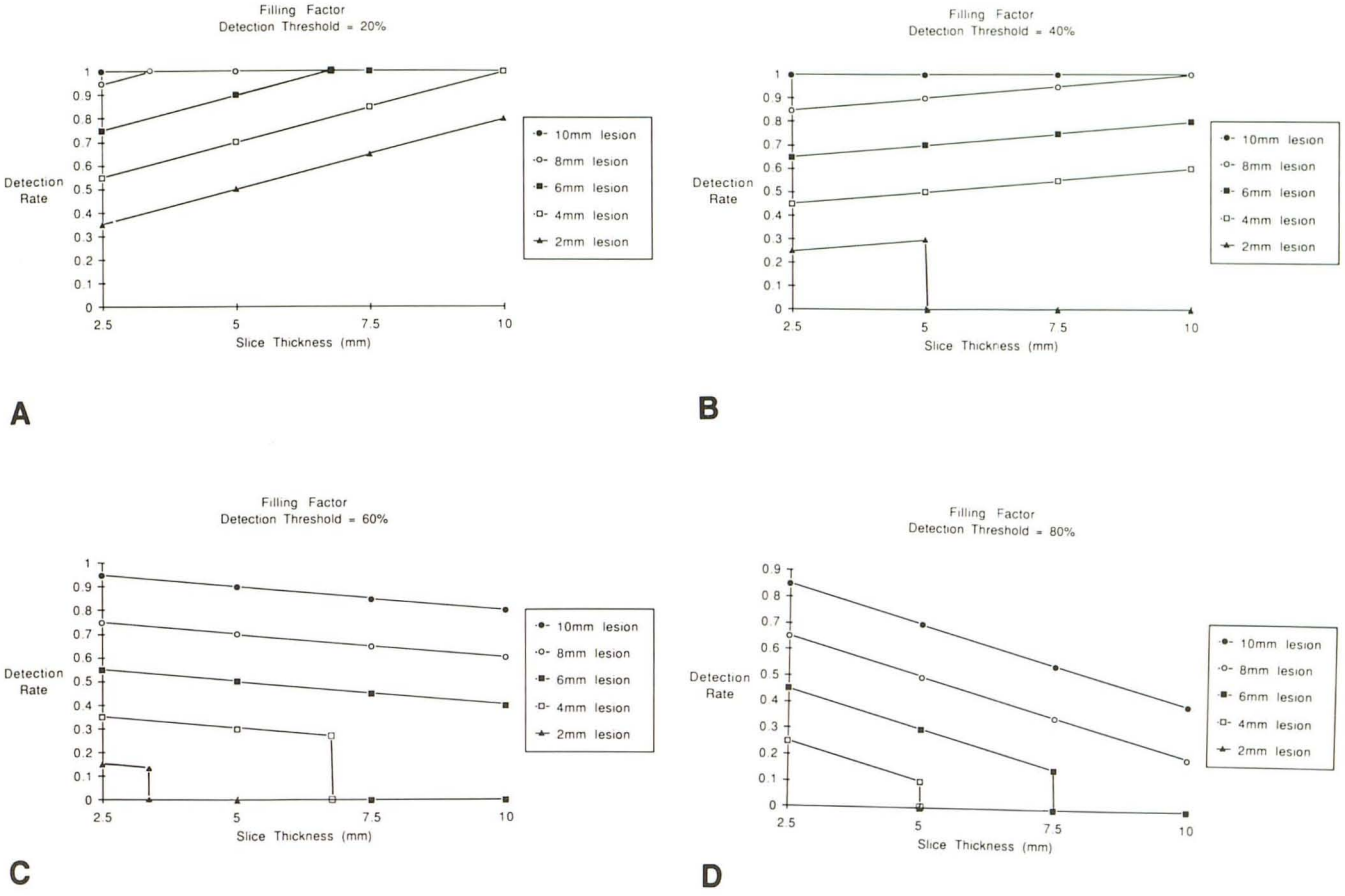

Fig. 2.—Calculated lesion-detection rate versus slice thickness and filling-factor detection threshold as a function of lesion size. Since the slice spacing or "interval" remains constant at 10 mm, the following gaps are associated with particular slice thicknesses: 2.5-mm slice (7.5-mm gap), 5-mm slice (5-mm gap), 7.5-mm slice (2.5-mm gap), and 10-mm slice (no gap). The detection rate of lesions with a 2-, 4-, 6-, 8-, or 10-mm diameter is determined for filling-factor detection thresholds of 20% (*A*), 40% (*B*), 60% (*C*), and 80% (*D*). An upward slope of detection rate versus slice thickness indicates predominance of interslice gap effects (seen with high-contrast lesions in *A* and *B*) while a downward slope indicates predominance of partial volume effects (seen with low-contrast lesions in *C* and *D*).

This distance, added to the distance of detection during overlap of slice A and divided by the interval INT, is equal to the probability of detection. Thus, combining equations 5 and 6, the probability of detection for situation 3 is:

$$P_3 = \frac{(LS - FF \times ST) + (ST - FF \times ST)}{INT}$$

$$= \frac{LS + ST - 2(FF \times ST)}{INT} \quad (7)$$

Methods

Using a commercial microcomputer,* equations 3, 4, and 7 were used to determine the probability of detecting a lesion of given size, inherent contrast-filling factor, and variable percentage of slice thickness relative to total interval. Lesion size was varied from 2–10 mm in 2-mm steps; the percent slice thickness varied from 25–100% in 25% increments, corresponding to the following combination of slice thicknesses and gaps over a constant interval of 10 mm: 2.5-mm slice/7.5-mm gap, 5-mm slice/5-mm gap, 7.5-mm slice/2.5-mm gap, 10-mm slice/no gap (contiguous slices). The effects of variable filling factor FF′ and inherent contrast were combined as the filling-factor detection threshold (FF), which was varied from 20–80% in 20% increments.

To demonstrate the clinical relevance of this analysis, a patient with multiple sclerosis (MS) having multiple, small, low-contrast lesions was studied using both 10-mm contiguous slices and 5-mm slices with a 5-mm gap. The patient was studied on a 0.35-T Diasonics MR imager using reduced bandwidth technology and equipped with a quadrature detection head coil. Both sequences used 256 × 256 acquisition matrixes in a 23.4-cm field of view for 0.95-mm in-plane spatial resolution. Both studies used a TR of 2 sec and two excitations for an acquisition time of 17 min. For the 10-mm contiguous slices, the TEs were 30 and 60 msec; for the 5-mm series, the TEs were 40 and 80 msec (to allow a longer echo sampling time, thereby partially equalizing the signal-to-noise ratio for the two techniques).

* MacIntosh-Plus with 20 MByte Hyperdrive.

Results

The calculated detection rate is plotted against slice thickness (for constant slice thickness plus gap interval of 10 mm) in Figures 2 and 3. Detection rates are calculated on the basis of an equal probability of lesion position at any point relative to the slice. In Figure 2, lesions ranging in size from 2–10 mm are shown for filling-factor detection thresholds (i.e., actual filling factors × intrinsic contrast) of 20% (Fig. 2A), 40% (Fig. 2B), 60% (Fig. 2C), and 80% (Fig. 2D). For high-contrast lesions (FF 20%), the detection rate is seen to increase as the slice thickness increases owing to a decrease in the interslice gap (Fig. 2A). Since high-contrast lesions need only fill a small percentage of the slice to be detected, the presence of any gap between slices decreases the overall lesion detection. As lesion contrast starts to decrease (Fig. 2B), an optimum slice thickness is noted for the smallest lesions. The detection rate initially increases as slice thickness is increased because of a decrease in the interslice gap. However, as the slice thickness continues to increase, the smaller, low-contrast lesions become undetectable because of overwhelming partial volume effects. The detection of larger lesions, on the other hand, continues to increase as the gap is decreased.

Continued decrease in lesion contrast (i.e., increase in

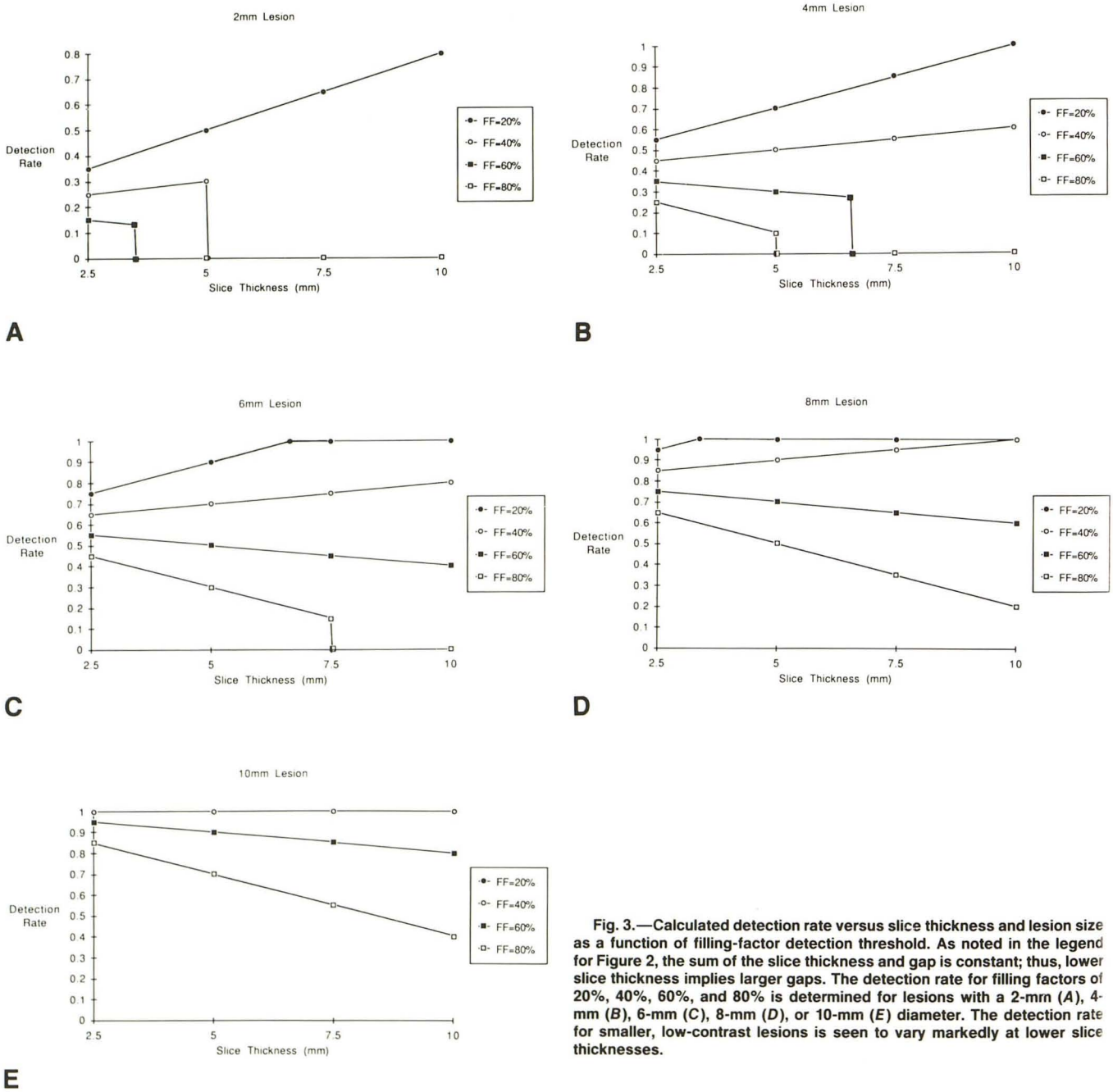

Fig. 3.—Calculated detection rate versus slice thickness and lesion size as a function of filling-factor detection threshold. As noted in the legend for Figure 2, the sum of the slice thickness and gap is constant; thus, lower slice thickness implies larger gaps. The detection rate for filling factors of 20%, 40%, 60%, and 80% is determined for lesions with a 2-mm (*A*), 4-mm (*B*), 6-mm (*C*), 8-mm (*D*), or 10-mm (*E*) diameter. The detection rate for smaller, low-contrast lesions is seen to vary markedly at lower slice thicknesses.

filling-factor detection threshold) leads to generally lower detection rates because of increasing partial volume effects (Fig. 2C). Smaller lesions may be missed entirely regardless of position as the slice thickness is increased because of partial volume effects. For the lowest-contrast lesions, which require a filling factor of 80% for detection, the detection rate falls off rapidly as the slice thickness is increased, because of increasing partial volume effects.

In Figure 3, variable filling-factor detection thresholds (FF) ranging from 20–80% are plotted for different lesion sizes: 2 mm (Fig. 3A), 4 mm (Fig. 3B), 6 mm (Fig. 3C), 8 mm (Fig. 3D), and 10 mm (Fig. 3E). The detection rate for smaller lesions (Fig. 3A) depends strongly on lesion contrast. The detection of high-contrast lesions (FF 20%) improves as slice thickness increases, because of concomitant decrease in the interslice gap (Fig. 3A). The rate of increase in detection with increasing slice thickness decreases rapidly as the contrast is decreased owing to increasing partial volume effects. Lower-contrast 2-mm lesions may not be detectable even at the minimum slice thickness. As the lesion size increases to 4 mm (Fig. 3B), the effect of contrast is decreased, the detection rate changing more slowly with increasing slice thickness. Larger, higher-contrast lesions are seen to be 100% detectable regardless of lesion size in Figures 3C–3E. The detection of large, low-contrast lesions is seen to decrease with increasing slice thickness because of increasing partial volume effects (Fig. 3E).

Figure 4 is a comparison of 10-mm-thick contiguous slices with 5-mm slices having a 5-mm gap. Both studies cover the entire brain and both take 17 min for acquisition (using 256 phase-encoded projections, two excitations, and a TR of 2.0 sec. Figure 4 illustrates the effect of varying slice thickness on the detection of low-contrast lesions in a patient with multiple sclerosis. The lesions are clearly better seen on the 5-mm slices (Figs. 4A and 4C) than on the 10-mm slices (Figs. 4B and 4D).

Discussion

At first glance, it might appear that a gap between slices is always detrimental to lesion detection, since lesions in the gap would be missed. Such gaps were accepted on early MR imaging systems to minimize the detrimental effect of "cross talk" (i.e., partial excitation of adjacent slices) on C/N. Indeed, once contiguous-slice technology became available, some MR manufacturers did not even offer an optional interslice gap in certain software releases. Unfortunately, there are

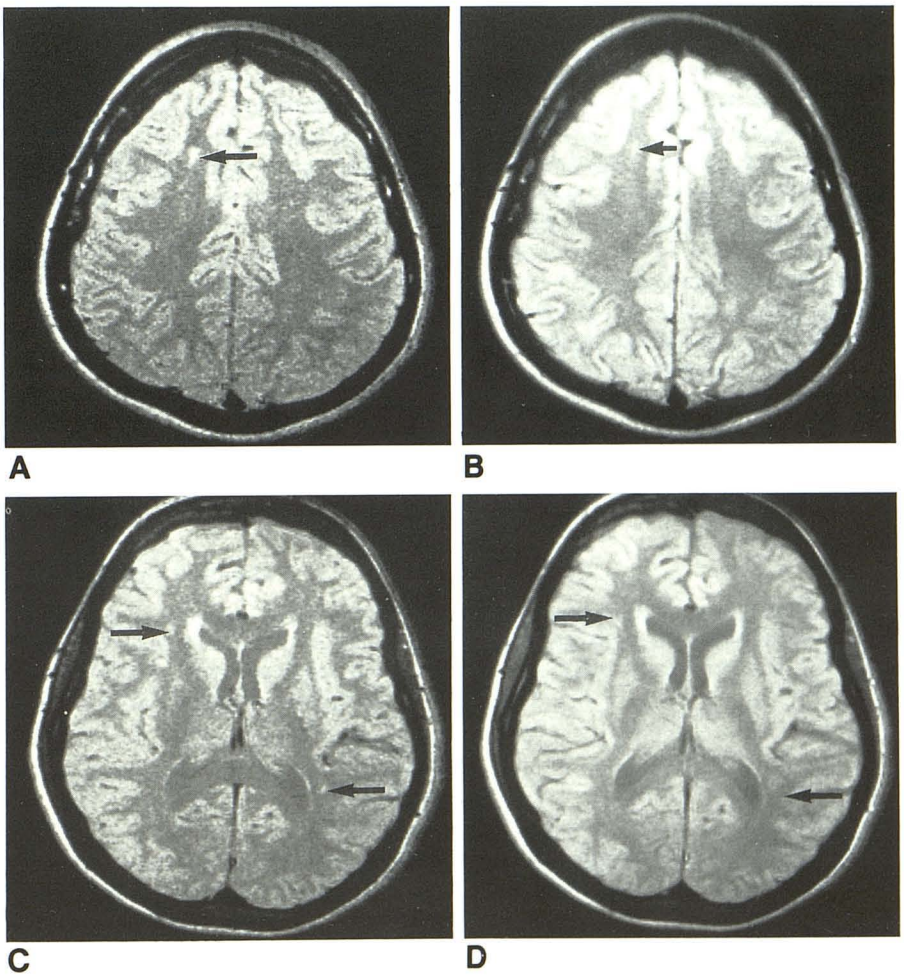

Fig. 4.—Comparison of 5- and 10-mm slice thicknesses in patient with multiple sclerosis. Five-millimeter slices with a 5-mm interslice gap (*A* and *C*) are compared with 10-mm contiguous slices (*B* and *D*) to determine the conspicuity of small, low-contrast multiple sclerosis plaques. This comparison reveals that small lesions may be missed when thick slices are used despite the absence of a gap between slices. When there is diffusely distributed disease, thin slices even with a gap may be preferable to thick contiguous slices.

***A*, 5-mm slice through centrum semiovale showing definite multiple sclerosis plaques (*arrow*).**

***B*, 10-mm slice through same level as *A* with significantly decreased lesion conspicuity (*arrow*).**

***C*, 5-mm section through lateral ventricles showing several demyelinating plaques (*arrows*).**

***D*, 10-mm slice through same section as *C* showing decreased lesion conspicuity (*arrows*). All images acquired with 0.95-mm in-plane spatial resolution (256 × 256 acquisition matrix), two excitations, 17-min acquisition time, TR = 2.0 sec, TE = 30 (*B*, *D*) or 40 msec (*A*, *C*).**

certain settings in which this restriction may decrease lesion detection.

Barring signal-to-noise limitations, thinner slices decrease partial volume effects, increasing the detection rate, particularly for low-contrast lesions. At constant TR (allowing the same number of slices in a 2DFT multislice acquisition), decreasing the thickness of multiple contiguous slices would decrease the coverage [4]. To cover a specified imaging volume (e.g., the entire brain) with thinner slices would thus entail an increase in total study time, which may be unacceptable in certain clinical settings [4]. For fixed study time, this analysis shows that lesion detection may be increased using thinner slices, even with an interslice gap. While it is obvious that small lesions within the gap will not be detected, it is less obvious that small, low-contrast lesions may not be detected at all with thicker slices.

For high-contrast lesions that need only fill a small percentage of a thick slice to be detected, the presence of the gap limits the lesion-detection rate. For lower-contrast lesions, however, partial volume effects are the main limitation to detecting them. As suggested by Figure 4, small MS plaques may be totally undetected with thick slices but may be well seen with thinner slices. Thus, for diffusely distributed disease involving small, low-contrast lesions, thin slices even with a gap between them may be preferable to thick, contiguous slices.

While the effect of decreasing slice thickness on S/N (and therefore on C/N) has been ignored, this is only strictly possible at high enough intrinsic values of S/N that such losses are imperceptible. Holding all the parameters constant, a decrease in the slice thickness will cause a proportional (i.e., linear) decrease in the S/N [5]. Since visual perception is logarithmic, such proportional decreases in S/N are actually only perceived as such at very low values [5]. Thus, to include the quantitative effect of changing slice thickness on perceived C/N would require knowledge of the absolute value of S/N as well as knowledge of a complex visual perception function (which is well beyond the scope of the present analysis). In reality, perceptible losses in S/N resulting from thinner slices are usually offset by additional excitations [5] or by decreasing the bandwidth. Increasing the number of excitations has the unfortunate side effect of increasing the acquisition time [6], while a lower bandwidth generally requires a longer echo delay time (TE). (The longer TE [40 msec] in Figs. 4A and 4C compared with 30 msec in Figs. 4B and 4D is the result of prolonging the echo sampling time to decrease the bandwidth.)

Unfortunately, Figure 4 is not a pure comparison; that is, TE, bandwidth, and S/N cannot be held constant while only varying slice thickness. Thus, while Figure 4 is intended primarily to demonstrate the effect of decreasing slice thickness on C/N, this will be influenced by the longer TE, the thinner slice, and the reduced bandwidth. Assuming T2 values of 75 msec for white matter and 94 msec for MS plaques [7], increasing the TE from 30 to 40 msec increases contrast by 14% (due to greater T2-weighting) and decreases S/N by 12% (due to greater T2 decay). The 50% reduction in slice thickness results in a 50% reduction in S/N and, therefore, in C/N. This is partially compensated by the reduced bandwidth, which increases S/N by approximately 14% (Mark Winkler, personal communication). How these second-order effects influence the perceived "conspicuity" of the lesions in Figure 4 depends in the final analysis on the absolute value of S/N and on the complicated process of visual perception.

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