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Assessment of MR Image Deformation for Stereotactic Neurosurgery Using a Tagging Sequence

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Summary: A tagging sequence is used to assess MR image deformations before a stereotactic neurosurgical procedure, in a test model and in two patients. This pulse sequence superimposes narrow parallel orthogonal tag lines on an image, which can be used as an internal reference frame. Image deformation is directly related to surface area variations in the squares produced by the tagging-sequence pulses. Small spatial deformations of the tags can be detected on the images used for measuring stereotactic-target spatial coordinates. A threshold of 2 SD guarantees that the distortion is smaller than one pixel.

Index terms: Biopsies, stereotactic; Biopsies, MR guidance; Brain, biopsy; Images, interpretation

The use of neurosurgical stereotactic methods in conjunction with new imaging techniques for diagnostic and therapeutic interventions is rapidly increasing. The basic principle of stereotaxy is precise definition of intracranial target coordinates in relation to an extracranial reference system attached to the head of the patient (1). Surgical accuracy requires images free from geometric deformations. For precise spatial location, computed tomographic examinations recently have been used. However, some lesions are seen better with magnetic resonance (MR) than with computed tomographic examination, and it is accepted that MR also could be a valuable tool for stereotactic guidance (1). Unfortunately, MR images are susceptible to spatial distortions, which hamper precise stereotactic guidance. Thus, it is necessary to assess image distortions before stereotactic procedures are performed when using MR.

MR image distortions produced by static-field inhomogeneities or by gradient nonlinearities can be easily corrected by using appropriate phantoms and by slightly modifying the reconstruction algorithms (2). Nevertheless, the patient also causes field inhomogeneities, which can be significantly increased by the presence of, for example, dental materials (3). Because these inhomogeneities are related to the individual patient, they are very difficult to estimate. In this article, we propose a method for the assessment of the distortion induced by the patient on the image used for stereotactic target location. This study was designed to detect and measure image distortion caused by the patient; no correction algorithms were used.

Toward this end, we modified a standard spin-echo sequence to produce a DANTE tagging (DT) sequence, which adds to the image a pattern of saturation bands. A similar approach has been used by Axel et al with binomial pulses (4, 5) for the imaging of heart wall motion. Mosher et al proposed the use of DT for the display of general motion (6) and for the measurement of variations in magnetic susceptibility (7). A DANTE pulse train applied in the presence of a constant-field gradient before a standard spin-echo sequence adds parallel tag lines on the image. Two DANTE pulses applied with orthogonal gradients generate a black grid pattern superimposed on the image. The distance between the tag lines and their thickness can be varied by adjusting the magnitude of the gradient field, the DANTE interpulse delay, and the total length of the DANTE pulse train (6). The distortion of the grid observed in such an image provides a map of the magnetic-field inhomogeneities intrinsic to the MR machine and/or created by the patient. Measurement of

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this grid distortion provides a direct measurement of the total image distortion (8).

Materials and Methods

Studies were performed on a 1.5-T whole-body MR installation (Siemens Magnetom 63SP; Siemens Medical Systems, Erlangen, Germany). A standard T1-weighted spin-echo sequence (700/20/1 [repetition time/echo time/excitations]) has been modified by adding two DT pulses (9, 10) before the usual 90° excitation pulse. The sequence is shown in Figure 1. The DANTE pulse train has a total duration of 2260 μsec. It is composed of 15 pulses of 20 μsec each with an interpulse delay of 140 μsec. Two DANTE pulses were applied successively in the presence of a 4-mT/m (0.4-Gy/cm) tagging gradient, respectively, in the readout and phase-encoding directions. The intensity of the tagging gradients was of the same order of magnitude as the readout and phase-encoding gradients used in a normal T1- or T2-weighted imaging sequence. Using these parameters, the two DANTE pulses generated a low-intensity (black) grid superimposed on the image with a line thickness of 3 mm and a distance of 15 mm between the lines.

Image analysis was performed on a Macintosh personal computer (Apple Computer, Cupertino, Calif) with the program IMAGE (public-domain software; National Institutes of Health, Bethesda, MD), which allows the measurement of the area of the squares defined by the saturation grid. The exact determination of these areas was obtained by an analysis of pixel intensities. The mean value of the pixels undoubtedly inside the square was considered as 100% and the background noise as 0%. We arbitrarily considered a pixel to be inside the square if its value is 20% over background. Variations in the area measurements provided measurements of image distortion.

To test the applicability of the DT sequence described above to evaluate geometric distortions, a cylindrical test object was designed and filled with doped water (manganese chloride), with a hole off center, as shown in Figure 2. In this hole, polyethylene bottles filled with different aqueous mixtures of gadolinium-tetraazacyclododecanetetraacetic acid (Gd-DOTA) or metallic objects were introduced. Because the distortions caused by susceptibility differences were position related, the measured squares were referenced according to their distance from the polyethylene bottles. We also measured the shift in pixel location at each intersection of the grid.

This technique was subsequently applied to a patient with a needle accidentally left in the occipital scalp and to a patient with a low-grade astrocytoma, visible only with MR, who underwent an MR stereotactic location procedure. Two T1-weighted DT sequences were applied in the sagittal and transverse planes before the usual T2-weighted transverse sequence.

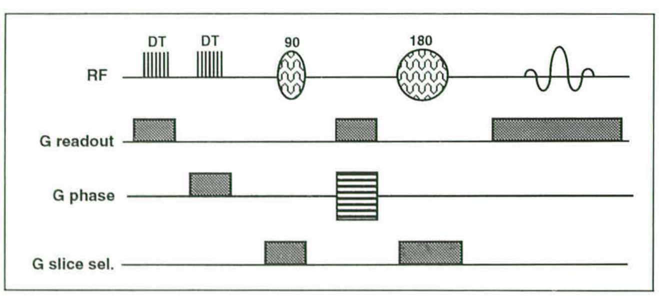


Fig. 1. The DT sequence, a standard spin-echo sequence preceded by two DANTE pulses applied successively with a magnetic-field gradient in the readout and phase-encoding directions.

Results

T1-weighted spin-echo images of the phantom are presented in Figure 2. The *squares* outlined by the orthogonal black tag lines are numbered 1 to 4, according to their distance from the hole (Fig 2A). A qualitative evaluation of the images shows the different distortions induced by the samples placed in the hole of the phantom. The distortions can be better appreciated with the superimposition of a grid on the image as shown on the *right* side of Figure 2. Figure 3 shows the standard error of measurements of the mean area of the squares as a function of the distance from the hole and shows an obvious increase with increasing local deformations of the grid. This measurement can be used as an index to evaluate the magnitude of geometrical distortions. On Figure 2D compared with 2A the intersections of the grid are shifted by a maximum value of four pixels in zone 1, two pixels in zone 2, one pixel in zone 3, and less than one pixel in zone 4. Comparing Figure 2C with 2A, the maximum shift is three pixels in zone 1. For Figure 2B, the maximum shift is two pixels in zone 1. To evaluate the degree of image distortion, we placed a horizontal line in Figure 3 at a value equal to two times the standard error of the measurement of all the square areas on the deformation-free image presented in figure 2A. We arbitrarily propose this value as a threshold to decide if any significant distortion is present in an image (97.7% confidence level for a gaussian distribution). This value corresponds to a distortion smaller than one pixel.

Figure 4 shows one sagittal and five transverse images obtained with the DT sequence (700/20, 256 × 256 matrix, 350-mm field of view, 12 sections of 5-mm section thickness, 10-mm intersection gap) of a patient with a needle accidentally left in his occipital scalp. The distortion of the MR images induced by the metallic fragment is highlighted by the tag lines. Figure 5 shows the variation of the square areas entirely included in

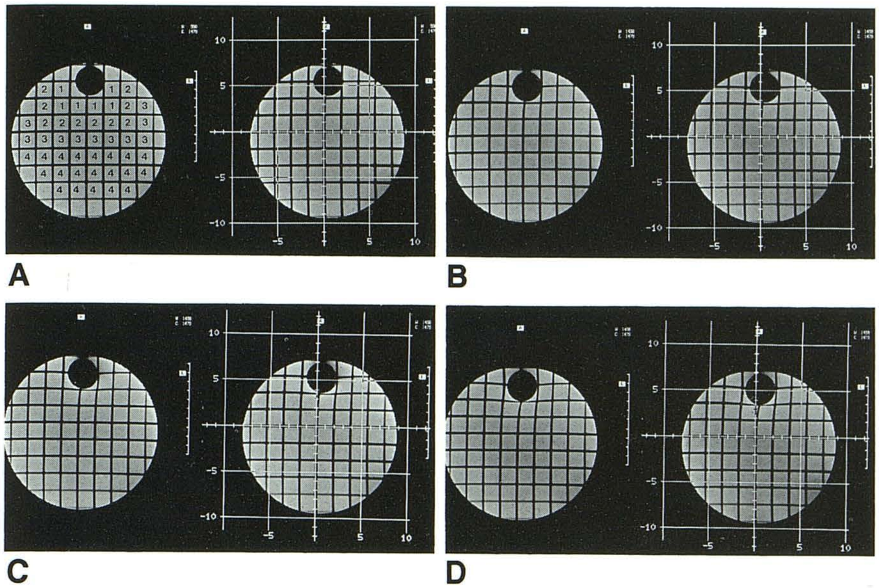


Fig. 2. DT superimposed on images of a phantom. The hole off center is empty (*A*), filled with a solution of Gd-DOTA at 0.25 mol/L (*B*), filled with a solution of Gd-DOTA at 0.5 mol/L (*C*), and probed with a metallic needle (*D*). For qualitative assessment of distortion a grid is superimposed on the images on the *right*. *Squares* are referenced from 1 to 4 according to their distance from the hole.

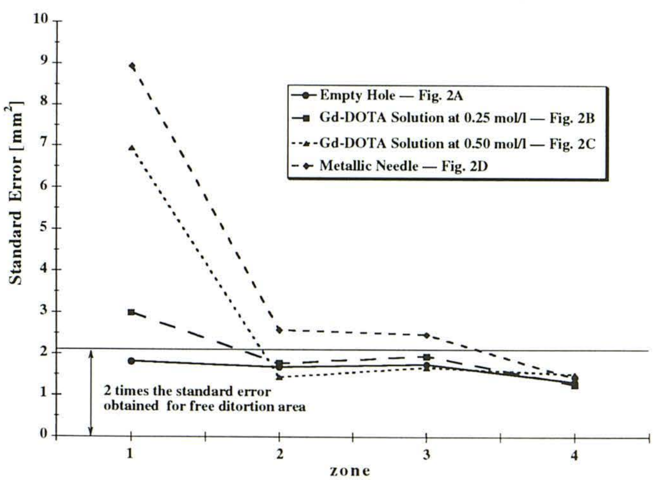


Fig. 3. The standard error in the measurements of square areas of the four zones defined in Figure 2A for the three samples used as artifact sources in Figures 2B, 2C, and 2D.

the brain. The standard error value is high for sections close to the artifact source.

The DT sequence has been applied to a patient having a low-grade astrocytoma who underwent a stereotactic biopsy with MR guidance. Figures 6A and 6B show the first and second echo of a T2-weighted sequence with a hyperintense signal from the frontal lesion. Because the stereotactic frame (BWR system; Radionics, Burlington, Mass) was better shown on the first echo of the T2-weighted sequence, this image has been used for target location. Figure 6C shows a T1-weighted DT image at the same level. The standard error of the square areas was below the approximately 2-SD threshold of significant distortion, confirming that the image was an accurate representation of the patient and therefore suitable for use in target location.

Discussion

Quality control of modern MR scanners includes assessment of the geometrical deformations; image distortion from nonpatient sources is generally well corrected. Such quality-control measurements include the parameters controlling the dimension of the DT grid and insure its stability over time. In addition, the global linear uncertainty in the position of each image point is corrected. However, patient-induced distortions are frequent. To increase the safety of stereotactic procedures under MR guidance it is necessary to assess nonlinear image distortion directly on the images used for target location. DT sequences have been proposed to asses cardiac motion (5) or magnetic susceptibility changes. In the latter case Mosher and Smith (6) used a DANTE pulse with a very weak gradient and tuned the pulse to obtain a grid pattern strongly affected by small-field heterogeneities induced by magnetic susceptibility variations.

In order to assess image distortion we have tuned our DANTE pulse to produce a grid pattern with a tagging gradient of the same order of magnitude as the readout gradient used in usual T1- or T2-weighted spin-echo sequences. The distortion of the grid we observe with this procedure gives an accurate reflection of actual image distortion. Image analysis is made by measuring the area of the squares defined by the DT and by computing the standard error of these

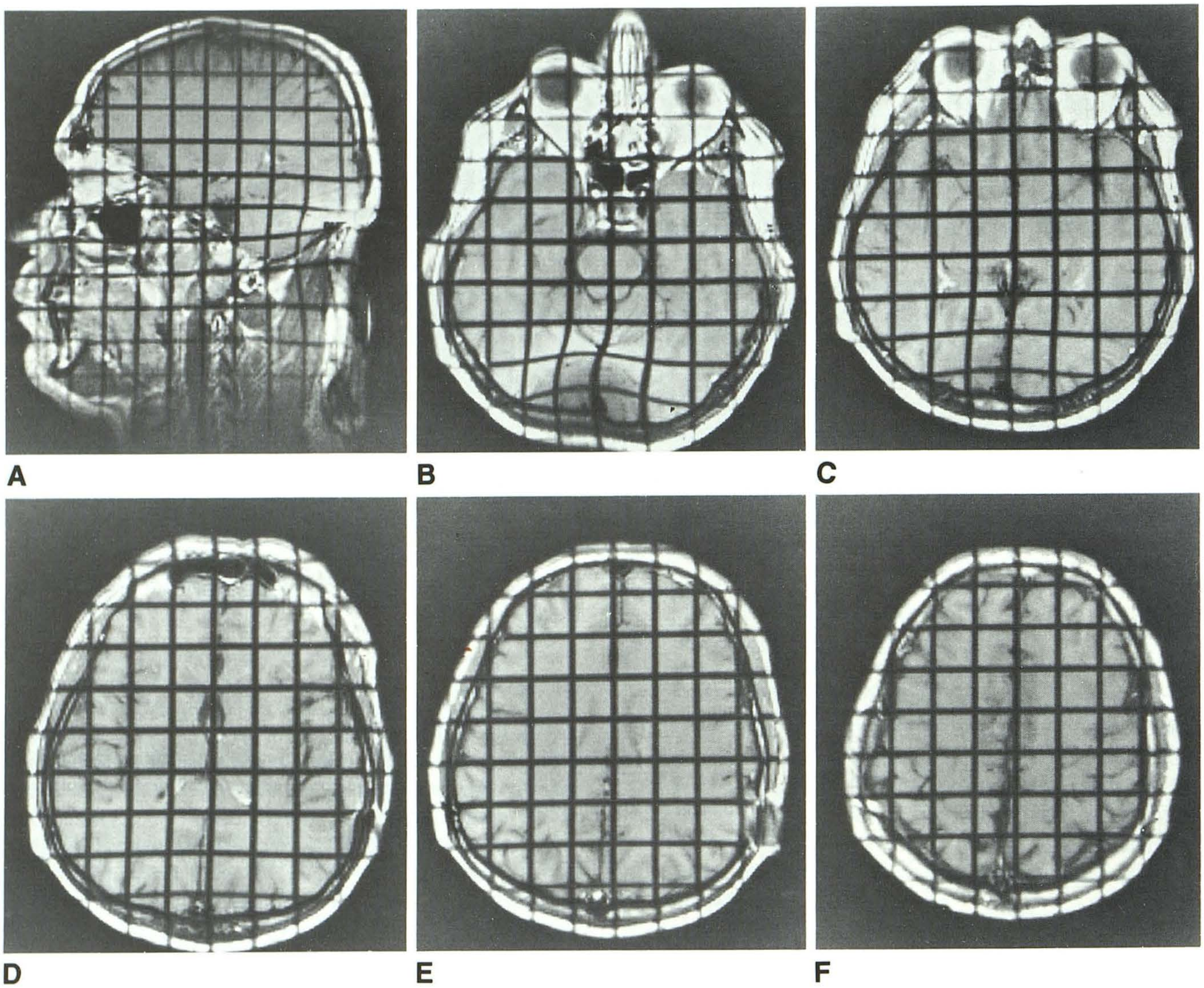


Fig. 4. Sagittal (*A*) and transverse (*B-F*) T1-weighted DT images of a patient with a needle accidentally left in his occipital scalp (700/20, 256 × 256 matrix, 350-mm field of view, 5-mm thickness, 10-mm intersection gap).

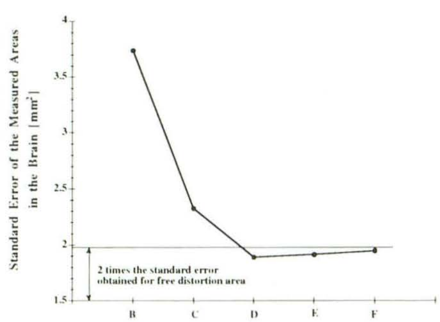
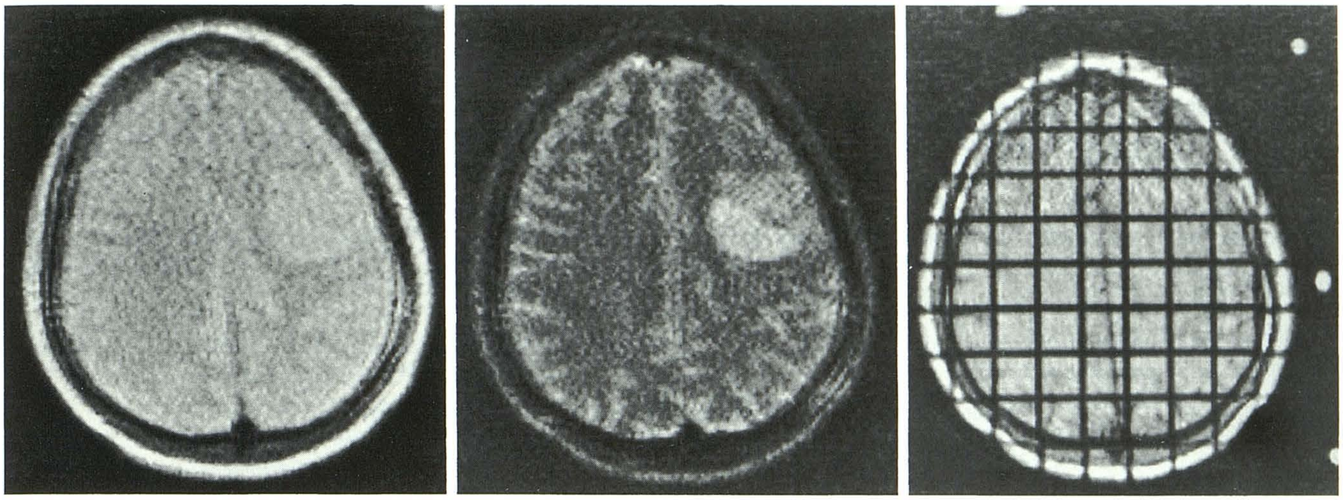


Fig. 5. Measurement of the standard error of the square areas entirely included in the brain for the sections shown in Figures 4B to 4F.

areas. We use a thresholding method to discriminate the pixels within the square and on the grid. This technique is easy to use because of the high contrast and sharp delineation of the grid. It also avoids intra- and interobserver variability. Calculation of standard error reflects the variation in size of the squares. This parameter is a good assessment of the distortion. Area measurements within 2 SE of the nondistorted area are proposed as a limit value. According to the phantom study, this value ensures that the distortion is smaller than one pixel. Thus the stereotactic target location will be within instrument error. This simple image analysis is used to reject cases with distorted images. In such a case we would advise giving up stereotactic guidance, even if the DT technique might be used as the basis of a correction algorithm.

The DT sequence can be, of course, T1 or T2 weighted depending on the repetition-time and



A B C

Fig. 6. First (*A*) and second (*B*) echoes of a T2-weighted sequence (2500/22–90, (256 × 256 matrix, 350-mm field of view, 5-mm thickness, 1-mm intersection gap) obtained on a patient with a low-grade astrocytoma who underwent a stereotactic biopsy with MR guidance.

C, DT T1-weighted image at the same level. Images were obtained with the body coil with its lower signal-to-noise ratio because the stereotactic frame would not fit in the head coil.

echo-time values chosen. The use of two orthogonal planes better demonstrates in-plane and through-plane distortions. In normal stereotactic procedures, we start with T1-weighted sagittal and transverse DT sequences to obtain a rapid assessment of distortion, followed by a T2-weighted sequence without DT to define the best target location. In this way qualitative evaluation of distortion is instantly made by adding an overlay grid to the T1-weighted DT images as detailed above. Then quantitative evaluation is made by measuring the standard error of the squares. This calculation could be automated and performed by the MR scanner computer. In conclusion, this technique provides the surgeon with a simple and quick way to increase the safety of MR-guided stereotactic procedures.

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