Mapping the Static Magnetic Field Using a Double-DANTE Tagging Sequence

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The image and spectral artifacts generated by static magnetic field ($B_0$) inhomogeneity have been the subject of several recent studies (1–4). To further evaluate these artifacts and develop methods for minimizing their effects it is necessary to measure small fluctuations in the magnetic field throughout the region of interest. Previous field-mapping techniques have utilized the measurement of phase shifts induced by the difference in the $B_0$ field (5–10). These methods have several limitations. First, a phase difference is typically measured requiring a minimum of two images to generate the field profile (11). As such, phase techniques can be time consuming and prone to artifacts if experimental conditions vary between images. Second, with magnitude-calculated images the phase map describes only the difference in field and not the absolute field strength. Third, errors arise from the phase shift induced in the transverse magnetization by the movement of molecules across a magnetic field gradient (12, 13). With phase techniques it is difficult to differentiate the effects of motion from those generated by magnetic field inhomogeneity. As a result these techniques cannot be used quantitatively with heterogeneous samples where the effects of motion may be nonuniform. Ideally one would prefer to determine the resonance frequency of water across a region of interest and thereby avoid the inherent limitations of phase techniques.

In this paper we report a method for mapping the resonant frequency in a single image using a double-DANTE-tagging (DDT) sequence. This sequence was previously described for the determination of sample motion (14). The DDT sequence uses a DANTE pulse train (15) in the presence of a continuous magnetic field gradient to spatially encode the magnetization within the sample just prior to imaging. Preirradiation with the DANTE pulse train produced excitation at the carrier frequency and the DANTE harmonic frequencies. These excited or "tagged" regions appear as a set of parallel dark lines in the subsequent image. The spacing between the lines is inversely proportional to the magnitude of the tagging gradient and the DANTE interpulse delay. It is possible to decrease the distance between adjacent tags by modulating the phase of the individual DANTE pulses as has previously been described in the double-DANTE experiment (16). With specific regard to the DDT sequence, modulation of the phase ($0°–90°$) results in excitation at two frequencies and will decrease the distance
between the lines by one-half. The distance between lines can be reduced by a factor of four by modulating the phase \((0^\circ - 180^\circ - 0^\circ - 0^\circ)\) (14).

Each tag represents an isochromat across regions where the total magnetic field is of equivalent magnitude. If the magnitude of the tagging gradient is small the position of the RF tag is sensitive to the inhomogeneity of the magnetic field. When the \(B_0\) field is homogeneous and the applied field gradient is linear, the tags will appear as straight, parallel lines. In this ideal case the position of the tag in the NMR image is a function of the frequency of the DANTE irradiation and the magnitude of the applied tagging gradient. Under conditions of an inhomogeneous \(B_0\) field the local field distortions shift the position of the lines in the NMR image. In a region where the \(B_0\) field is increased, the position of the tag must be shifted to a position where the applied tagging gradient is reduced by an equivalent amount. Likewise in areas where the \(B_0\) field is decreased, the tag is displaced to a higher gradient strength in order to compensate for the decrease in field. From the magnitude of the applied tagging gradient and the displacement of the tag in the NMR image it is possible to quantitatively measure the regional field perturbation.

To demonstrate the utility of this sequence in generating field maps, we obtained results using a Bruker AM-400 WB spectrometer equipped with microimaging capability and operating at 400 MHz for protons. Sample phantoms consisted of 18 mm i. d. NMR tubes filled with a 5 mM EDTA solution. Images of \(256 \times 256\) pixels were obtained with a slice thickness of 500 \(\mu m\) and an inplane pixel resolution of \(100 \times 100 \mu m\) using a single-slice spin-echo imaging sequence perpendicular to the \(B_0\) field. All images were taken with an echo time (TE) of 25 ms and a repetition time (TR) of 1090 ms. The images are displayed with the frequency-encoding axis along the \(X\) axis with higher frequency toward the left. The phase-encoding axis is shown with higher frequency at the bottom of the image.

A double-DANTE pulse train employing 20 pulses and an interpulse delay of 6.25 ms were employed to generate the tags in the presence of a 0.0928 G/cm tagging gradient. This gradient strength was chosen to give an approximately 400 Hz (1 ppm) shift over 1 cm. Thus a 1 mm shift in the line position corresponds to a 0.1 ppm difference in the magnetic field. The phase of the individual DANTE pulse was modulated \((0^\circ - 180^\circ - 0^\circ - 0^\circ)\) to generate evenly spaced tags at an interval of 40 Hz (0.1 ppm). With the phase-modulated sequence the tagging time was 125 ms per axis. Thus the bandwidth of the tags is approximately 8 Hz, which corresponds to a tag thickness of 200 \(\mu m\) or 2 pixels. The standard DANTE train in which the phase is not modulated would require an interpulse delay of 25 ms to achieve an equivalent tag interval. Note that this would result in a tagging time of 500 ms, with a tag thickness of 50 \(\mu m\), which is smaller than 1 pixel in width. The overall sensitivity of this technique is limited by the field change necessary to displace the line by a distance of 1 pixel, which in this study corresponds to a field change of 4 Hz (0.01 ppm).

Time-dependent field fluctuations, which also vary spatially, may be introduced by eddy currents generated from pulsed magnetic field gradients. To evaluate the feasibility of using this sequence to map the spatial component of eddy currents, the tagging period was preceded by a 10 ms gradient pulse at half-maximal gradient amplitude (23 G/cm) along the \(X\) axis. The gradient preemphasis was adjusted to minimize eddy currents. When the optimized gradient pulse was followed by a 3.0 ms delay there was no increase in the water linewidth.
Figure 1 demonstrates the sensitivity of the DDT sequence to $B_0$ field inhomogeneity. Prior to acquiring the DDT image the field homogeneity within the phantom was optimized on the water signal to yield a linewidth of 40 Hz over the entire sample volume. The results of a single-slice DDT image through the center of the phantom are presented in Fig. 1a. The distortions noted at the edge of the phantom demonstrate regions of field inhomogeneity. In Fig. 1b the magnetic field was purposely made inhomogeneous by changing the value of the $XY$ room temperature gradient. As can be seen in this image there is notable distortion in both the $X$ and the $Y$ lines, with the tags shifted toward lower frequency. This distortion in field is most evident in the upper right corner of the image. In Fig. 1c, the $Z^3$ room temperature gradient has been grossly misadjusted. As expected this generates large field gradients at the periphery of the phantom, demonstrated by the loss of line resolution. Within the center of the phantom the field remains homogeneous as indicated by the presence of a uniform grid.

The effects of eddy currents on the tagged image are demonstrated in Fig. 2. In Fig. 2a the gradient preemphasis has been adjusted to minimize eddy-current effects. Near the edge of the phantoms there are clear regions where the lines are poorly resolved and slightly displaced. In Fig. 2b the $X$-gradient preemphasis was misadjusted to produce significant distortions in the water peak. With the DDT image there is marked displacement and loss of resolution in the tags along the $X$ axis. These effects are most noticeable across the $X$ axis of the phantom. Two effects may account for this observation. First, the displacement of the RF tag is most sensitive to orthogonal field gradients. Large field gradients along the $X$ axis would be expected to cause significant displacement of primarily the $X$ tags. Second, the $X$ tags are placed prior to the placement of the $Y$ tags. Thus field gradients which diminish with time would produce distortions in the $X$ lines without affecting the $Y$ lines.

The generation of eddy currents in the system results in both gross displacement of the RF tags and loss of line resolution. It is suggested that these effects are determined by the decay time of the eddy currents in comparison to the frequency at which the DANTE pulses are applied. Eddy currents which persist with time will act to displace the tags due to their effect on the local $B_0$ field. Eddy currents which rapidly change in amplitude will act to destroy the coherence of the transverse magnetization generated by the DANTE pulses. This increases the effective bandwidth of the DANTE tag, producing poorly resolved lines. Sample motion due to acoustical ringing generated by the pulsed gradient could produce a similar appearance. However, if this were the case one would expect the phenomenon to be uniformly distributed throughout the phantom rather than in the localized pattern observed.

With the DDT sequence, the effects of diffusion and stochastic flow are different from those observed with phase mapping. These processes result in a mixing of the tagged and untagged spins which in theory may increase the linewidth and decrease

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Fig. 1. A 400 MHz $^1$H microimage of an 18 mm phantom demonstrating the effect of $B_0$ inhomogeneity. A shift of 1 mm in line position corresponds to a field change of 0.1 ppm. The images are displayed with increasing frequency toward the left and bottom of the image. (a) Optimized room temperature gradients resulting in a water linewidth of 40 Hz. (b) $XY$ room temperature gradient misadjusted and (c) $Z^3$ room temperature gradient misadjusted to generate an inhomogeneous $B_0$ field.
the overall grid contrast. Since they do not result in displacement of the tags, they do not cause an error in the measurement of magnetic field. In practice, the width of the tag is significantly greater than the diffusion path length of water for typical tagging times. As a result, diffusion does not significantly alter the observed lines. Coherent sample motion, such as that which occurs with a rotating sample or a beating heart, will cause a translational displacement of the tags which could be mistaken for a change in field. Typically, most types of motion are obvious and have a characteristic pattern which may be identified. Motional artifacts can be reduced by gating the acquisition to the periodicity of the movement.

In this study, we have demonstrated the utility of the sequence for evaluating magnet homogeneity. The resulting images are sensitive to changes in field of 0.01 ppm, with
a spatial resolution of 100 μm. The sensitivity can be further increased by decreasing the field of view of the image or the magnitude of the tagging gradient. The technique provides spatial information for evaluating eddy currents which is currently very difficult to obtain. A spatial description of the effects of eddy currents might be useful both in the design of new gradient technology and in the evaluation of current imaging systems. By evaluating the types of distortions observed, it is possible to infer temporal information regarding these field fluctuations. Other potential uses for this technique include measuring susceptibility effects, artifacts generated by implants, and chemical-shift differences within an image.

In conclusion the DDT sequence provides a simple, sensitive method for rapidly mapping the resonant frequency in a magnetic resonance image. Unlike phase-mapping techniques, this sequence requires only one image to generate a field map, thereby reducing the time required to perform the experiment and minimizing potential artifacts generated by differences in experimental parameters. Since this technique measures absolute frequency, it can differentiate between regions of diamagnetic and paramagnetic susceptibility within a sample. Due to the narrow excitation profile of the DANTE pulse train thin lines may be generated even in the presence of very small tagging gradients. By modulating the phase of the pulse train the number of tags can be increased. As a result the DDT sequence can be made extremely sensitive to small changes in B0 field, yet still maintain good spatial resolution. Also the sensitivity to field inhomogeneities and the spatial resolution may be adjusted independently, allowing the sequence to be optimized for a specific task. As described previously, the DDT sequence is a very flexible method for generating RF tags within a sample. It does not require hardware modifications to existing systems and can easily be adapted to run on standard imaging systems. For the sequence described above the technique can be expanded to multislice or 3D acquisitions.

REFERENCES