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MR Imaging of Magnetic Ink Patterns via Off-Resonance Sensitivity

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Abstract

Purpose—Printed magnetic ink creates predictable B_0 field perturbations based on printed shape and magnetic susceptibility. This can be exploited for contrast in MR imaging techniques that are sensitized to off-resonance. The purpose of this work was to characterize the susceptibility variations of magnetic ink and demonstrate its application for creating MR-visible skin markings.

Methods—The magnetic susceptibility of the ink was estimated by comparing acquired and simulated B_0 field maps of a custom-built phantom. The phantom was also imaged using a 3D gradient echo sequence with a presaturation pulse tuned to different frequencies, which adjusts the range of suppressed frequencies. Healthy volunteers with a magnetic ink pattern pressed to the skin or magnetic ink temporary flexible adhesives applied to the skin were similarly imaged.

Results—The volume-average magnetic susceptibility of the ink was estimated to be 131 ± 3 ppm across a 1-mm isotropic voxel (13,100 ppm assuming a 10- μ m thickness of printed ink). Adjusting the saturation frequency highlights different off-resonant regions created by the ink patterns; for example, if tuned to suppress fat, fat suppression will fail near the ink due to the off-resonance. This causes magnetic ink skin markings placed over a region with underlying subcutaneous fat to be visible on MR images.

Conclusion—Patterns printed with magnetic ink can be imaged and identified with MRI. Temporary flexible skin adhesives printed with magnetic ink have the potential to be used as skin markings that are visible both by eye and on MR images.

Keywords

magnetic ink; magnetic susceptibility; field mapping; skin markings

Introduction

Magnetic susceptibility differences between materials create geometry-dependent variations in the static magnetic (B_0) field (1); this off-resonance produces artifacts such as signal loss,

failure of fat suppression, and geometric distortion in MR images (2). These artifacts are commonly seen near air-tissue interfaces or metal implants inside the body. To mitigate these artifacts and improve image quality, spin-echo sequences and short echo times can be used to reduce signal loss, and high readout bandwidths can be used to reduce geometric distortion (3). Various specialized methods address the challenges of imaging the large susceptibility variations near metal, including view-angle tilting (4) and multi-spectral imaging (MSI) techniques such as SEMAC (5), MAVRIC (6), and 2D MSI (7).

Magnetic ink is used to print bank checks for magnetic ink character recognition (MICR) so that account numbers can be automatically recognized by bank machinery; it has a higher iron oxide content than modern conventional printer ink, and a much higher magnetic susceptibility than that of water. Similar to metal implants, patterns printed with magnetic ink therefore create B_0 variations when placed inside an MR scanner. It has been noted previously that such patterns can be used intentionally as passive shims (8), but should be avoided during imaging due to unwanted artifacts (9). This work proposes that through careful adjustment of the shape, size, and density of printed ink to provide a desired, limited susceptibility difference, the resulting off-resonance can potentially be exploited in order to visualize the ink pattern in MR images.

If magnetic ink patterns of desired shape and size are applied to the skin as temporary flexible adhesives, they can be used as skin markings that are visible both by eye and in MRI. Compared with current MR markers such as Beekley spots or IZI Medical markers, skin markings of arbitrary shape that are thin, flexible, and can be left on for days may offer advantages in applications such as fusion of MR data to the body via augmented reality, surgical planning, radiation therapy, tracking of joint movement, or other image registration scenarios.

The purpose of this work was to characterize the magnetic susceptibility of magnetic ink, to evaluate the ability to see magnetic ink patterns in MRI via gradient-echo scans with spectral presaturation, and to assess the efficacy of temporary flexible adhesives printed with magnetic ink for use as MR-visible skin markers in vivo.

Methods

Phantom Construction

The lid of a polypropylene container (LOCK & LOCK USA, INC., Gardena, CA) was modified to attach a custom-built acrylic clamping system that suspends a laminated piece of paper in the middle of the container body. A 2.5 cm-diameter circle was printed with laser printer magnetic ink (microMICR Corporation, Dania, FL) on standard printer paper, which was trimmed, laminated, and submerged in water filling the container body (reference photos in Fig. 1). The circle plane was oriented parallel to the B_0 field when the phantom was placed inside the scanner.

Magnetic Susceptibility Estimation

It is important to have an accurate estimate of the magnetic susceptibility in order to characterize the off-resonance caused by the ink and therefore design appropriate patterns

for skin markings. A flowchart of the MR-based method for estimating the volume-average magnetic susceptibility (χ) of the magnetic ink is shown in Figure 1; this method incorporates measurements taken in the same scanner environment as where the skin markings will ultimately be used, and therefore accurately reflects the off-resonance.

Coronal 3D gradient-echo scans of the phantom were acquired on a GE Discovery MR750 3T scanner (GE Healthcare, Waukesha, WI) using an 8-channel cardiac coil with: 25.6 cm field of view (FOV); 1 mm slice thickness; 256×256×80 matrix; repetition time (TR)=15.0 ms; echo time (TE)=4.0, 4.5 ms; 5° flip angle; ±125 kHz bandwidth. B_0 field maps were calculated based on the difference in phase accumulation between the scans (10,11); the TE=0.5 ms resulted in maps of ±1 kHz bandwidth. This TE was chosen to obtain a field map bandwidth large enough to prevent aliasing in the off-resonance shifts caused by the ink pattern.

Field perturbations caused by a distribution of magnetic susceptibility values ($\chi(\mathbf{r})$, where $\mathbf{r}$ denotes 3D spatial coordinates) across a volume can be estimated by convolving $\chi(\mathbf{r})$ with a dipole-pattern kernel (3,12,13). This can be represented as a multiplication in the k-space domain after Fourier transformation and is calculated via:

$$\Delta\tilde{B}_0(\mathbf{k}) = B_0 \left(\frac{1}{3} - \frac{k_z^2}{k_x^2 + k_y^2 + k_z^2} \right) \tilde{\chi}(\mathbf{k}), \quad [1]$$

where the tilde denotes a Fourier transform, and $\mathbf{k}$ denotes the k-space coordinates (3).

Simulated B_0 field maps (1 mm isotropic resolution to match the acquired field maps) were generated in MATLAB (MathWorks, Natick, MA) using Eq. 1 with test χ values of 10 to 500 ppm in intervals of 10 ppm. Note that the estimate for χ of the magnetic ink is a volume-average estimate due to the resolution limits of the simulation—it assumes a printed ink thickness of 1 mm when in reality the ink can be estimated as 10 μm thick (14,15).

The mean squared error was calculated between the acquired field map and each simulated field map in high-signal areas near the center of the phantom; the estimate for χ was determined by minimizing that error. After calculating an initial estimate of $\chi=130$ ppm, the search range was reduced to 110 to 140 ppm in intervals of 1 ppm. The variability in the estimate for χ due to measurement noise was assessed by repeating the experiment 20 times.

Phantom Imaging

Coronal 3D gradient-echo scans of the phantom with a spectral presaturation pulse (600 Hz full bandwidth) were acquired using: 25.6 cm FOV; 1 mm slice thickness; 256×256×84 matrix; TR=8.7 ms; TE=1.7 ms; 5° flip angle; ±125 kHz bandwidth. The saturation frequency (relative to water) was adjusted from −500 to 500 Hz in intervals of 10 Hz.

In Vivo Imaging

Informed consent was obtained from all subjects before scanning, as approved by our university's institutional review board.

Coronal 3D breath-held gradient-echo scans with a spectral presaturation pulse (600 Hz full bandwidth) of a healthy male volunteer with a magnetic ink pattern printed on paper pressed against the skin of the chest were acquired using the 8-channel cardiac coil with: 32.0 cm FOV; 1 mm slice thickness; 256×100×32 matrix; TR=8.3 ms; TE=1.2 ms; 5° flip angle; ±125 kHz bandwidth, 27 s scan time. The saturation frequency (relative to water) was tuned to suppress fat (−440 Hz), both fat and water (−220 Hz), or neither (−880 Hz).

Sagittal 3D gradient-echo scans with spectral presaturation of a healthy volunteer with flexible adhesive patterns printed in magnetic ink using temporary tattoo paper (BEL USA LLC, Medley, FL) applied to the skin of the calf were acquired using a 16-channel knee flex coil (NeoCoil, Pewaukee, WI) with: 25.6 cm FOV; 1 mm slice thickness; 256×256×130 matrix; TR=8.9 ms; TE=1.2 ms; 15° flip angle; ±125 kHz bandwidth. The saturation frequency was tuned to suppress fat (−440 Hz) or water (0 Hz).

Coronal 3D breath-held gradient-echo scans with spectral presaturation of a healthy male volunteer with a temporary flexible adhesive grid pattern (2.5-cm squares, 0.6-cm thick lines) printed in magnetic ink applied to the skin of the chest were acquired using the 8-channel cardiac coil with: 36.0 cm FOV; 2 mm slice thickness; 256×100×72 matrix; TR=7.6 ms; TE=0.8 ms; 5° flip angle; ±125 kHz bandwidth, 28 s scan time with parallel imaging (acceleration=2×1). The saturation frequency was tuned to suppress fat (−440 Hz), water (0 Hz), both fat and water (−220 Hz), or neither (−880 Hz). The volunteer was imaged in two positions (with the arm down at the side, and with the arm up above the head) in order to assess the deformation of the grid pattern.

Results

Magnetic Susceptibility Estimation

Example acquired and simulated B_0 field maps of a coronal slice of the phantom are shown in Figure 1. The field maps are displayed over a range of ± 500 Hz for better visualization of the off-resonance caused by the ink pattern. The circle pattern creates regions of negative off-resonance anterior and posterior to itself as well as to the left and right, and superior and inferior regions of positive off-resonance. Note that the acquired field map shows variations at the superior and inferior edges of the phantom due to the air-water boundary. However, the printed magnetic ink pattern is small enough in size that these variations do not interfere with the perturbations caused by the pattern itself, which allows for an accurate estimation of χ .

An estimate of $\chi = 131 \pm 3$ ppm minimizes the mean squared error ($N=20$). Assuming a 10- μm thickness of printed ink on paper, this implies $\chi = 13,100$ ppm in the ink at this printed density. Signal line plots comparing example slices of an acquired field map vs. a simulated field map with $\chi = 131$ ppm correspond well near the ink pattern in both the coronal and sagittal planes (Fig. 2). However, there are discrepancies at the superior and inferior ends of the vertical signal line plots due to the additional susceptibility effects from the air-water boundary at the edges of the phantom.

Phantom Imaging

Tuning the saturation frequency adjusts which resonance frequencies are suppressed (saturation frequency ± 300 Hz), and produces images with different contrasts. Example slices in the coronal and axial planes at three saturation frequencies (-450 , 0 , and 250 Hz), along with reference photos, are shown in Figure 3. With a saturation frequency of -450 Hz, most of the phantom is visible, with a signal void near the circle pattern. At 0 Hz, the saturation pulse removes signal from most of the phantom, except for the edges (due to the air-water boundary) and regions of large positive or negative off-resonance near the pattern. The regions of negative off-resonance near the ink pattern are unsuppressed when a 250 Hz saturation frequency is used, while the rest of the phantom is suppressed.

In Vivo Imaging

The chemical shift between fat and water is ≈ 3.5 ppm (16) and at 3T this corresponds to ≈ 440 Hz; because the bandwidth of the saturation pulse used is 600 Hz, fat and water can be suppressed separately. Similar to phantom results, the field distortions of the magnetic ink pattern pressed to the skin of a human subject are visible with different contrasts as the saturation frequency is adjusted (Fig. 4). Due to the off-resonance, the pattern is visible and identifiable when both fat and water are suppressed (Fig. 4d), and produces signal voids when neither is suppressed (Fig. 4b). The vertical lines in the pattern are not visible because they are parallel to the B_0 field. The ink itself does not produce signal; any off-resonance signal due to the patterns comes from the underlying tissue. The signal is therefore quite bright because it comes from subcutaneous fat.

The magnetic ink temporary flexible skin adhesives on the calf are best visualized with a maximum intensity projection (MIP) of the 3D MR data acquired with the saturation frequency tuned to fat; colored arrows indicate which patterns in the photos correspond to which patterns in the MIP (Fig. 5a). The patterns generally appear brighter than the other tissues because the signal comes from subcutaneous fat. It is important to note, however, that the expected signal at the superior edge of the circle pattern indicated by the red arrow is missing, perhaps due to poor shimming. In addition to the effect of underlying tissue, the visibility of the patterns also varies across the leg depending on the pattern shape and size.

The grid pattern applied to the chest is best visualized with a MIP of the 3D MR data acquired with the saturation frequency tuned to suppress both fat and water. The grid deformation due to changes in arm position is visible in both the reference photos and the MIP of the MR data (Fig. 5b). Note that the superior regions of the grid pattern have lower signal when the arm is positioned above the head compared to when the arm is down.

Discussion

Magnetic ink patterns generate predictable off-resonance variations that depend on their geometry. Previous work has used positive contrast generated via spectrally selective presaturation or excitation to visualize superparamagnetic iron oxide nanoparticles (17,18). Our work proposes using similar contrast in order to visualize patterns printed with magnetic ink; imaging with spectrally selective presaturation allows for indirect visualization of the

pattern by suppressing specified regions of the off-resonance (Figs. 3,4). In the case of magnetic ink skin markings, patterns placed on the skin over subcutaneous fat can be visible with positive contrast due to the off-resonance, which causes fat suppression to fail near the ink (Fig. 5).

The markings create a known susceptibility variation that is superimposed on the underlying B_0 and chemical shift variations. As an example, for the large circle pattern placed below the knee and indicated by the red arrow (Fig. 5a), the expected top portion of the off-resonance superior to the pattern is not visible. This may be due to B_0 variations across the leg, and could perhaps be improved with better shimming. As another example, the superior portions of the grid pattern applied to the chest produce less signal when the arm is held above the head (Fig. 5b), perhaps because there is more underlying muscle than subcutaneous fat in this position. In contrast, patterns placed in regions with plenty of underlying subcutaneous fat provide a bright signal. Therefore additional resonance frequency shifts due to B_0 variations or chemical shift make it more complicated to visualize ink patterns on the skin, depending on where they are placed and if there is more than one underlying tissue type.

One of the advantages of using printed skin markings is the ability to create patterns of arbitrary shape and size, which may be more useful than current MR-visible markers for image registration and image processing tasks, such as recognizing deformation. It is possible to visualize magnetic ink circle and line patterns with spectral presaturation (Fig. 4), and to recognize skin deformation using a grid pattern (Fig. 5b). However, it may be challenging to visualize more complicated patterns of magnetic ink (e.g. combinations of shapes of different sizes), since this method only images them indirectly. For example, the circles applied to the lateral side of the calf create different magnitudes of off-resonance depending on their size, and therefore the unsuppressed off-resonant regions can appear as rings (Fig. 5a). More work needs to be done to ensure that the shape, size, and position of the pattern can be accurately identified. In addition, line patterns parallel to the B_0 field will not create off-resonance that can be exploited for this purpose, as shown in Figure 4, and should be avoided.

It is promising, however, that simple gradient-echo imaging with presaturation is only one of multiple ways to add off-resonance sensitivity to MR images, and that other imaging methods can be explored for visualizing magnetic ink skin markings. Other techniques that could be evaluated include: spectrally selective excitation, T_2^* -weighted imaging, echo-planar spectroscopic imaging (EPSI), or multi-spectral methods for imaging near metal. Work has also been done to estimate metal implant geometries from B_0 field maps (19), which may be particularly applicable in this scenario, since knowledge of the exact geometry and location of the skin markings is desired. Future work will include comparing these methods for their use in accurately identifying the geometry and location of magnetic ink temporary flexible adhesives applied to the skin.

There may be potential safety concerns about using magnetic ink on the skin because of past reports of patients with permanent tattoos who experienced heating or burning of the skin near the tattoos during MR scans (20,21). However, this occurs quite rarely and the mechanism behind it is not well understood; some sensation could be caused by torque on

the ferromagnetic iron oxide materials due to the B_0 field, and heating may be caused by eddy currents from the changing magnetic field (20). Despite these concerns, it is recommended that patients still undergo the scan but be closely monitored throughout, and perhaps have a cold compress applied to the tattooed area as a preventative measure (22,23). None of the subjects in this study reported any heating or burning sensation due to the magnetic ink during scanning; therefore, cold compresses do not seem necessary with temporary magnetic ink skin adhesives.

Conclusion

Magnetic ink patterns create predictable B_0 field perturbations and are visible in MR images sensitive to this off-resonance. It is feasible to make temporary flexible skin adhesives with magnetic ink patterns of arbitrary shape and size for use as MR-visible skin markings, which could have applications in tasks involving image registration such as surgical planning, radiation therapy, joint movement tracking, or fusion of MR images to the body through augmented reality. These markings can be imaged efficiently by exploiting the presence of high-signal subcutaneous fat and the failure of fat suppression due to susceptibility variation created by the magnetic ink.

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Figure 1.

Flowchart depicting the estimation method for the volume-average magnetic susceptibility (χ) of the magnetic ink. Coronal and axial reference photos show the custom-built phantom containing a laminated piece of paper with the 2.5 cm-diameter circle pattern, which is held in place by plastic supports attached to the container lid and submerged in water. Acquired B_0 field maps of the phantom were compared to simulated B_0 field maps generated with test values of χ from 10 to 500 ppm. An estimate for χ was determined by finding the minimum mean squared error (MSE) between the acquired and simulated maps. The volume-average χ was determined to be 131 ± 3 ppm across 20 experiments. The simulated field maps assumed a 1-mm thickness for the ink; if a more realistic thickness of 10 μ m is assumed, this corresponds to $\chi = 13,100$ ppm in the ink.

Figure 2.

Comparison of acquired and simulated B_0 field maps (displayed at ± 500 Hz) in (a) a coronal slice and (b) a sagittal slice. Acquired field maps were masked to remove areas in the original images that had no signal; simulated field maps were generated with a volume-average magnetic susceptibility value (χ) of 131 ppm for the magnetic ink. The signal line plots compare the field maps (acquired = blue, simulated = red) along the indicated white lines.

Figure 3.

(a) Coronal and axial reference photos. Gradient-echo images through the center of the phantom acquired with spectral presaturation pulse frequencies of (b) -450 Hz, (c) 0 Hz, and (d) 250 Hz (relative to water) show how images with different contrast are produced as the range of suppressed frequencies (saturation frequency ± 300 Hz) is varied. Yellow arrows and text indicate the approximate resonance frequency of protons in the unsuppressed regions of the phantom.

Figure 4.

Example in vivo coronal and axial gradient-echo images of the magnetic ink pattern (a) pressed to the skin of the chest of a human subject with the saturation pulse tuned to different frequencies to suppress different tissues (600 Hz full bandwidth): (b) neither fat nor water, (c) fat, and (d) both fat and water. B₀ field perturbations from the ink pattern extend into the subcutaneous fat; therefore, adjusting the saturation frequency affects the image contrast. The vertical lines in the pattern are not visible because they are parallel to the B₀ field. The signal in the patterns is brighter than the other tissues because it comes from fat, although there is some inadvertent fat suppression in (b) due to an offset in the imaging frequency while scanning, which reduces its brightness.

Figure 5.

(a) Three photos at different angles of temporary flexible adhesives printed with magnetic ink applied to the skin of the calf of a volunteer, and a 3D maximum intensity projection (MIP) from in vivo gradient-echo images with presaturation, where the saturation frequency was tuned to suppress fat (600 Hz full bandwidth). Colored arrows indicate which skin markings correspond to which patterns in the MIP. The signal in the patterns is generally quite bright due to subcutaneous fat, although the visibility varies depending on the pattern geometry (which affects the locations of the suppressed off-resonant regions and can produce rings for the circle patterns) and B_0 variations across the leg. (b) Reference photos of a temporary flexible adhesive magnetic ink grid pattern applied to the skin of the chest of a male volunteer. A MIP from gradient-echo images with the saturation frequency tuned to suppress both fat and water of the arm held up above the head and the arm held down at the side. The grid visibly deforms in the reference photos, and this deformation is also tracked in the MR data.