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MR Measurement of Alloy Magnetic Susceptibility: Towards Developing Tissue-Susceptibility Matched Metals

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Abstract

Magnetic resonance imaging (MRI) can be used to relate structure to function mapped with high-temporal resolution electrophysiological recordings using metal electrodes. Additionally, MRI may be used to guide the placement of electrodes or conductive cannula in the brain. However, the magnetic susceptibility mismatch between implanted metals and surrounding brain tissue can severely distort MR images and spectra, particularly in high magnetic fields. In this study, we present a modified MR method of characterizing the magnetic susceptibility of materials that can be used to develop biocompatible, metal alloys that match the susceptibility of host tissue in order to eliminate MR distortions proximal to the implant. This method was applied at 4.7 T and 11.1 T to measure the susceptibility of a model solid-solution alloy of Cu and Sn, which is inexpensive but not biocompatible. MR-derived relative susceptibility values of four different compositions of Cu-Sn alloy deviated by less than 3.1% from SQUID magnetometry absolute susceptibility measurements performed up to 7 T. These results demonstrate that the magnetic susceptibility varies linearly with atomic percentage in these solid-solution alloys, but are not simply the weighted average of Cu and Sn magnetic susceptibilities. Therefore susceptibility measurements are necessary when developing susceptibility-matched, solid-solution alloys for the elimination of susceptibility artifacts in MR. This MR method does not require any specialized equipment and is free of geometrical constraints, such as sample shape requirements associated with SQUID magnetometry, so the method can be used at all stages of fabrication to guide the development of a susceptibility matched, biocompatible device.

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Keywords

magnetic resonance imaging; magnetic susceptibility; magnetic field perturbation; field mapping; alloys

1. Introduction

Magnetic susceptibility is a macroscopic property that characterizes the magnetization of a material in response to an applied magnetic field (1). For spatially varying susceptibility, local field perturbations arise at interfaces, such as the boundary between recording electrodes and surrounding brain tissue, resulting in distortions in MR images and spectra (2–5). We are investigating a method of mitigating these image distortions by developing conductive, solid solution alloys of diamagnetic and paramagnetic metals to match the susceptibility of brain tissue. Solid solution alloys exhibit a single, homogenous phase and therefore have the advantage that the magnetic properties of the material should be a continuous function of their composition. However, the magnetic susceptibility of some potentially biocompatible solid solution alloy systems (such as gold-platinum and silver-palladium) cannot be predicted using a linear combination of component metal susceptibilities (6,7). Additionally, susceptibility may be affected by manufacturing processes that induce deformation in the material (e.g. swaging, forging, extrusion, rolling) used to generate the final form of the alloy. Therefore susceptibility measurements are integral to the process of developing susceptibility-matched alloys by characterizing susceptibility as a function of metal content as well as manufacturing processes.

Superconducting quantum interference device (SQUID) magnetometry can be used to measure the absolute magnetic susceptibility of materials, but this method places constraints on the sample length and diameter, based on the pick-up coil diameter and separation (8), of roughly 5 mm for each. As an alternative, MRI has been used to measure susceptibility of materials relative to a surrounding media, usually water, and relaxes the geometric constraints on the sample, which for MRI are dependent on the magnet bore size and achievable imaging resolution. Therefore in this study, we evaluate the use of MR at 4.7 and 11.1 T for measuring the magnetic susceptibility of metals by measuring the susceptibility of solid solution alloys of a model system of copper (Cu) and tin (Sn) and compare these measurements to values obtained with SQUID magnetometry. Although Cu and Sn are not biocompatible, these metals were chosen as a binary alloy test system because of their relatively low cost, ease of fabrication and potential to form solid solution alloys (9).

The MR method, initially proposed by Cheng et al. (10) and Neelavalli et al. (11), used in this study employs a Fourier-based method of rapidly simulating external field perturbations for objects with an arbitrary geometry and susceptibility distribution (12). In their application, Cheng et al. compared simulated and experimentally-derived phase maps, measured using a gradient echo sequence, around an air phantom to quantify magnetic susceptibility. The comparison of phase maps to quantify susceptibility restricts their analysis to binary systems of magnetic susceptibility: the susceptibility of the object of interest and the susceptibility of the surrounding medium. In the study reported here, the relative magnetic susceptibility of an object is estimated by comparing experimentally-derived and simulated field perturbation maps, rather than phase maps, enabling multiple material susceptibilities to be calculated simultaneously relative to the surrounding media susceptibility. Additionally, our method employs an asymmetric spin echo sequence (13,14) in which intravoxel phase dispersion accumulates only during the echo-offset delay time, rather than the entire time to echo in gradient echo imaging. This is important because gradient echo sequences have a fixed minimum TE (~ 5 to 10 ms for the hardware and type

of imaging parameters used in this study) during which intravoxel dephasing causes greater signal loss than spin echo sequences (2). For asymmetric spin echo sequences, phase accumulation is limited to echo-offset delay (in this study, values between 0.0 and 1.0 ms at 4.7 T, and 0.0 and 0.75 ms at 11.1 T), so signal intensity distortions are reduced further in regions of large susceptibility differences, such as near metal objects. Therefore the use of asymmetric spin echoes minimizes signal distortions in regions proximal to the object of interest, where susceptibility differences are large, and improves the quality of the field perturbation maps for greater accuracy in susceptibility estimation.

2. Materials and Methods

2.1 Preparation of Cu-Sn Alloys

Although not biocompatible, a binary alloy system of Cu and Sn was chosen as a proof-of-concept prototype alloy to demonstrate the method due to their low cost and ability to form solid solution alloys within a limited composition range (up to 9 at. % Sn). Pure Cu (99.9% minimum purity shot, 1–10mm diameter, Alfa Aesar, Ward Hill, MA, USA) and Sn (99.8% minimum purity shot, 8–20 mesh, Alfa Aesar, Ward Hill, MA, USA) were mixed to create four samples consisting of 1.5, 3.0, 5.1 and 7.0% Sn in atomic percent. Each of the four samples was melted in a graphite crucible coated with boron nitride in open air at 1175 °C until a liquid solution was formed. The molten solutions were poured into sand molds in the shape of a 5 mm diameter cylinder and allowed to air-cool. Each sample was solutionized at 800 °C for 24 hours, water quenched, sanded with 150, 200, and 300-grit sandpaper to remove surface oxides and residue deposited during the casting process and then cut to a length of approximately 2 cm for subsequent MR testing.

2.2 MR Imaging

During MR imaging, a nylon collar and nylon screw were used to secure Cu-Sn samples in a 50 ml test tube that was filled with distilled-deionized water and wrapped with Teflon tape to ensure an air tight seal. The sample was then centered in a quadrature birdcage coil, and centered in the bore of a 4.7 or 11.1 T magnet. MR imaging was performed using Agilent Direct Drive consoles (Agilent Technologies, Inc., Santa Clara, CA, USA) connected to an Oxford 4.7 T horizontal bore magnet (Oxford Instruments, Abingdon, England) and Magnex Scientific 11.1 T horizontal bore magnet (Agilent Technologies, Inc., Santa Clara, CA, USA). Field perturbations were measured for all four Cu-Sn alloy samples at 4.7 T and two samples (3.0 and 5.1% Sn) at 11.1 T. Magnetic field perturbations, due to sources other than the sample metals, were first minimized by manual first and second order global shimming performed on the sample holder containing only distilled, deionized water that resulted in linewidths of approximately 10 Hz at 4.7 T and 14 Hz at 11.1 T. These same global shim values were used during field mapping measurements. A spin echo sequence with an echo-offset free precession delay was utilized for mapping the field perturbations around sample alloys (14) as discussed in Section 2.3. Free precession delays (T_{fp}) ranged from 0 ms to 1 ms for measurements performed at 4.7 T and from 0 ms to 0.75 ms at 11.1 T with at least 6 T_{fp} 's collected for each Cu-Sn alloy sample. Other imaging parameters include: TR = 3000 ms, TE = 30 ms, NA = 1, bandwidth = 55 kHz, FOV = $3 \times 3 \text{ cm}^2$, 128×128 matrix with 5 slices of 1 mm thickness with a 1 mm gap.

2.3 Mapping B Field Perturbations

The spatially-dependent phase of an MR image acquired with an asymmetric spin echo sequence can be described as,

$$\phi(x, y) = -2\gamma\Delta B_z(x, y)T_{fp} + \phi_0(x, y), \quad (1)$$

where ϕ is the spatially-dependent phase, B_z is the spatially-dependent magnetic field perturbation, T_{fp} is the free-precession delay, and ϕ_0 is phase-offset factor. The phase-offset factor can be eliminated by dividing, in complex exponential form, the Fourier transform of two asymmetric spin echo data sets with different T_{fp} , $T_{fp,i}$ and $T_{fp,i+1}$. This results in a subtraction of image phase terms, so that the resulting phase becomes,

$$\phi_{CD}(x, y, \Delta T_{fp}) = -2\gamma\Delta B_z(x, y)(T_{fp,i+1} - T_{fp,i}) = -2\gamma\Delta B_z(x, y)\Delta T_{fp}. \quad (2)$$

The resulting spatially-dependent phase of the complex-divided image, ϕ_{CD} , is a function of the difference in T_{fp} of the two data sets, $T_{fp} = T_{fp,i+1} - T_{fp,i}$, and is linearly dependent on the magnetic field perturbation. Therefore B_z can be determined through linear regression of Equation 2 after collecting multiple data sets with different T_{fp} .

The field perturbation maps around each sample were determined first by complex-dividing each non-zero T_{fp} image by an image without an echo time shift, and then calculating the phase angle by evaluating the four-quadrant inverse tangent for the ratio of the imaginary to the real part of the resultant complex-divided image, while maintaining T_{fp} at values short enough to avoid phase aliasing (15). Finally, MR-derived field perturbation maps, B_{zMR} , were calculated on a voxel-by-voxel basis using linear regression of $|\phi_{CD}|$ vs. T_{fp} data (see Equation 2). A correction for weak residual background inhomogeneities, assumed to have a linear spatial dependence within the imaging field of view, was applied in the frequency and phase encoding directions. The residual background perturbation correction was applied by performing a linear fit to voxels located at the edges of B_{zMR} (10–15 voxels of either side) along a line bisecting the alloy in either the frequency or phase encoding directions.

2.4 Estimating Magnetic Susceptibility

Figure 1 summarizes the method of estimating the volume susceptibility of the Cu-Sn alloy using B_{zMR} . External field perturbations around the Cu-Sn alloys were simulated using a Fourier-based method proposed by Marques and Bowtell (12), which requires an input model geometry in the form of a magnetic susceptibility spatial distribution. For simulation of the field perturbation maps around these Cu-Sn alloys, the outer diameter of each cylindrical sample was measured with a micrometer and a circular region of interest (ROI) was drawn at the image position of the metal cylinder determined by the symmetry in

B_{zMR} (16). Alternatively the sample geometry can be determined directly from a spin-echo MR image in which the frequency bandwidth per pixel is large enough to overcome the susceptibility distortion. Although this image will have a reduced signal-to-noise ratio (SNR), the geometry can be accurately defined for an object of any shape.

The volume susceptibility of the surrounding media (i.e. distilled, deionized water, $\chi_{media} = -8.90$ ppm) was then assigned to voxels outside of the circular ROI. The object susceptibility, χ_{obj} , was an iterative variable and assigned to voxels inside of the circular ROI to generate field perturbation maps as a function of object susceptibility. B_{zMR} was compared to simulated field perturbation maps, B_{zSim} , by computing the coefficient of determination, r^2 , value for either: 1) a line profile in the phase encoding direction bisecting the alloy or 2) a 64×64 window of the two dimensional field map centered on the alloy. The magnetic susceptibility of each Cu-Sn alloy was estimated by maximizing the r^2 value between B_{zMR} and B_{zSim} over a range of assigned object susceptibility. Sensitivity of the susceptibility values to input geometry was evaluated by perturbing the location and diameter of the sample and iterating the analysis to obtain new values.

2.5 SQUID Magnetometry

The SQUID magnetometer (Magnet Property Measurement System XL, Quantum Design, Inc., San Diego, CA, USA) was calibrated with a palladium (Pd) reference standard. Cu-Sn alloy samples were cut to a standard length of 3 mm to avoid geometric corrections to the magnetization measurements. The magnetization of each sample was then measured at 300 K in a varying field ranging from 0 to 7 T. A plot of magnetization was made for each sample and linear regression was used to extract the mass susceptibility at high fields, 5 T $H > 7$ T, because within this range diamagnetic and/or paramagnetic responses are dominant and any trace ferromagnetic contributions are negligible. The dimensionless volume susceptibility of each sample was obtained by multiplying the measured mass susceptibility by the density of the sample. The susceptibility of distilled and deionized water used in MR experiments was measured. The distilled water was deionized using a PURELAB Ultra water purification system (PURELAB Ultra, Elga LLC, Woodridge, Illinois, USA) that produces type 1+ (trace metal detection grade) and type 1 (HPLC grade) water.

3. Results and Discussion

Magnetic field perturbation maps, $B_{z,MR}$, were calculated for all alloys at 4.7 T (Figure 2, second row) and for 3.0 and 5.1% at. % Sn alloys at 11.1 T (Figure 3). The top row of Figure 2 shows r^2 of the linear regression performed on $\phi_{CD} (T_{fp})$ data (see Equation 2) on a voxel-by-voxel basis to determine $B_{z,MR}$. As expected, $|B_{z,MR}|$ is highest near the surface of the alloy and then diminishes as the distance from the alloy increases. Similarly, r^2 values are greater than 0.9 for distances less than 4 mm from the surface of the alloys. Since $|B_{z,MR}|$ decreases with distance away from the alloy, the relative contribution of noise to $\phi_{CD} (T_{fp})$ increases leading to smaller r^2 values, so a 64×64 sub-window of $B_{z,MR}$ (dashed box in Figure 2) was used for v_{obj} estimations.

Magnetic field perturbation maps were collected at 4.7 and 11.1 T for 3.0 and 5.1% Sn samples and, to compare the results at two field strengths, $B_{z,MR}$ was normalized by the field strength at which the data was acquired (Figure 3, top row). The normalized magnetic field perturbation maps $B_{z,MR}/B_0$, acquired at 4.7 or 11.1 T, should be equivalent because the magnetic field perturbations scale linearly with external field strength. For the 3.0% Sn alloy, $B_{z,MR}/B_0$ collected at 4.7 and 11.1 T have an r^2 value of 0.83 for a 64×64 window centered about the metal. An r^2 value of 0.93 was calculated when comparing $B_{z,MR}/B_0$ for the 5.1% Sn alloy. In both cases, the r^2 value was calculated by neglecting masked voxels located outside of the 64×64 window and within the region occupied by the alloy. The bottom row of Figure 3 shows the line profiles of $B_{z,MR}/B_0$ along the phase encoding direction (to avoid mismatch due to increased geometric distortion in the frequency encoding direction at 11.1 T), centered on the metal (dashed lines in the top row of Figure 3). An r^2 value of 0.90 was calculated when comparing line profiles of 3.0% Sn $B_{z,MR}/B_0$ data, while 5.1% Sn line profiles exhibited an r^2 value of 0.97. Overall, good agreement was observed when comparing $B_{z,MR}/B_0$ collected at 4.7 and 11.1 T.

Table 1 and Figure 4 summarize and compare the v_{obj} values obtained by SQUID magnetometry and estimated using MR, with distilled water as a common reference, for each of the Cu-Sn alloys. The largest deviations between the two methods were 1.8% (5.1% Sn sample) and 2.0% (5.1% Sn sample) using the image and line fit methods, respectively, at 4.7 T. Image and line fits were also performed to estimate v_{obj} using $B_{z,MR}$ data acquired at 11.1 T for 3.0 and 5.1% Sn samples resulting in a maximum deviation of 3.1% from the SQUID magnetometry measured value of v_{obj} (5.1% Sn sample) for both the image and line fit methods. Figure 2 demonstrates the similarity between $B_{z,MR}$ (second row) and $B_{z,Sim}$ (third row), where $B_{z,Sim}$ was derived using estimates of v_{obj} obtained from the image fit method at 4.7 T. Difference maps ($B_{z,MR} - B_{z,Sim}$) show that the

largest disagreement between the model and measurement occurs near the surface of the cylinders (Figure 2, fourth row).

Linear regressions were performed (Figure 4) to determine the relationship between Sn content and volume susceptibility, measured using SQUID magnetometry and MRI, resulting in a slope of -0.68 ± 0.04 ppm and y-intercept of -9.22 ± 0.19 ppm for SQUID measurements and slope of -0.68 ± 0.03 ppm and y-intercept of -9.00 ± 0.13 ppm for MR measurements. The y-intercept determined by both measurements indicates a pure Cu susceptibility of -9.0 to -9.2 ppm, which is similar to the reported value of -9.32 ppm for 99.999% pure Cu (17). A similar trend was observed by Henry and Rogers who measured the magnetic susceptibility of Cu-Sn alloys with 1.0, 1.9, 2.6, and 5.2 atomic % Sn (18) resulting in a slope of -0.61 ppm per at. % Sn and y-intercept of -9.71 ppm. In a solid solution of Cu-Sn, the susceptibility varies in a predictable manner within the tested solid-solution range of compositions. Therefore, the linear dependence on Sn composition can be used to generate alloys with susceptibilities ranging from -10 ppm to -14 ppm. Hence, the outlined MR method can be used to characterize alloy χ as a function of composition to match biocompatible alloys susceptibility to target tissues in a predictable fashion only for particular composition regimes. However, potentially biocompatible systems such as Ag-Pd and Au-Pt exhibit non-linear dependence of χ on alloy composition throughout the entire composition range (6,7) and demonstrate a linear dependence only for a limited range of compositions (~ 10 – 75 at. % for Au-Pt, ~ 20 – 50 at. % Ag for Ag-Pt). Although the magnetic susceptibility of the Cu-Sn alloys varies linearly with Sn content, this relationship cannot be described by a weighted-average of Cu and Sn susceptibilities, supporting the need for susceptibility measurements during alloy development. The negative slope of these linear fits indicate a trend of increasing diamagnetism for the Cu-Sn alloys with increasing paramagnetic Sn content. Although contrary to expectations when mixing diamagnetic and paramagnetic metals, this result is consistent with work reported by others (15–17), who performed magnetic susceptibility measurements on Cu-Sn alloys. In other words, this alloy system displays deviations from “ideal” mixing behavior, specifically an increase in diamagnetism after addition of paramagnetic Sn, due to a decrease in the density of states (18) or number of available states at a particular energy level. As the Sn content of the Cu-Sn alloy increases, the number of unpaired Cu electrons decreases, thereby reducing the paramagnetic component of Cu susceptibility and increasing the overall diamagnetism of the alloy.

SQUID magnetometer $\chi_{v,obj}$ measurements had a standard deviation ranging from 0.02 to 0.04 ppm after propagating error from each step in the measurement, including the Cu-Sn alloy density estimation. MR-derived values of $\chi_{v,obj}$ at 4.7 T had a standard deviation ranging from 0.06 to 0.22 ppm and 0.03 to 0.14 ppm for line fit and image fit estimations, respectively. At 11.1 T, the standard deviation of the line fit result ranged from 0.03 to 0.14 ppm and the standard deviation of the image fit result ranged from 0.03 to 0.18 ppm. Image fit and phase-encode-direction line fit estimations of $\chi_{v,obj}$ were performed for data collected at an in-plane resolution of 0.234×0.234 mm² (5.5 % of the average sample diameter). Estimations of $\chi_{v,obj}$ were also performed after down-sampling the k-space data to result in imaging resolutions of 0.468×0.468 mm² (11% of the average sample diameter), 0.936×0.936 mm² (22% of the average sample diameter), and 1.87×1.87 mm² (44% of the average sample diameter), and executing the image fit and line fit procedure on a single slice. Down-sampling the k-space data allows for analysis of resolution effects on $\chi_{v,obj}$ estimation while keeping the SNR constant and the results of this analysis are summarized in Figure 5. The analysis of image resolution effects on $\chi_{v,obj}$ estimation using the MR method indicate that at low resolution, the percent difference between MR derived values of $\chi_{v,obj}$ and SQUID magnetometry values increase with Sn content (Figure 5). As the difference between alloy susceptibility and water susceptibility increases, the resolution of

$B_{z,MR}$ had a larger impact on v_{obj} estimations, since the magnetic field gradient created at the alloy-water boundary increases as the susceptibility mismatch increases between the alloy and surrounding media. The lower resolution of $B_{z,MR}$ is unable to capture the abrupt changes in the magnetic field perturbation so the apparent field perturbations are reduced, resulting in an underestimation of v_{obj} as shown in Figure 5. Therefore, the appropriate imaging resolution for estimating v_{obj} using this MR method will depend on the susceptibility mismatch between the metal and surrounding media.

In addition to analysis of image resolution, the impact of model geometry (cylinder diameter and position) on v_{obj} estimation was also evaluated (Figure 6) for a single Cu-Sn alloy (3.0% Sn). The line fit method of estimating v_{obj} was most sensitive to improper positioning of the object in the frequency encoding direction, since the apparent diameter of the cylinder is reduced in the phase encoding direction, leading to an overestimation of v_{obj} by up to 27%. Although the image fit method was less sensitive to improper positioning, displacing the object by nearly 50% of its diameter resulted in a 11% difference (1.3 ppm) between MR-image-derived v_{obj} and SQUID magnetometry measurements. Correct placement of the model geometry with an improper diameter resulted in error that affected both the image fit and line fit methods of estimations in the same manner (Figure 6A). Using an object diameter that was smaller than the actual diameter resulted in an overestimation of v_{obj} , whereas a larger object diameter resulted in an underestimation of v_{obj} .

The present MR method is restricted to measuring the magnetic susceptibility of objects with a fixed cross-sectional profile because the image slices may be distorted by the susceptibility-induced magnetic field perturbations. Therefore, the magnetic field perturbations result in slice profiles that have a position-dependent distortion. For objects with a fixed cross-sectional profile, these distortions have little effect on field perturbation maps when the slice is coplanar with the cross-section of the object, since the field perturbations are constant in the slice direction far from the ends of the object. However, the present method could be extended to three dimensions by replacing the slice excitation scheme with a 2nd phase encoding direction, since the phase encoding process is not distorted by constant susceptibility-induced magnetic field perturbations. The implementation of a 2nd phase encoding direction would increase scan times but would enable the presented method to be applied to objects with any arbitrary geometry.

In conclusion, we have demonstrated that relative susceptibility can be quantified using an MR method for objects with a fixed cross-sectional profile. This method was applied to solid solution alloys of Cu and Sn to demonstrate that the relative magnetic susceptibility of an alloy can be accurately measured, and the susceptibility can be modified by altering the volume fraction of component metals. MR measured values of magnetic susceptibility for Cu-Sn alloys of four different atomic percent compositions of Sn deviated by less than 3.1% from SQUID magnetometry measurements. We plan to use this method to develop biocompatible alloys for the production of implants (e.g. electrodes and cannulae) that are susceptibility-matched to host materials (e.g. brain) to reduce or eliminate susceptibility artifact in MR images and spectra.

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Highlights

- Magnetic susceptibility measurement without SQUID magnetometry shape requirements
- Method evaluated with Cu-Sn solid solution alloys of 1.5 to 7% Sn at 4.7 and 11.1 T
- Less than 3.1% difference between proposed MR method and SQUID magnetometry
- Method can be used to guide fabrication of tissue susceptibility-matched devices

Figure 1.

Flow-chart summarizing the process of estimating $\chi_{v,obj}$ from $B_{z,MR}$. The mask of the metal cylinder is generated using the magnitude MR images and by masking voxels with a signal intensity that is less than 5% of the maximum signal intensity in the image.

Figure 2.

(Top row) Map of r^2 values generated by performing linear regression on Equation 2 on a voxel-by-voxel basis. (Second row) $B_{z,MR}$ maps acquired at 4.7 T for cylindrical Cu-Sn alloy samples composed of 1.5%, 3%, 5.1% and 7% Sn. The dashed box indicates the 64×64 fitting window used when comparing $B_{z,MR}$ to $B_{z,Sim}$ for the purpose of estimating the susceptibility of the material. Comparison of $B_{z,MR}$ (Second row) and $B_{z,Sim}$ (Third row) simulated using MR-derived measurements of v_{obj} using the image fit method at 4.7 T. (Fourth row) Difference maps show good agreement between $B_{z,MR}$ and $B_{z,Sim}$ with the largest deviations occurring at the edge of the Cu-Sn alloy. (Bottom row) The line plots indicate the agreement between $B_{z,MR}$ and $B_{z,Sim}$ simulated using MR-derived measurements of v_{obj} using the line fit method. The plots consist of data from the dashed lines indicated in the top row of images.

Figure 3.

(Top row) Comparison of $B_{z,MR}$ maps, normalized by acquisition field strength ($B_0 = 4.7$ T or 11.1 T), for alloys composed of 3% Sn (left) and 5.1% Sn (right). (Bottom row) Line profiles (indicated by dashed lines in Top row) of $B_{z,MR}/B_0$ in the phase encoding direction. Because $B_{z,MR}$ is linearly dependent on B_0 , the normalized line profiles are nearly identical for data acquired at 4.7 and 11.1 T.

Figure 4.

Summary of $\chi_{v,obj}$ for each of the Cu-Sn alloys measured using SQUID magnetometry and estimated using the MR method outlined in this study at 4.7 T and 11.1 T by using a media susceptibility of -8.90 ppm. The x-axis of the graph depicts the atomic % Sn (A_{Sn}) of the sample. The image fit series denotes $\chi_{v,obj}$ estimated by comparing $B_{z,MR}$ and $B_{z,Sim}$ using a 64×64 window (Figure 2, dashed box) centered about the metal. The line data series corresponds to estimates of $\chi_{v,obj}$ using a line profile of $B_{z,MR}$ and $B_{z,Sim}$ in the phase encoding direction which bisects the metal. See text for additional details.

Figure 5. The effect of in-plane resolution on MR-derived measurements of $\chi_{v,obj}$ for the line fit (A) and image fit methods (B) for the values of isotropic pixel resolution indicated in the legend compared to the SQUID magnetometer values.

Figure 6.

MR-derived measurements of $\chi_{v,obj}$ were performed on the 3.0% sample measured at 11.1 T after changes in the simulation model geometry. Measurements were performed for correct placement of the object while varying the object outer diameter (A) and for the correct object diameter while varying model placement (B).

Table 1

Measured magnetic susceptibility (mean $\pm$ sd) of Cu-Sn alloys using SQUID magnetometry and the presented MR method.

	χ_{obj} (ppm)			
	1.5% Sn (at. %)	3.0% Sn (at. %)	5.1% Sn (at. %)	7.0% Sn (at. %)
SQUID	-10.4 ± 0.03	-11.1 ± 0.04	-12.7 ± 0.02	-14.0 ± 0.02
Line Fit (4.7 T)	-10.2 ± 0.06	-10.8 ± 0.15	-12.4 ± 0.12	-13.9 ± 0.22
Image Fit (4.7 T)	-10.3 ± 0.03	-11.0 ± 0.14	-12.5 ± 0.03	-14.0 ± 0.09
Line Fit (11.1 T)		-11.1 ± 0.14	-12.3 ± 0.03	
Image Fit (11.1 T)		-10.9 ± 0.18	-12.3 ± 0.03	