

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

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Introduction: Magnetic susceptibility is a macroscopic property that characterizes the magnetization of a material in response to an applied magnetic field. Local field perturbations arise at susceptibility interfaces, such as the boundary between implanted recording electrodes and surrounding brain tissue, and may result in distortions in MR images and spectra. We are investigating a method of mitigating these image distortions by developing conductive, solid solution alloys from an amalgamation of diamagnetic and paramagnetic metals such that the alloy magnetic susceptibility matches that of brain tissue. However, the magnetic susceptibility of some potentially biocompatible alloy systems, such as gold-platinum and silver-palladium, cannot be predicted using a linear combination of component metal susceptibilities. Additionally, magnetic susceptibility may be affected by manufacturing processes (e.g. swaging, annealing) used to generate the final form of the alloy. Therefore, we have developed an MR method of measuring relative magnetic volume susceptibility (χ_v) that will be integral to the process of developing susceptibility-matched alloys by characterizing susceptibility as a function of metal content as well as manufacturing processes. This method can be implemented by any facility with MR hardware and is free of sample geometric constraints associated with SQUID magnetometry.

Methods: Pure Cu (99.9% purity) and Sn (99.8% purity) were mixed to create four solid solution, cylindrical samples consisting of 1.5%, 3.0%, 5.1% and 7.0% Sn in atomic percent (at. %), then the absolute magnetic volume susceptibility of the samples was measured using a SQUID magnetometer. The MR method of measuring magnetic volume susceptibility consisted of first using MR images to map the external magnetic field perturbations (ΔB_{MR}) around the sample metals by acquiring data using a spin echo sequence with multiple echo-offset free precession delay times (T_{fp})¹. Next, a Fourier method^{2,3} was used to simulate magnetic field perturbations (ΔB_{Sim}) around the metal samples while iterating the magnetic volume susceptibility of the metal sample ($\chi_{v,obj}$). Finally, the susceptibility of the sample was determined by finding the best fit between ΔB_{MR} and ΔB_{Sim} which was characterized by computing an r^2 value for either: 1) a line profile in the phase encoding direction bisecting the metal (line fit) or 2) a 64 x 64 window of the 2D field map centered on the metal (image fit).

Results: Figure 1 compares ΔB maps measured at 4.7 T to simulated ΔB maps generated using a Fourier method and a $\chi_{v,obj}$ that minimizes the difference between ΔB_{MR} and ΔB_{Sim} . Line profiles in part A & B of Figure 1 demonstrate the similarity of measured and simulated ΔB values for the 3% Sn and 7% Sn samples. Figure 2 shows the MR-derived and SQUID magnetic susceptibility for the four alloys plotted as a function of Sn at. % (A_{Sn}). MR and SQUID derived values of $\chi_{v,obj}$ exhibited a linear dependence on Sn at. % with y-intercepts indicating a pure Cu susceptibility of -9.1 ppm and -9.2 ppm, respectively (χ_v of 99.999 % purity Cu = -9.32 ppm). MR and SQUID values of $\chi_{v,obj}$ varied by less than 3.1%.

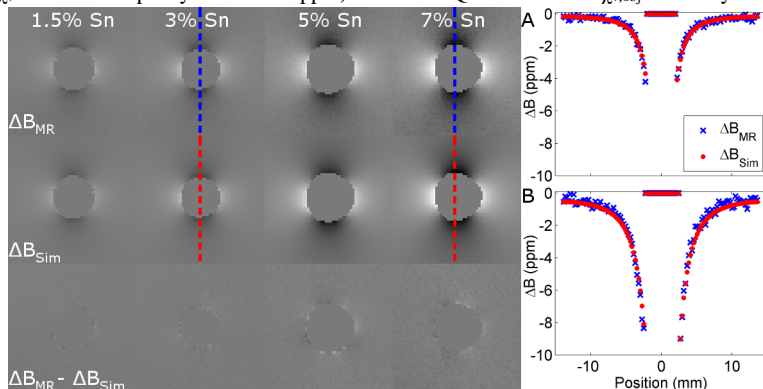


Figure 1. Comparison of measured and simulated ΔB maps. Plots A and B show line profiles (dashed lines in figure) of the ΔB in the phase encoding direction.

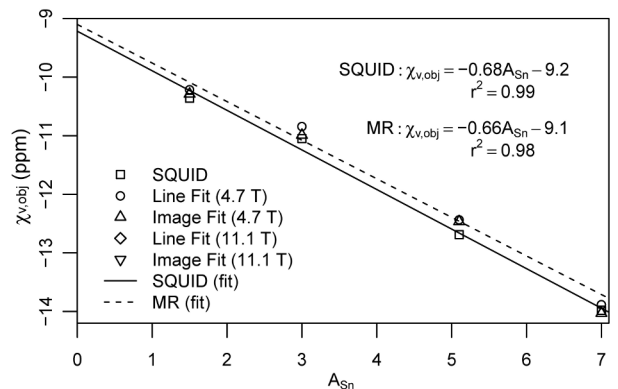


Figure 2. MR and SQUID derived values of $\chi_{v,obj}$ exhibited a linear dependence on Sn at. %.

Discussion: The linear dependence suggests Cu-Sn alloy susceptibility can be altered in a predictable manner; however, it cannot be modeled using a weighted-average of Cu and Sn magnetic susceptibilities. This result illustrates the importance of characterizing alloy susceptibility when developing novel alloys that are susceptibility-matched to a specific target tissue.

Conclusions: We have demonstrated that the susceptibility of an alloy can be controlled by altering the ratio of component metals and the change can be quantified using the MR method presented here, which does not require any specialized equipment, is free of geometrical constraints, such as sample length and width requirements, associated with SQUID magnetometry, and can be utilized to develop biocompatible alloys that are susceptibility-matched to host materials in order to reduce or eliminate susceptibility artifacts in MRI/S.

References: 1) Koch, K.M., et al., Phys Med Biol, 2006. 51: p. 6381-402. 2) Marques, J.P. and R. Bowtell, Concepts Magn Reson B, 2005. 25B: p. 65-78. 3) Cheng, Y.C., et al., Phys Med Biol, 2009. 54: p. 1169-89.

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