HIGH-PRECISION MAGNETIC SUSCEPTOMETRY APPLIED TO 3D-PRINTED RF COIL CONSTRUCTION

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Target Audience: Engineers and scientists engaged in RF coil or NMR/MRI apparatus construction

Purpose: 3D printing has become widely available and is attractive for fabricating RF coil components due to low cost, ease of fabrication and minimal geometric constraints. A large number of 3D-printed plastics are currently available[1], and while manufacturers report dielectric/mechanical/thermal properties, there have been no reports of magnetic susceptibility to the best of our knowledge. Our laboratory has begun constructing RF coil components from 3D-printed materials for use at high fields, which demands magnetic susceptibility be similar to water to avoid significant ΔB_0 artifacts at coil-sample interfaces. To this end, we have constructed a high-precision apparatus for measuring volume magnetic susceptibility (χ) with MRI, which we report here with measurements of $\Delta\chi = \chi_{material} - \chi_{water}$ from pure versions of popular RF coil plastics and their 3D-printed analogs.

Methods: Susceptibility measurements were performed at 9.4T on a Varian/Agilent small animal imaging system. 2D multiple GRE sequences were used to obtain field maps (128×64 matrix, 32×32 mm^2 FOV, 4 acquisitions, 30deg FA, 18 TEs ranging 5-64 ms, 50 kHz BW, and 75 ms TR). An apparatus for susceptibility measurements was constructed from Ultem PEI 1000 (McMaster-Carr), consisting of hollow voids that defined 1) an annular imaging volume (I.V., 2mm thick, 25mm outer diameter, 6mm inner diameter) and 2) an interior cylindrical sample volume (S.V., 5mm diameter, 38mm height) containing the material of interest. The two separate volumes were machined into a single ultem core; the I.V. was loaded with 1% agarose gel, and the core was press-fit into a larger ultem holder (Fig. 1). An index pin on the holder engaged a feature on a 72mm RF coil, allowing the entire apparatus to be removed from the MRI bore for S.V. reloading and returned to within a few 10's µm. This geometry placed the S.V. orthogonal to B_0 and approximated an infinite cylinder bisecting the I.V. This arrangement creates a dipole-shaped B_0 perturbation[2] in the I.V., dictated by $\Delta\chi$ between I.V. and S.V. A perturbation map with no background fields was calculated by taking the difference in field maps when S.V. contained either deionized water (reference) or a material of interest. $\Delta\chi$ was calculated by least-squares fitting to the dipole model. The apparatus and fitting were validated with known dilutions of Magnevist (Bayer), and measurements were performed on pure engineering plastics relevant to RF coil construction (Table 1) and their 3D-printed analogs (3DSystems and Stratasys), with n=3 in each case to measure material variability.

Results and Discussion: Observed perturbation maps were well described by a dipolar field (Fig. 2), and fitted $\Delta\chi$ was accurate to within 1% based on theoretical Gd^{3+} molar susceptibility[3] (Fig. 3). $\Delta\chi$ precision was 0.9 ppb (determined from repeated Gd^{3+} measures) and was limited by precision in repositioning the ultem apparatus for consistent background ΔB_0. Table 1 shows $\Delta\chi$ for the coil materials, with st.dev. that reflect material property variation. Given its large $\Delta\chi$, 3D-printed ultem may not be suitable for use near the MR sample; this likely arises from air-filled porosity introduced by the ultem 3D-printing process, which is not present in the other materials studied here. Characterization of other 3D-printed materials is ongoing.

Conclusions: A high-precision (< 1 ppb) magnetic susceptibility measurement apparatus was implemented and used to obtain previously unavailable measures of 3D-printed materials relevant to RF coil construction. Ultem does not maintain its normally close susceptibility match to water when 3D-printed, however 3D-printed poly(methyl methacrylate) and polycarbonate analogs may serve as substitutes. The apparatus shown here has broad use for studying macroscopically homogenous materials such as tissues with a high degree of precision.

Fig 1. Ultem core and holder for $\Delta\chi$ measurement, noting sample volume (S.V.) and imaging volume (I.V.).

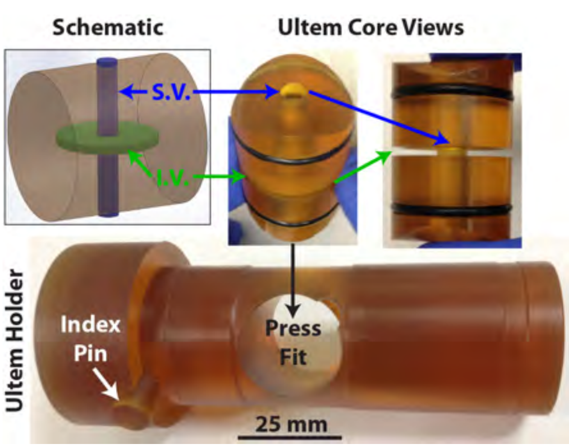


Fig 2. Representative I.V. field perturbation and fit residuals.

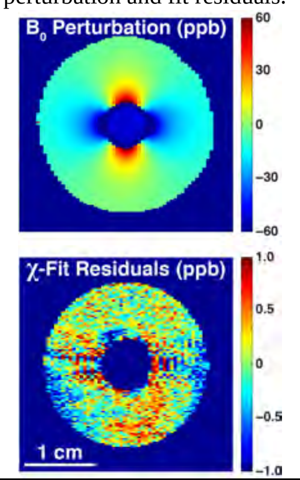
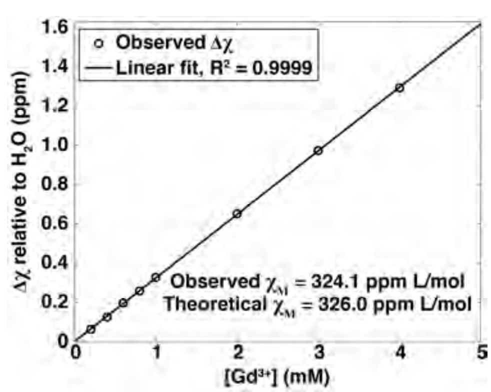


Fig 3. Validation via relative χ measures from Gd^{3+} serial dilutions and observed vs. theoretical molar susceptibility estimates. Error bars are too small to be shown, ≈ 1 ppb.



References: 1) see manufacturer specifications at www.stratasys.com/materials and www.3dsystems.com/materials/production. 2) Robert Weisskoff and Suzanne Kiihne. MRM 24:375-383 (1992). 3) Ludovic de Rochefort, et al. MRM 60:1003–1009 (2008).

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Table 1. $\Delta\chi$ for pure and analogous 3D-printed coil materials.

	Pure Material ***Δχ (ppm)***	***3D-Printed*** ***Analog Δχ (ppm)***
Poly(methyl methacrylate)	0.010 ± 0.005	0.025 ± 0.012
Polycarbonate	-0.156 ± 0.003	-0.205 ± 0.015
Ultem PEI 1000	0.086 ± 0.002	0.620 ± 0.124