Characterization of a Dielectric Phantom for High-Field MRI Applications

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Target Audience: MR physicists, engineers.

Purpose: At high field, due to wavelength effects, the amplitude and the phase of the radio frequency (RF) transmit field (the B_1^+ field) and the associated electric field (the E field) become increasingly dependent on the dielectric properties of the object. As estimation of the effects on imaging performance and RF tissue heating may be inaccurate with RF field simulations, it is desirable to perform measurements on phantoms that are realistic in terms of their dielectric and heat diffusion properties. Several approaches have been proposed in the past two decades[1-5]. Here we propose a low cost sucrose-NaCl-based gel phantom and systematically evaluate the dielectric properties over a range of sucrose and NaCl concentrations. The dielectric measurements were subsequently used to generate a generic recipe that provides the concentration of sucrose and NaCl required for a desired conductivity and permittivity at a frequency between 150 MHz and 4 GHz.

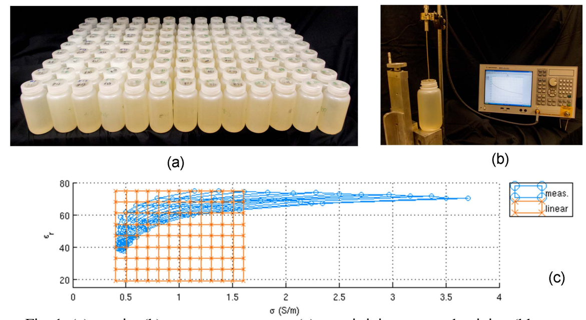

Fig. 1: (a) matrix; (b) measurement setup; (c) permittivity v.s. conductivity (blue grid: measured, orange grid: linear assumption) at 500MHz

Methods: Ingredients: All ingredients are chosen for low cost and water solubility and reported in terms of mass per unit water volume. 1) Solvent: Deionized water was chosen as the solvent given its favorable MR properties, low cost, and general availability. 2) Ingredient to primarily control conductivity: American Chemical Society grade NaCl. 3) Ingredient to primarily control permittivity: sucrose in the form of pure cane sugar was used to reduce water permittivity. 4) Preservative: Benzoic acid was chosen as a non-toxic preservative at a fixed concentration (0.1%). 5) Gelling agent: Agar was used as the gelling agent at a fixed concentration (1.5%).

Concentration Matrix and Recipe Fitting: To investigate the effect of NaCl and sucrose on dielectric properties, 250ml phantom samples were made with the following range of ingredients: NaCl ranged from 0.9% to 3.6% at intervals of 0.23% and sucrose ranged from 15.6% to 189% at intervals of 21.7%. This 9x13 concentration matrix (Fig.1a) was designed to cover a reasonable range of dielectric properties. The properties of each sample were measured using an invasive probe from 150 MHz to 4 GHz in 5 MHz steps at approximately 22° C (slim form model; Agilent 85070E dielectric probe with Agilent E5071C network analyzer, see Fig.1b). To generate a recipe for target dielectric properties at a given frequency, the measurements were fitted to a three-dimensional polynomial using customized Matlab software, where the dimensions represent NaCl and sucrose concentration and frequency. Polynomial fitting was chosen for several reasons: robustness to measurement noise, the ability to extrapolate beyond the solute concentrations explicitly measured, the feasibility for incorporating new data points, and the fact that it yields a parameterized recipe that is convenient to distribute.

Validation: 1) Three samples with the same concentrations (118% sucrose and 1.43% NaCl) were made to evaluate repeatability (reported as standard deviation of six repeated measurements). 2) Phantoms mimicking muscle tissue at 7T (σ=0.79S/m, ε_r=59) and average brain tissue at 11.7T[6] (σ=0.63S/m, ε_r=48) were made to evaluate the accuracy of the recipe.

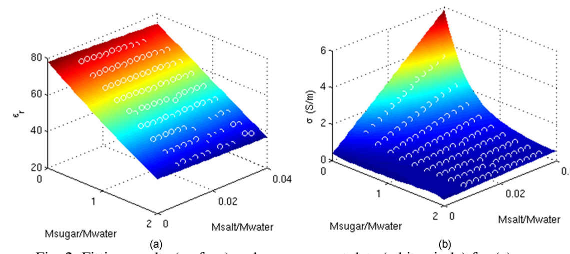

Fig. 2: Fitting results (surface) and measurement data (white circle) for (a) relative permittivity and (b) conductivity at 500MHz

Results and Discussion: Strong nonlinearity and coupling between the solvent concentrations and dielectric properties were observed, especially for the conductivity values (see Fig.1c for representative conductivity-permittivity plot at 500MHz). The fitted curves in Fig.2 indicate that the polynomial recipe captured the data dynamics at 500MHz. The validation results for the brain and muscle phantoms over the entire frequency range show excellent agreement between the measured (blue) and predicted values (red) (RMSEs < 1.7%, see Fig. 3). The differences between measurement and prediction were less than twice the standard deviation (~ 1.7%) of the repeatability measurement (i.e. within the 95% confidence interval). The recipe was derived within the following ranges: conductivity 0-6S/m, permittivity 30-80 (lower values may not be possible with sucrose solute due to incomplete solubility as well as undesirably short T_2^* <5ms), and frequency 150MHz-4GHz.

The complex relationship between the solute concentrations and the resulting dielectric properties prevents prediction based on simple linear and independent relationships between NaCl and conductivity and between sucrose and permittivity. The nonlinear relationship derived in this work is expected to guide the preparation of dielectric phantoms in practice. Note that the recipe also includes the total solution volume per unit water, which may vary significantly in low permittivity samples. The recipe is publically available as a web application at http://www.amri.ninds.nih.gov/phantomrecipe.html. It was also found that high sucrose concentration caused predictable non-linear behavior on proton-resonance-frequency-based MR thermometry.

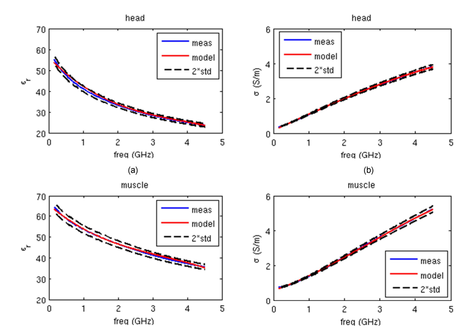

Fig. 3: validation for the 11.7T head phantom (a,b) and 7T muscle phantom (c,d): (a,c) relative permittivity; (b,d) conductivity

Conclusion

A generic recipe for Sucrose-NaCl based gel phantoms that mimic tissue dielectric properties at low cost (~$5/L) was generated by systematically characterizing the nonlinear and interdependent relations between the solvents and the resulting dielectric properties. The availability of this recipe will facilitate estimation of wavelength effects on imaging performance and RF tissue heating at high field.

Reference

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