

NOTE

Measurement of the specific heat capacity of liver phantom

Punit Prakash¹, Mark C Converse², David M Mahvi²
and John G Webster¹

¹ Department of Biomedical Engineering, University of Wisconsin, Madison WI 53706, USA

² Department of Surgery, University of Wisconsin, Madison WI 53792, USA

E-mail: Webster@engr.wisc.edu

Received 17 January 2006, accepted for publication 12 July 2006

Published 1 August 2006

Online at stacks.iop.org/PM/27/N41

Abstract

Phantoms are often used to simulate tissue during the development, testing and calibration of medical devices. In order to infer the specific absorption rate (SAR) and resistive heating in phantoms from temperature measurements, the specific heat capacity and density of the phantom are needed. Stauffer *et al* (2003 *Int. J. Hyperth.* **19** 89–101) developed several phantoms that mimic dielectric properties of liver tissue at 915 MHz. However, thermal properties of the phantoms were not presented. We have measured specific heat capacities and densities for these phantoms. We also present dielectric properties for these phantoms measured from 0.7 to 20 GHz, including 2.45 GHz—a commonly used frequency for microwave hyperthermia and ablation.

Keywords: liver phantom, specific heat measurement, dielectric properties measurement, microwave hyperthermia

1. Introduction

Phantoms are often used to simulate tissue during the development, testing and calibrating of medical devices. These devices include imaging technologies such as MRI, CT, or ultrasound and treatment devices such as hyperthermic tumor ablation systems (Bertram *et al* 2006). Phantoms have been developed to mimic the dielectric properties of tissues in the microwave range. Formulae for various phantoms of different tissue types, generally specific to a discrete frequency, are available in the literature (Chou *et al* 1984, Hartsgrove *et al* 1987, Robinson *et al* 1991, Stauffer *et al* 2003). These phantoms are often used in place of real tissue when measuring the electromagnetic (EM) field distribution or the SAR (W kg^{-1}) (EM power absorbed by the medium per unit mass) around an antenna or an array of antennas. These

Table 1. Formulae for liver phantoms presented by Stauffer *et al* (2003).

	Phantom A	Phantom B	Phantom C
Water	51.02%	51.6%	52.4%
Sucrose	46.01%	46.54%	45%
Sodium chloride	0.82%	1.24%	1.4%
HEC 4400	2.05%	0.52%	1.0%
Dowicil 75	0.1%	0.1%	0.1%

are measured either directly or indirectly. Direct measurement is done using an EM probe, while the indirect measurement measures the temperature rise in the phantom near the antenna immediately after power is applied. Assuming thermal conductivity is negligible, the heat equation yields the magnitude of the electric field based on the physical parameters of the phantom and the rate of change of temperature:

$$\text{SAR} = c \frac{dT}{dt},$$

where c is the specific heat ($\text{J} (\text{kg K})^{-1}$). If these material properties are known, the SAR at that location due to an external source applied to the phantom can be inferred from temperature measurements made over a period of time (Lin and Wang 1996). Note $\text{SAR} = \sigma E_{\text{peak}}^2 / (2\rho)$ where σ is the dielectric conductivity and ρ is the density (kg m^{-3}), so the peak electric field can be determined if the dielectric conductivity and density are known.

Stauffer *et al* (2003) developed a phantom with dielectric properties similar to that of liver tissue at 915 MHz. We can find no other phantom that has been developed specifically to match properties of liver. At 915 MHz, the dielectric properties of Stauffer's phantom closely match those of liver. However, we can find no available data on thermal properties of the material or the dielectric properties at 2.45 GHz, which is now a frequency also commonly used for hyperthermia and ablation. In order to use this phantom to measure the SAR of an antenna or array of antennas with the temperature technique, these properties need to be known.

Using a technique developed by Haemmerich *et al* (2005, 2006), we have measured the thermal properties of several of the phantoms developed by Stauffer *et al* (2003) and have compared them to the values estimated from empirical formulae. In addition, we also report measurements of the dielectric properties measured at frequencies between 0.7 and 20 GHz.

2. Methods

We constructed phantoms using three of the formulae provided by Stauffer *et al* (2003). Table 1 shows these formulae. Phantom A corresponds to the recipe that Stauffer *et al* (2003) found best approximates the mean dielectric properties of liver at 915 MHz.

The dielectric measurement and data processing procedure used in these experiments was previously described in Popovic *et al* (2005), and will be explained briefly here. The complex reflection coefficient at the calibration plane of an open-ended borosilicate coaxial probe was recorded. A de-embedding model, based on probe-specific numerical simulations that accounted for the specific probe geometry, was used to translate the reflection coefficient from the calibration plane to the aperture plane. Subsequently, a rational function model (Stuchly *et al* 1994, Anderson *et al* 1994) was used to convert the de-embedded reflection coefficient into the complex permittivity of the tissue. For each phantom recipe, dielectric properties were

measured for a single sample. The measurement was performed at five different locations in order to confirm sample homogeneity.

Specific heats of phantoms were measured using the technique of Haemmerich *et al* (2005). A sample of known mass was placed in a 6 cm × 5 cm × 5 cm Styrofoam container. The sample was heated uniformly using plate electrodes. Power (35 W) was supplied by a commercial RF generator (PDX-500, Advanced Energy). Two Luxtron fiberoptic temperature probes (Luxtron Corp., Santa Clara, CA, USA) were used to measure temperature every 0.25 s. The probes were positioned in the center of the container (3 cm from the bottom) and 1 cm apart. Temperature between the probes did not exceed 4 °C, which falls within the range of uniform heating assumed by Haemmerich *et al* (2005). Temperatures recorded from each probe were averaged and all subsequent calculations were performed on these averaged values. The phantom was heated up from room temperature to 60 °C. At 40 °C, power was turned off for 90 s in order to compute the rate of cooling. At room temperature, the rate of cooling is assumed to be zero. A linear approximation of these values was used to estimate the cooling rate at temperatures between 25 and 60 °C. A moving window of size 6 °C was used to average dT/dt , in order to reduce noise. The specific heat of the sample was then computed using

$$c = \frac{P}{m \cdot \left(\frac{dT}{dt} \Big|_{t_{\text{off}}^-} - \frac{dT}{dt} \Big|_{t_{\text{off}}^+} \right)},$$

where P is the applied power (W), m is the mass of the sample (kg) and t_{off} is the time at which power was turned off in order to compute the cooling correction. Based upon agar measurements performed in Haemmerich *et al* (2005), experimental error is under 3.1%. For each phantom, we performed three specific heat measurements. Density was calculated by direct measurement of mass and volume.

Chou *et al* (1984) provides empirical formulae for specific heat and density:

$$c = \sum_{i=1}^n \tilde{m}_i c_i \quad \rho = \sum_{i=1}^n \tilde{m}_i \rho_i.$$

Here c_i and \tilde{m}_i are the specific heat and mass fraction, respectively, of the i th component of the material, and ρ_i is the density.

3. Results and discussion

Measurements of the phantom dielectric properties were performed over the range 0.7–20 GHz. Currently treatment applications for liver cancer almost exclusively use 915 MHz and 2.45 GHz. However, future treatment and imaging technologies may utilize a wider range of frequencies and so we include the results of those measurements. As 915 MHz and 2.45 GHz are currently the most significant frequencies we have specifically tabulated the response at those frequencies. Table 2 lists the dielectric properties (relative permittivity and conductivity) for each of the phantom recipes measured at 915 MHz and 2.45 GHz. Also shown are the properties determined by Stauffer *et al* (2003) for these phantoms and their measured values for liver and tumor tissue at 915 MHz. Our phantom measurements at 915 MHz compare well with those reported by Stauffer *et al* (2003)—with the maximum difference being 3.6% for permittivities, and 9.42% for conductivities. Standard deviations between our measurements were less than 0.1% for each sample.

Table 2. Dielectric constants of phantoms at 915 MHz and 2.45 GHz

Phantom	915 MHz (Stauffer)		915 MHz		2.45 GHz	
	ϵ	σ	ϵ	σ	ϵ	σ
A	51.3	0.96	51.9	1.00	42.7	2.74
B	52	1.53	52.5	0.96	43.0	2.80
C	54.7	1.38	52.7	1.25	43.5	3.00
Normal liver	50.8	0.79				
Primary tumor	55.3	0.88				
Metastatic tumor	57.4	1.11				

Table 3. Cole–Cole parameters from fit to experimental measurements of the dielectric constant of phantoms.

Phantom	ϵ_∞	$\Delta\epsilon$	τ	α	σ_s	Maximum error
A	8.21	45.4	2.83×10^{-11}	0.110	0.571	5.00%
B	8.10	45.9	2.84×10^{-11}	0.110	0.605	5.64%
C	8.19	45.7	2.70×10^{-11}	0.110	0.858	5.24%

Table 4. Measured and estimated specific heat and density mean and range ($n = 3$).

Phantom	Estimated values		Measured values (mean)		Measured values (range)	
	c (J (kg K) $^{-1}$)	ρ (kg m $^{-3}$)	c (J (kg K) $^{-1}$)	ρ (kg m $^{-3}$)	c (J (kg K) $^{-1}$)	ρ (kg m $^{-3}$)
A	2820	1440	3050	1160	3020–3100	1130–1220
B	2850	1290	3000	1210	2960–3040	1170–1240
C	2880	1280	2730	1190	2640–2820	1150–1250

To increase the utility of the data, we present the wideband frequency measurements as Cole–Cole coefficients. The Cole–Cole equation is a well-established fitting equation for the dielectric response of tissue as a function of frequency (Gabriel *et al* 1996):

$$\epsilon_r = \epsilon_\infty + \frac{\Delta\epsilon}{1 + (i\omega\tau)^{1-\alpha}} + \frac{\sigma_s}{i\omega\epsilon_0},$$

where ϵ_∞ , $\Delta\epsilon$, τ , α , σ_s are fitting parameters and ϵ_r is the relative complex permittivity. Table 3 shows the fitting parameters for each phantom as well as the maximum error between the experimental measurement and the permittivity determined from the Cole–Cole equation.

Table 4 shows thermal properties measurements, for each of the three phantoms. Table 4 lists the mean measured specific heat and density at 25 °C as well as the range of values measured for the three samples of each recipe. Specific heat at 25 °C was determined by averaging the measured specific heat between 24 and 26 °C. For comparison, table 4 also shows the specific heat and density estimated from the empirical formulae.

The measured specific heats are similar to the estimated values with <10% difference between measured and estimated specific heats. Table 4 shows that the range of the specific heat of phantom C appears to be much larger than for other samples. Phantom C was observed to be substantially less viscous than the other phantoms. Since the measurement technique was designed for solids and appears to handle viscous gels well, it may result in greater

measurement variability with less viscous gels where it may be possible for convective effects to play a role.

The difference between measured and estimated density is less than 8% for phantoms B and C. The difference in phantom A is about 18%. This may be due to the presence of more air bubbles in phantom A as a result of its greater viscosity.

We performed paired *t*-tests to test the statistical significance of changes in specific heat at temperatures of 35, 45 and 55 °C, compared to the value at 25 °C. We define statistical significance as indicated by *p*-values less than 0.05. Phantoms A and B showed no statistically significant change in specific heat as a function of temperature. For phantom C, there was no significant change in specific heat at 35 and 45 °C. However, at 55 °C, we obtained a significance value of 0.0159, indicating a statistically significant change from the measurement at 25 °C. All statistical calculations were performed using the R software (version 2.2.0; <http://www.r-project.org/>).

Leonard *et al* (1984) measured specific heat capacities, density, thermal conductivities and diffusivities of various RF and microwave phantoms. Their results are on the same order of magnitude as those presented in table 4.

4. Conclusion

We have measured the specific heat and density of liver phantoms developed by Stauffer *et al* (2003). The specific heat and density from the empirical formulae do a relatively good job of predicting the measured values. We also present dielectric properties measured over the range 0.7–20 GHz, including 2.45 GHz—which is a common operating frequency for microwave treatment systems.

Acknowledgment

This work was supported by the National Institute of Health (NIH) under Grant DK58839. We wish to thank D Schutt and D Haemmerich for assistance related to this work.

References

- Anderson J M, Sibbald C L and Stuchly S S 1994 Dielectric measurements using a rational functional model *IEEE Trans. Microw. Theory Tech.* **42** 199–204
- Bertram J M, Yang D, Converse M C, Webster J G and Mahvi D M 2006 Antenna design for microwave hepatic ablation using an axisymmetric electromagnetic model *Biomed. Eng. Online* **5** 15
- Chou C K, Chen G W, Guy A W and Luk K H 1984 Formulas for preparing phantom muscle tissue at various radiofrequencies *Bioelectromagnetics* **5** 435–41
- Gabriel S, Lau R W and Gabriel C 1996 The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues *Phys. Med. Biol.* **41** 2271–93
- Haemmerich D, Schutt D J, dos Santos I, Webster J G and Mahvi D M 2005 Measurement of temperature-dependent specific heat of biological tissues *Physiol. Meas.* **26** 59–67
- Haemmerich D, dos Santos I, Schutt D J, Webster J G and Mahvi D M 2006 *In vitro* measurements of temperature-dependent specific heat of liver tissue *Med. Eng. Phys.* **28** 194–7
- Hartsgrove G, Kraszewski A and Surowiec A 1987 Simulated biological materials for electromagnetic radiation absorption studies *Bioelectromagnetics* **8** 29–36
- Leonard J B, Foster K R and Athey T W 1984 Thermal properties of tissue equivalent phantom materials *IEEE Trans. Biomed. Eng.* **31** 533–6
- Lin J C and Wang Y J 1996 The cap-choke catheter antenna for microwave ablation treatment *IEEE Trans. Biomed. Eng.* **43** 657–60

- Popovic D, McCartney L, Beasley C, Lazebnik M, Okoniewski M, Hagness S C and Booske J H 2005 Precision open-ended coaxial probes for *in vivo* and *ex vivo* dielectric spectroscopy of biological tissues at microwave frequencies *IEEE Trans. Microw. Theory Tech.* **53** 1713–22
- Robinson M P, Richardson M J, Green J L and Preece A W 1991 New materials for dielectric simulation of tissues *Phys. Med. Biol.* **36** 1565–71
- Stauffer P R, Rossetto F, Prakash M, Neumann D G and Lee T 2003 Phantom and animal tissues for modeling the electrical properties of human liver *Int. J. Hyperth.* **19** 89–101
- Stuchly S S, Sibbald C L and Anderson J M 1994 A new aperture admittance model for open-ended waveguides *IEEE Trans. Microw. Theory Tech.* **42** 192–8