Short Papers

Muscle-Equivalent Phantom Materials for 10–100 MHz

M. J. Hagmann, R. L. Levin, L. Calloway, A. J. Osborn, and K. R. Foster

Abstract—**New tissue-simulating materials are described which are aqueous solutions. Glycine is used to obtain the large permittivity of muscle at frequencies below 100 MHz. The lack of suspended solids simplifies preparation, and ensures the dielectric properties are homogeneous, stable and reproducible. The solutions are transparent, facilitating placement of probes for measuring temperature or electric field. The optical clarity of the phantom mixtures may also be desirable in a quick assessment of RF applicators by the use of liquid crystalline display sheets. Long-term stable gelling, with no measurable change in dielectric properties, can be obtained with 1 to 2 percent of agarose or carrageenan.**

I. INTRODUCTION

Materials with dielectric properties similar to those of biological tissues have been used in phantom tissue models to determine the interaction of electromagnetic fields with the human body. Such simulations have been used to evaluate possible biological hazards [1], as well as to determine the heating patterns produced in diathermy [2] and hyperthermia for the treatment of cancer [3], [4].

The dielectic properties of tissues have considerable dispersion. For example, the relative permittivity of muscle is less than that of water above 100 MHz, but is large (several million) at low frequencies [5], [6]. Thus different mixtures are generally required to simulate muscle at various frequencies. These mixtures [7]–[11] are typically water-based, with electrolyte added to adjust the conductivity, and other ingredients to alter the permittivity. Ingredients decreasing the permittivity of water-based mixtures to simulate muscle above 100 MHz, include polyethylene powder [2], [7], [8], glycerol [2], sucrose [10] and ethanol [11]. Powdered aluminum metal [7], [8] and titanates [9] have been used to increase the permittivity of water-based mixtures, to simulate tissue at frequencies below 100 MHz.

Most phantom mixtures require a gelling agent to prevent the segregation of solid ingredients such as polyethylene powder or powdered aluminum metal [2], [7]–[9] from suspension. Since gelled phantoms are generally opaque, small air bubbles or other heterogeneities may go undetected. Gelling also interferes with repackaging, as well as the addition of water to compensate for losses by evaporation. Gellation is required to limit heat transfer by convection when measuring local temperature [12], but is not necessary in other measurements. Gelling impedes the movement of an electric field probe [12], and prevents stirring a phantom mixture for the determination of total energy deposition [12], [13].

We describe new phantom mixtures in which all ingredients are in solution, thus simplifying preparation and ensuring that the dielectric properties are homogeneous, stable and reproducible. We also describe optional additives which provide long-term stable gelling without measurably changing the dielectric properties or limiting the transparency of the mixtures.

II. DESCRIPTION OF THE NEW FORMULATIONS

We have considered a number of solutes which modify the dielectric constant of water from its value of approximately 80 at low frequencies. Table I shows the dielectric constants of several saturated aqueous solutions. A number of solutes, including glycerol [2], sucrose [10], [14], ethanol [11], albumen and dextrose [14], decrease the dielectric constant below that of water. Aqueous solutions of urea [14]–[16], formamide [17], glycine [14], [16], [18], and several n-methylamides [19], [20] have permittivities appreciably greater than that of water.

The present work focused on solutions with dielectric constants greater than that of water, to simulate muscle at frequencies below 100 MHz. Sucrose solutions simulating muscle at higher frequencies were described previously [10]. Our testing was limited to aqueous solutions of formamide, urea, and glycine due to the high cost of n-methylamides. Of these, glycine is preferred since it causes the greatest increase in dielectric constant. Solutions using the combined effects of both glycine and urea, or the n-methylamides, could be used to simulate muscle at frequencies below 10 MHz.

Table II contains the formulations for three of our new ungelled aqueous solutions that simulate muscle at different frequencies. The concentrations of sodium chloride and glycine in these formulations were adjusted so that the measured dielectric properties agree with published data [21]. Due to the large magnitude of the permittivity of muscle at 13.56 MHz, the concentration of glycine required to simulate muscle at that frequency is near saturation.

Several gelling agents were tested with the new formulations in Table II. Agarose [22] and carrageenan (Gelcarin HWG and DG from the FMC Corporation, Marine Colloids Division, P. O. Box 70, Springfield, NJ 07081) provide long-term stable gelling at low concentrations. Samples with 1 percent of agarose, or 2 percent of either Kappa or Iota carrageenan remained stable in two years of storage at 37°C, with 0.05 percent of Proxel CRL (a preservative from ICI Americas Inc., Wilmington, DE 19897). At these concentrations, agarose, carrageenan, and the preservative do not measurably alter the dielectric properties, or limit the optical clarity of the mixtures. We have found agarose and carrageenan are also compatible with phantom materials described by others [10].

Polyacrylamide [23], [24] is an alternative gelling agent for applications where the phantom must have a shelf life well in excess of one year, because the substance is more stable than agarose or

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TABLE I
APPROXIMATE PERMITTIVITY OF SATURATED AQUEOUS SOLUTIONS AT 1 MHz

	ϵ'	References
n-Methyl Formamide	190	19, 20
n-Methyl Propionamide	180	19, 20
n-Methyl Acetamide	180	19, 20
Glycine	145	14, 16, 18
Formamide	110	17
Urea	100	14, 15, 16
Sucrose	40	10, 14
Albumin	32	14
Dextrose	26	14

TABLE II
FORMULATIONS FOR THE NEW MUSCLE-SIMULATING PHANTOMS

	Weight Percent			Dielectric Properties	
Frequency MHz	Water	Glycine	NaCl	ϵ'	σ S/m
13.56	79.4	20	0.58	145	0.6
27.12	88.5	11	0.49	112	0.6
40.68	93.5	6	0.52	97	0.7

carrageenan. Polyacrylamide is not an efficient gelling agent: a minimum of 10 percent polyacrylamide is required for stable gelling.

TX-150 (obtained from Oil Center Research, P. O. Box 51871, Lafayette, LA 70505) [1], [3], [8] is an alternative gelling agent in applications where the phantom must be reshaped or cut, since this ingredient provides a rehealing cross-link for a dough-like consistency. Agarose, carrageenan, and polyacrylamide form brittle gels that can not be reshaped or repackaged without melting. A concentration of at least 12 percent of TX-150 is required for stable gelling, and the effect of such a high percentage of TX-150 on the permittivity of the mixture is not clear.

III. DETERMINATION OF DIELECTRIC PROPERTIES

The dielectric properties of the phantom materials were determined from 1 MHz to 1 GHz using an automatic impedance analyzer (Hewlett-Packard model 4191) under computer control. The open-ended coaxial line reflection method was used, with a sample cell fabricated from a coaxial connector, similar to that described by Stuchly [25].

Figs. 1 and 2 show the relative permittivity and conductivity of glycine solutions as functions of the concentrations of glycine and sodium chloride, respectively. The results for the glycine solutions agree with earlier data from Aaron and Grant [26]. Apart from a small increase in conductivity that is noticeable at the upper end of the frequency range (due to dipolar loss of water) the glycine solutions show no dispersion (Glycine is a small polar molecule that exhibits a dispersion centered at about 3 GHz at 25°C).

There are simple ways to estimate the dielectric properties of aqueous solutions such as those used in this study. Our measurements have shown that in the frequency range of 1 MHz to 1 GHz, the solutions are nondispersive, i.e., their dielectric properties are essentially independent of frequency. The permittivity of the solutions depends principally on the concentration of glycine; the conductivity depends on the concentrations of both sodium chloride and glycine.

To produce a solution with specified dielectric properties, one should first choose the appropriate glycine concentration, c to produce the desired permittivity. This will give the required weight fraction w of glycine, which then should be converted to the volume fraction $p \approx w/1.4$, where the density is approximately 1.4 g/ml.

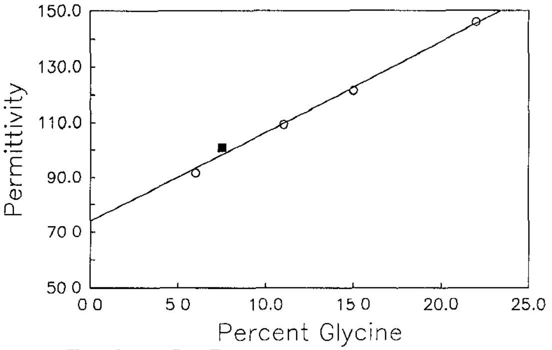

Fig. 1. Relative permittivity of aqueous glycine solutions at 436 MHz. x = present results with 0.5 percent (by weight) sodium chloride, square = data of Aaron and Grant [26] with no sodium chloride.

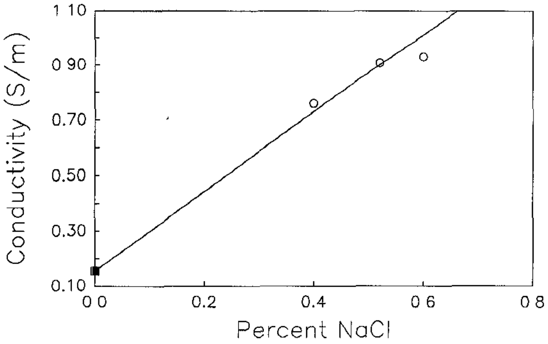

Fig. 2. Conductivity of aqueous solutions of sodium chloride. x = present results with 6 percent (by weight) glycine, line = data from [29].

The conductivity σ_e of the electrolyte in which the glycine should be dissolved is given approximately by

$$\sigma_e = \sigma_c(1 + p)/(1 - 2p) \tag{1}$$

where σ_c is the desired conductivity of the phantom. This is an empirical mixture relation for polymer solutions, which includes the contribution of the water of hydration of the solute [28]. Tables of concentrative properties of aqueous solutions are helpful in this regard [29]. Equation (1) is an approximate expression, so the conductivity of the solution may have to be further adjusted. Since the solution is nondispersive, measurements with a standard laboratory conductance meter will suffice.

V. DISCUSSION AND CONCLUSION

The new phantom materials are transparent, which facilitates positioning probes for measuring temperature and electric field. Since they have no ingredients which can settle, gellation is only required to limit heat transfer by convection when measuring local temperature [12]. The gelling agent may be deleted to facilitate the placement of electric field probes [12], or to allow stirring when measuring the total energy deposition [12], [13]. Since the ungelled mixtures have low viscosity, they may be circulated for cooling in boluses which match electromagnetic applicators to the human body [27].

Precise matching of the dielectric constant of phantom to that of muscle might not be ncessary in simulations under quasistatic conditions at frequencies less than 100 MHz [4]. This is because muscle is primarily resistive below 100 MHz; the loss tangent (the ratio of the loss factor to the dielectric constant) increases from 2.1 at 100 MHz to 5.8 at 13.56 MHz for dog skeletal muscle [5]. Others have used phantoms simulating both the dielectric constant and the conductivity of muscle at frequencies below 100 MHz [7]-[9], and the new mixtures described may also be considered in applications requiring complete simulation of the dielectric properties of muscle.

We do not report thermal properties of these new tissue-simulating materials. However, other phantom materials [30] and diverse biological materials [31] with high water content have heat capacities and thermal conductivity values close to those of pure water, and we expect that the materials described here will as well. For precise studies involving calorimetry, the heat capacity of any phantom should be measured directly by the investigator.

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Microstrip Resonators on Anisotropic Substrates

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Abstract—**The spectral domain method is applied to study shielded microstrip resonators printed on anisotropic substrates. A Green's function that takes into account the dielectric anisotropy effects is derived through a fourth order formulation. Galerkin's method is then applied to form the characteristic equation from which the resonant frequency of the microstrip resonator is numerically obtained. Results**

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