

Simulated Biological Materials for Electromagnetic Radiation Absorption Studies

G. Hartsgrove, A. Kraszewski, and A. Surowiec

University of Ottawa, Department of Electrical Engineering, Ottawa, Ontario, Canada

For the study of electromagnetic dosimetry and hyperthermia, it is necessary to simulate human biological materials. This can be done by chemical mixtures that are described in this paper. Formulas are presented for simulating bone, lung, brain, and muscle tissue in the frequency range of 100 MHz to 1 GHz. By using these preparations a realistic equivalent to the human body can be constructed.

Key words: simulated biological materials, electromagnetic dosimetry, tissue equivalent materials

INTRODUCTION

Recently, electromagnetic dosimetry and hyperthermia have required more and more complex models of biological materials to investigate the electric field (SAR, temperature) distributions induced inside a real body. Experimental verification of calculations based on these more complex structures needs a more realistic model of the biological object constructed from materials that simulate the permittivity and conductivity of various tissues in the frequency range of interest. Most of the tissue equivalent materials developed to date simulate skeletal muscle. The majority of these materials lose their properties after a short time, because of sedimentation, chemical reactions, and bacterial action. The purpose of this paper is to present recipes for materials at room temperature that simulate the permittivity and conductivity of muscle, brain, lung, and bone tissues at body temperature (37°C) in the frequency range of 100–1000 MHz. These materials are all easy to prepare, inexpensive, and retain their properties for an extended period of time. Muscle simulating materials that have been prepared have retained these properties for over 1 year.

SIMULATED MATERIALS

Muscle Tissue

Our initial attempt was to simulate the properties of skeletal muscle [Hurt, 1985] because this is one of the major components of man. Previous formulas [Chou et al, 1984; Guy, 1971] have been developed for muscle material but they were found to have problems. The major problems were lumping of the gelling agent during mixing,

Received for review January 28, 1986; revision received June 6, 1986.

Address reprint requests to G. W. Hartsgrove, University of Ottawa, Department of Electrical Engineering, 770 King Edward Avenue, Ottawa, Ontario, Canada K1A 6N5.

© 1987 Alan R. Liss, Inc.

separation of the components of the mixture, and a short lifetime before the onset of bacteria growth. The problems with the previous mixtures appeared to be mostly associated with the gelling agent; therefore, a substitute was sought. A compound used commercially for increasing the viscosity of many water based compounds was found to be an excellent material for our application. This material is a nonionic water-soluble polymerizing agent called hydroxyethylcellulose (HEC), also known as Natrosol. This material is available in a wide range of viscosities and is easily mixed with water. Because of the particular requirements of our project (immersion of a fragile probe into the material to measure the electric field), we needed a liquid or semi-liquid form of tissue equivalent materials. All recipes presented here are for semi-liquid materials (except for castable bone) which have viscosities in the range of 15,000-25,000 mPa. However, by increasing the amount of HEC one can obtain a more solid form of the materials with the same electrical properties.

The other components of the muscle material were sodium chloride (NaCl), to increase conductivity, and sucrose to lower the dielectric constant. One other component, a bactericide, was also added to prevent breakdown of the polymer by bacterial agents. The bactericide used was Dowicil 75[®][1-(3-chloroallyl)-3, 5, 7-triaza-1-azoniaadamantane chloride]. Sucrose is available in the form of cane sugar and is much cheaper than polyethylene powder used in previous formulas. See the Appendix for a list of suppliers. Table 1A gives the proportions by weight for each of the materials, and Table 2 lists the dielectric constants and the conductivities in mS/cm at several selected frequencies. Figure 1 shows the dielectric constant and the conductivity for simulated muscle material as well as expected values based on data from several sources [Hurt, 1985; Stuchly and Stuchly, 1980; Foster et al, 1985; Pethig, 1984; Durnay et al, 1978]. The measured dielectric constants are shown as circles, crosses depict the measured conductivities, solid lines present the expected dielectric constant, and dashed lines the conductivity.

Brain Tissue

The properties of brain tissue [Foster et al, 1979] are similar to those of skeletal muscle and the same components are used to produce brain equivalent material. Most of the brain consists of both grey and white matter with grey material having a higher dielectric constant and conductivity than white matter. The formula that is presented here will give properties averaged between those of white and grey matter. The recipe is presented in Table 1A, and frequency characteristics are shown in Figure 2 and in Table 2.

Lung Tissue

The lungs also have been identified as a part of the human body that has properties significantly different from skeletal muscle. It is, however, a complex structure that has different properties depending upon whether the lungs are inflated or deflated [Surowiec et al, in press]. In order to provide the best simulation an average was taken of these two states.

The basis of the lung simulation is the same as the skeletal muscle, as described above, but with the addition of hollow silica microspheres that range in diameter from 30-180 μm with a wall thickness of about 1.5 μm . This size is of the same order as the aveoli in the human lung, which is in the range of 100-200 μm in diameter. The skeletal muscle material is mixed with the microspheres by volume in a ratio of 47%

TABLE 1. (A) Composition by Weight of Muscle and Brain Equivalent Material. (B) Percentage by Volume of Filler Used in Lung Material. (C) Castable Bone Material Components. (D) Liquid Bone Material Components.

A. Muscle and brain material		Percentage by weight	
Material	Muscle	Brain	
Water	52.4	40.4	
Salt (NaCl)	1.4	2.5	
Sugar	45.0	56.0	
HEC	1.0	1.0	
Bactericide	0.1	0.1	
B. Lung material			
Material	Percentage by volume		
Muscle material (above)	47		
Microspheres	53		
C. Bone material (castable)			
Material	Percentage by weight		
Two ion epoxy	35.0		
Epoxy	35.0		
Hardener	28.0		
KCl Solution			
D. Bone material (liquid)			
Material	Percentage by weight		
TW/EEN	57.0		
n-Amyl alcohol	28.5		
Paraffin oil	9.5		
Water	4.5		
Salt (NaCl)	0.5		

TABLE 2. Dielectric Constant and Conductivity of Tissue Equivalent Materials at Selected Frequencies

Material	Frequency (MHz)					
	100		400		900	
	ϵ'	σ	ϵ'	σ	ϵ'	σ
Muscle	70.5	6.8	62.5	9.0	54.7	13.8
Brain	63.0	4.7	50.3	7.5	41.2	12.2
Lung	37.0	3.4	32.6	4.3	28.0	6.6
Bone cast	13.6	0.08	9.3	1.1	7.4	1.6
Bone liquid	10.8	0.35	9.1	0.66	7.2	1.2

muscle equivalent material to 53% microspheres. The properties of the simulated lung material are shown in Figure 3 and in Table 2.

Bone Tissue

Bone material is a very inhomogeneous structure, containing parts of different dielectric properties. The data found in literature [Foster and Schwan, 1985; Pethig,

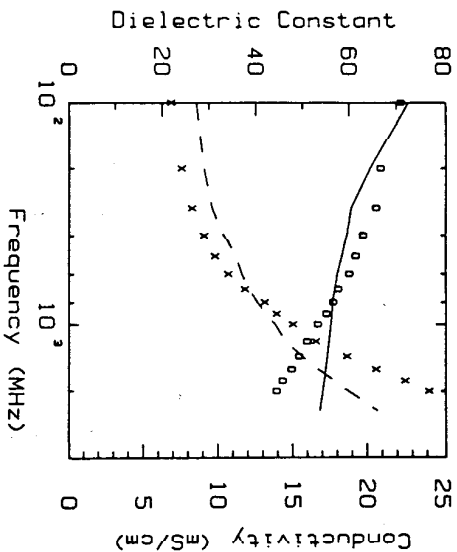


Fig. 1. Dielectric constant (O) and conductivity (X) of muscle equivalent material from 10 MHz to 2.45 GHz. Solid and dashed lines represent expected values of dielectric constant and conductivity, respectively.

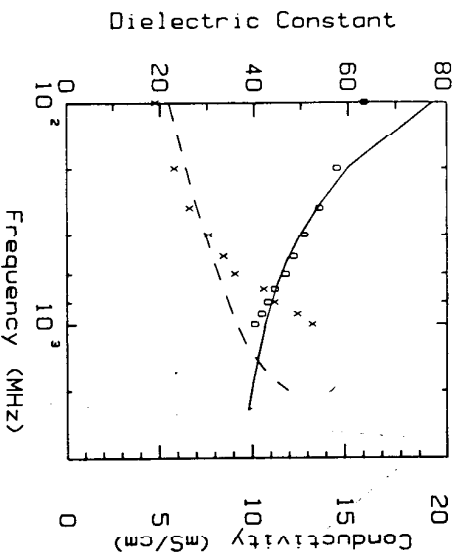


Fig. 2. Properties of simulated brain material compared to expected values (average of white and grey matter). Symbols for Figures 2-5 as in Fig. 1.

1984; Stuchly and Stuchly, 1980) differ significantly. The expected values plotted in Figure 4 and 5 are based on an average of the existing data. In order to simulate bone properties a different approach was necessary because of the relatively low dielectric constant and the desire to have a material that can be cast into the shape of a real bone. There are also experimental situations where it would also be desirable to have a liquid form of bone material so that the interior of the bone may be investigated. To this end we have devised two formulas for bone, one liquid, and the other castable.

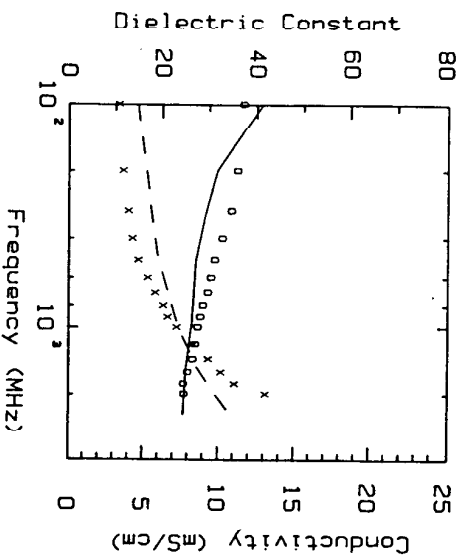


Fig. 3. Simulated lung material dielectric constant and conductivity compared to average properties of inflated and deflated lung.

The castable version is simply made from Devcon two-ton epoxy with a highly conductive potassium chloride (KCl) solution added. The concentration of the salt solution can be adjusted to vary the conductivity of the material and the dielectric constant. The desired conductivity may be achieved when the electrolyte is incorporated into the epoxy, thus forming ionic conduction carriers in the bone equivalent material. The composition of this material is given in Table 1C.

Due to the exothermic reaction some of the water evaporates and the resulting material contains about 0.5% less water than in the original case. The specific density of the resulting material is 0.98 g/cm⁻³.

This preparation has been found to be easy and fast to produce and it provides reproducible results. The most important aspect of this material is that the dielectric properties of bone material are simulated over a wide frequency range, as shown in Figure 4.

The liquid form of the bone material is made from several chemicals forming a microemulsion. This microemulsion is the same as presented by Foster et al [1982]. Saline solution is added to the microemulsion in order to increase the conductivity.

The amount of NaCl solution and other components of the microemulsion are given in Table 1D. Properties for the liquid bone material are given in Figure 5 and Table 2.

PREPARATION METHODS

The procedure for preparing the tissue equivalent materials are presented here. It is important that the instructions are followed carefully and the material is weighed accurately to obtain reproducible results.

Muscle, Brain, and Lung Tissue Equivalent Material

The following procedure was used to prepare muscle, brain, and lung tissue

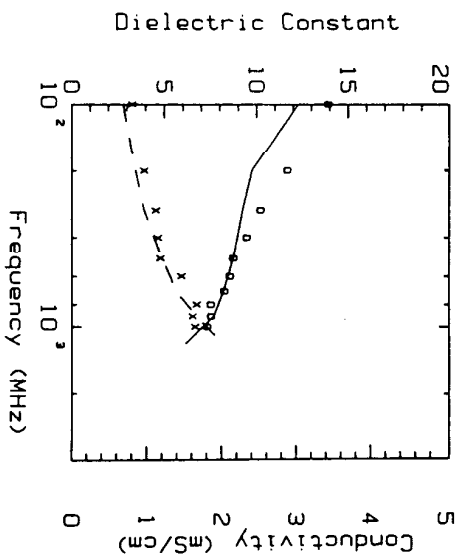


Fig. 4. Electric properties of castable bone-equivalent material.

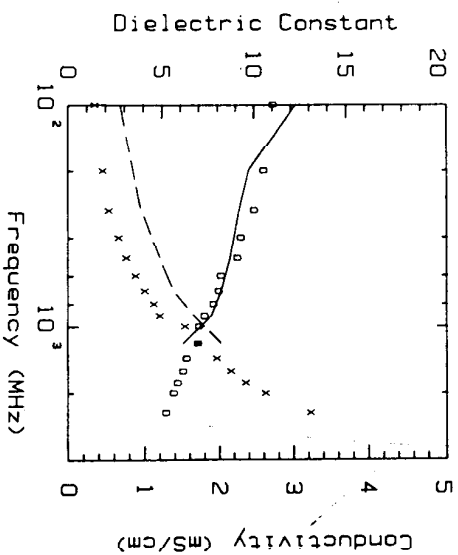


Fig. 5. Electric properties of liquid bone-equivalent material.

equivalent material: (1) Weigh all ingredients accurately. (2) Heat water to 40°C. (3) Add salt and bactericide while stirring. (4) Add sugar (and microspheres in case of lung). (5) Continue to stir at low speed to minimize the amount of air bubbles in the solution. (6) Add the hydroxyethylcellulose (HEC). (7) Remove from heat. (8) Continue to stir until mixture thickens. (9) Let cool to room temperature.

When not in use the material should be stored in a covered container to prevent evaporation of water. If, however, the material does lose some water the original properties can usually be restored by the addition of a small amount of water that is simply stirred into the existing material.

Bone Tissue Equivalent Material

The procedure for preparing the bone equivalent material is as follows: (1) Mix the KCl solution in the proportions given in Table 1C. (2) Add one-quarter of the total amount of KCl solution to the epoxy resin and mix until a homogeneous paste is obtained. (3) Add another 25% of the KCl solution and mix until the material is homogeneous, white, and no water appears on the surface. (4) Add the hardener and mix carefully for about 1 min. (5) Add 25% more KCl and mix using an electric mixer until homogeneous (less than 1 min). (6) Add the remainder of the KCl and continue to mix for 1-2 min. (7) Pour the mixture into molds to set. (8) The material will then slowly begin to solidify producing an exothermic reaction. (9) The material will harden in about 4 h.

The material should then be kept in a moist environment to prevent evaporation of water.

MEASURING TECHNIQUES

The dielectric properties of the tissue simulating materials were measured using an open-ended coaxial-line sensor and a computer-controlled automatic network analyzer [Kraszewski et al., 1983]. The system was calibrated with the sensor open-circuited, short-circuited, and immersed in a saline solution to minimize the errors related to the system imperfections. The sensor was then immersed into the material under test (being a liquid or semi-liquid) or was firmly pressed into the flat smooth surface of the cast bone sample. The uncertainty of the measurement was evaluated as being less than 3% for the dielectric constant and 2% for the conductivity of muscle, brain, and lung materials, and less than 5 and 10%, respectively, for bone simulating material.

A summary of the properties of all the materials that have been described are presented in Table 2. This table gives dielectric constants and conductivities at frequencies of 100, 400, and 900 MHz.

SUMMARY

Formulas have been presented along with mixing instructions for the preparation of simulated bone, lung, brain, and muscle material in the frequency range of 100 MHz to 1 GHz. These materials are easy to prepare, inexpensive, reproducible, and retain their properties for a long period of time.

The dielectric properties of each of the described materials can easily be changed to match the particular need of an experiment. In general the amount of sodium chloride (or KCl) is responsible for the material's conductivity, and the amount of water influences mainly the value of its dielectric constant. In a limited range these two parameters can be changed almost independent of each other, thus allowing precise simulation of tissue properties at a particular frequency.

With this information it is possible to construct a more realistic model of man for electromagnetic dosimetry studies.

ACKNOWLEDGMENTS

This work was supported by grants from the U.S. Environmental Protection Agency, Health and Welfare Canada, and from the Natural Science and Engineering

Research Council of Canada. The guidance of Dr. S. Stuchly, who proposed this project, is gratefully acknowledged. The authors also wish to thank S. Symons, C. Sibbald, D. M. Bui, J. Daddkhah, and P. Kratchanov for their help in preparing the samples and measuring their dielectric properties.

APPENDIX

List of suppliers for this project includes: Two Ton Epoxy (Devcon Corp., Danvers, MA 01923; NaCl (any grocery store); sucrose (granulated cane sugar, any grocery store); HEC (100,000 A; BP Chemicals) or Natrosol 250 HHR (Hercules Inc., Wilmington, DE 19899); Dowicel 75 (Dow Chemical, Midland, MI 48840); Microspheres (Ecospheres SI, Emerson and Cuming, Canton, MA 02021); KCl, TWEEN, n-amyyl alcohol, paraffin oil (Sargent-Welch, Skokie, IL 60077).

REFERENCES

- Chou CK, Chen GW, Guy AW, Luk KH (1984): Formulas for preparing phantom muscle tissue at various radiofrequencies. *Bioelectromagnetics* 5:435-441.
- Durney CH, Johnson CC, Barber PW, Massoudi H, Iskander MF, Lords JL, Ryer DK, Allen SJ, Mitchell JC (1978): "Radiofrequency Radiation Dosimetry Handbook, second ed." Brooks AFB, TX: Air Force School of Aerospace Medicine Report, SAM-TR-78-22, pp 50-59.
- Foster KR, Epstein BR, Jenni PC, Mackay RA (1982): Dielectric studies on nonionic microemulsions. *J Colloid Interface Sci* 88:233-246.
- Foster KR, Schepps JL, Stoy RD, and Schwan HP (1979): Dielectric properties of brain tissue between 0.01 and 10 GHz. *Phys Med Biol* 24:1177-1187.
- Foster KR, Schwan HP (1986): "Dielectric Properties of Tissue—A Review." Handbook of Biological Effects of Electromagnetic Radiation. Cleveland: CRC Press.
- Guy AW (1971): Analysis of electromagnetic fields induced in biological tissues on equivalent phantom models. *IEEE Trans Microwave Theory Tech MMT-19*:205-214.
- Hurt WD (1985): Multiterm Debye dispersion relations for permittivity of muscle. *IEEE Trans Biomed Eng* BME-32:60-64.
- Kraszewski A, Stuchly SS, Stuchly MA, Symons SA (1983): On the measurement accuracy of the tissue permittivity in vivo. *IEEE Trans Instrum Meas IM-32*:37-42.
- Petig R (1984): Dielectric properties of biological material: Biophysical and medical applications. *IEEE Trans Elect Insulation EI*:19:453-475.
- Stuchly MA, Stuchly SS (1980): Dielectric properties of biological substances—tabulated. *J Microwave Power* 15:19-26.
- Surowiec A, Stuchly SS, Keane M, Swarup A (in press): Dielectric spectroscopy of inflated and deflated lung. *IEEE Trans Biomed Eng*.

Acute, Whole-Body Microwave Exposure and Testicular Function of Rats

R.M. Lebovitz and L. Johnson

Departments of Cell Biology (L.J.) and Physiology (R.M.L.), University of Texas Health Science Center, Dallas

Male Sprague-Dawley rats were exposed for 8 h to continuous-wave microwave radiation (MWR, 1.3 GHz) at a mean specific absorbed dose rate of 9 mW/g. MWR exposure and sham-irradiation took place in unidirectionally energized cylindrical waveguide sections, within which the animals were essentially unrestrained. The MWR treatment in this setting was determined to yield an elevation of deep rectal temperature to 4.5 °C. The animals were taken for analysis at 6.5, 13, 26, and 52 days following treatment, which corresponded to .5, 1, 2, and 4 cycles of the seminiferous epithelium. Net mass of testes, epididymides, and seminal vesicles; daily sperm production (DSP) per testis and per gram of testis; and the number of epididymal sperm were determined. The levels of circulating follicle-stimulating hormone (FSH) and leutinizing hormone (LH) were derived via radioimmunoassay of plasma samples taken at the time of sacrifice. Despite the evident acute thermogenesis of the MWR at 9 mW/g, no substantial decrement in testicular function was found. We conclude that, in the unrestrained rat, whole body irradiation at 9 mW/g, while sufficient to induce evident hyperthermia, is not a sufficient condition for disruption of any of these key measures of testicular function.

Key words: neurohormones, testis

INTRODUCTION

In previous reports, we indicated that repeated daily exposure to microwave radiation (MWR, 1.3 GHz) at a dose rate of 6.3 mW/g, 6 h per day for 9 days did not significantly perturb testicular function in the adult male rat [Lebovitz and Johnson, 1983; Johnson et al, 1984]. At no stage in the development of the male germ cells could a significant physiologic or morphologic deficit be found. Our approach was to examine testicular function following irradiation at intervals that corresponded to multiples of the 13-day cycle of the seminiferous epithelium of the Sprague-Dawley rat [Clermont, 1962; Clermont and Harvey, 1965; Leblond and Clermont, 1952]. It would thus be possible to test, if a deficit in spermatogenesis were detected at all, at which stage(s) of germ cell maturation maximal sensitivity was evident, and whether this agreed with the results of conventional heating [Seitchell and Wailes, 1972].

Since, in the previous series of experiments, a moderately thermogenic level of MWR was used (1 to 1.5 °C elevation in rectal temperature), a prolonged course of exposure was felt to be necessary in order to demonstrate any change in testicular

Received for review February 10, 1986; revision received June 27, 1986.

Address reprint requests to Dr. Robert Lebovitz, Department of Physiology, University of Texas Health Science Center, 5323 Harry Hines Blvd., Dallas, TX 75235.

© 1987 Alan R. Liss, Inc.