CHAPTER 26

Electromagnetic Phantom Materials

26.1 Introduction

A state-of-the-art interest in electromagnetic research is to elucidate and characterize the interactions between *nonionizing* radiations *versus* living systems. The purpose is threefold: (1) To understand the mechanism(s) of interactions involved; (2) to investigate any deleterious effects which may result from such interactions; and (3) to consider the possibilities of such interactions inducing beneficial effects in the living systems.

A subset of relevant studies refers to electromagnetic dosimetry and hyperthermia considerations. In both cases, it is of interest to know the extent of absorption of nonionizing radiation by living systems.

Nonionizing radiation in general refers to electromagnetic (EM) waves from the quasistatic region to the end of visible radiation. Characteristically, unlike ionizing radiation such as X-rays and/or radioactive emissions, nonionizing radiation is not of sufficient energy to ionize the molecules of the medium (such as air) through which it proliferates.

Simulating materials to depict the dielectric and thermal characteristics of various biological structures over different frequency ranges refer to synthesizing the EM phantom materials. The biological materials are in general not monolithic and are invariably constituted by two are more substances. Development of materials which mimic the behavior of biological substances in their response to EM interactions, is therefore directed at synthesizing composite media as appropriate. Such endeavors warrant clear specifications on the complex dielectric parameters of various biological materials.

Such characteristics are, however, largely dependent on data measured under *in vivo* or *in vitro* conditions, temperature, and living systems from which the test specimens were gathered.

Therefore unique specifications for the complex dielectric parameters of biological materials are not feasible. However, on the basis of various experimental works, the data gathered are summarized in the next section which represents the average values of the relevant parameters, as reported in the available literature.

26.2 Complex Dielectric Properties of Biological Materials

Essentially, biological substances can be classified into the following categories:

- Biological fluids
- Water-borne tissues, muscles, skin etc. (with large water content)
- Bones, fat, and tissues (with low water content)

Depending on the frequency band of interest, the measured data on specific resistance and the complex permittivity parameters (namely, $\varepsilon' - j\varepsilon''$) have been widely reported in the literature, a compendium of which is presented in the following tables (Tables 26.1 to 26.6):

26.2.1 Biological Fluids

Table 26.1 The Complex Dielectric Constant of Human Blood at Room Temperature

Relative Permittivity of Blood: $\varepsilon_B = (\varepsilon_B' - j\varepsilon_B'')$

Frequency in MHz (f)	Volume Fraction of RBC* (Hematocrit Value) (c)	Measured Values due to Bianco et al. [1]	
		ε_B'	ε_B''
100	0.14	68.7466	–196.5908
	0.28	67.6619	–181.7745
	0.41	66.9199	–164.5834
	0.53	65.9390	–155.2289
	0.84	63.6034	–123.1350
500	0.14	65.5428	–42.4751
	0.28	62.7100	–39.6517
	0.41	61.0684	–36.4393
	0.53	59.0783	–34.4925
	0.84	54.4693	–28.4197
1000	0.14	63.8943	–23.9896
	0.28	60.9095	–22.2137
	0.41	59.1531	–20.6747
	0.53	57.1505	–19.6454
	0.84	52.4498	–16.3249
1500	0.14	63.0756	–18.3516
	0.28	59.9311	–17.0036
	0.41	57.9560	–15.9502
	0.53	55.8107	15.3838
	0.84	50.9991	12.9609
2000	0.14	63.0435	–15.8471
	0.28	59.5073	–14.8409
	0.41	57.5331	–14.0258
	0.53	55.2680	–13.5188
	0.84	50.2958	–11.4703

Note: RBC*: Red blood corpuscles.

Table 26.2 Conductivity of Human Blood

Frequency in MHz	Hematocrit Value c	Conductivity of Blood σ_B siemen/meter
		Measured Values Bianco et al. [1]
100	0.14	1.0937
	0.28	1.0112
	0.41	0.9156
	0.53	0.8636
	0.84	0.6850
500	0.14	1.1815
	0.28	1.1029
	0.41	1.0136
	0.53	0.9594
	0.84	0.7905
1000	0.14	1.3300
	0.28	1.2358
	0.41	1.1502
	0.53	1.0929
	0.84	0.9082
1500	0.14	1.5314
	0.28	1.4190
	0.41	1.3310
	0.53	1.2807
	0.84	1.0816
2000	0.14	1.7632
	0.28	1.6512
	0.41	1.5606
	0.53	1.5041
	0.84	1.2762

Note: $\sigma_B = (55.631452 \times 10^{-12}) \times \varepsilon''_B \times$ frequency (in Hz) siemen/meter.

Table 26.3 Resistivity of Blood [5]

Substance	Resistivity (ohm-cm)	Frequency	Temp. (°C)	Remarks
Human blood	150	d.c.	40	
	155	20–5 KHz	40	
	165 aver. (148-176)	1 KHz	37	Normal subject
	137.8	1 KHz	37	34.4% hematocrit
	170.3	1 KHz	37	37.2% hematocrit
	169.1	1 KHz	37	40.2% hematocrit
	176.0	1 KHz	37	42.5% hematocrit
	131.2	1 KHz	37	43.9% hematocrit
	230.9	1 KHz	37	50.9% hematocrit
	199.8	1 KHz	37	55.6% hematocrit
	180.0	1 KHz	37	56.4% hematocrit (all calculated values)
	160.0	d.c.	37	
	154 aver. (of two methods)	120 KHz	36.3 aver.	Flowing venous blood
	200.0	d.c.	20	
	195.0	20–5 KHz	20	
	230.0	d.c.	18	
	363.0	120 KHz	1.3	Flowing blood
Human blood	63 aver. (61-67)	1 KHz	37	Normal subjects
	100	d.c.	18	
	70	d.c.	Body	
Dog blood	108	100 KHz	Body	29% hematocrit
	118	100 KHz	Body	33% hematocrit
	120	100 KHz	Body	36% hematocrit
	129 and 158	100 KHz	Body	40% hematocrit
	155	100 KHz	Body	41% hematocrit
	153	100 KHz	Body	47% hematocrit
	156-243	Inductorium	38	Measured within 1 min
	207 aver. (185-230)	1 KHz	Body	Approx. 50% hematocrit
Dog serum	138 aver. (98-178)	1 KHz	Body	

(continued...)

Substance	Resistivity (ohm-cm)	Frequency	Temp. (^oC)	Remarks
Cow blood	145	20–5 KHz	38	
	131	d.c.	37	
Cow-pig blood	137 aver. (119-152)	Audio	37	
	192 aver.	Audio	20	
Cow blood	190	d.c.	20	
	180	20– 5 KHz	20	
	169.6 aver. (164.5–174)	1 KHz	Room	Stationary 70% cells
	164 aver. (159–168)	1 KHz	Room	Flowing at 15 cm/sec–70%cells
	271.75	1 KHz	Room	100% cells stationary
	249.75	1 KHz	Room	100% cells flowing–15 cm/sec
	116.15	1 KHz	Room	40% cells stationary
	114.65	1 KHz	Room	40% cells flowing–15 cm/sec
	80.75	1 KHz	Room	5% cells stationary
	80.75	1 KHz	Room	5% cells flowing–15 cm/sec
	196.5 aver.	1 KHz	Room	80% hematocrit–stationary
	189.25 aver.	1 KHz	Room	80% hematocrit flowing–15 cm/sec
	145.4 aver.	1 KHz	Room	60% hematocrit–stationary
	142.25 aver.	1 KHz	Room	60% hematocrit flowing–15 cm/sec
	91.5 aver.	1 KHz	Room	20% hematocrit–stationary
	91.35 aver.	1 KHz	Room	20% hematocrit flowing–15 cm/sec
Cow-pig blood	91 aver.	25–100 MHz	37	
	133 aver.	25–100 MHz	20	
	99 aver.	25–100 MHz	37	
Cow blood	89 aver. (89–96)	200–900 MHz	27	

(continued...)

Substance	Resistivity (ohm-cm)	Frequency	Temp. (^{o}C)	Remarks
Cow plasma	65	20 Hz – 5 KHz	40	
Cow-pig serum	62.5	Audio	37	
	83	Audio	20	
Cow plasma	90	20 Hz–5 KHz	20	
Calf serum	89.4	87 KHz–4.52MHz	21.6	
Cow-pig serum	62.5	25–100 MHz	37	
	83	25–100 MHz	20	
Horse red cells	3890	1 KHz	25	Centrifuged and packed
	840	400 KHz	25	Centrifuged and packed
	410	1 MHz	25	Centrifuged and packed
	285	2 MHz	25	Centrifuged and packed
	232	3.5 MHz	25	Centrifuged and packed
Rabbit blood	128 (117–136)	1 KHz	39	
	129–176	Inductorium	39	
Turtle serum	120	Inductorium	16	
	110	Inductorium	20	
	103 aver.	Inductorium	24	
	91 aver.	Inductorium	30	
	78 aver.	Inductorium	38	

Table 26.4 Resistivity of Other Body Fluids

Substance	Resistivity (ohm-cm)	Frequency	Temp. (^{o}C)	Remarks
C.S.F.				
Human	64.6 (64.0–65.2)	1–30 KHz	24.5	
Cat	65.7 (65.5–66.1)	1–30 KHz	24.5	
Rabbit	55.9 aver. (51–62)	1 KHz	39	
Bile				
Cow-pig	60	Audio	37	
	78	Audio	20	
	59	50 MHz	37	
	76	50 MHz	20	
Rabbit	66.2 aver. (61–72)	1 KHz	39	
Amniotic fluid				
Sheep	65	1 KHz	25	Measured after 2 days of refrigerated storage
	39	1 KHz	37.5	
Urine				
Cow-pig	30	Audio	37	
	39	Audio	20	
Physiological solutions				
Saline	72	d.c.	18	
Saline 0.9%	57 aver. (56–58)	200–900 MHz	27	
Tyrode	52	Not given	37	
Saline 0.9%	70	1 KHz	20	
	50.5	1 KHz	37.5	
3 M KCL	4.28	–	20	
	3.26	–	37.5	
	3.85	–	23.5	
	3.70	–	38	
Saline 1%	55.5	–	23.5	
	50.0	–	38	
Saline 2M	7.14	–	23.5	
	5.88	–	38	

26.2.2 Biological Solid Substances

Table 26.5 Dielectric Properties of Fat, Bone, and Tissues with Low Water Content

Frequency (MHz)	Dielectric Constant ε_L	Conductivity σ_L (millisiemen/meter)
1		
10		
27.12	20.0	10.9–43.2
40.68	14.6	12.6–52.8
100	7.45	19.1–75.9
200	5.95	25.8–94.2
300	5.70	31.6–107
433	5.60	37.9–118
750	5.60	49.8–138
915	5.60	55.6–147
1500	5.60	70.8–171
2450	5.50	96.4–213
3000	5.50	110–234
5000	5.50	162–309
5900	5.05	186–338
8000	4.70	255–431
10000	4.50	324–549

Table 26.6 Dielectric Properties of Muscle, Skin, and Tissues with High Water Content

Frequency (MHz)	Dielectric Constant (ε_H)	Conductivity σ_H (mho/m)
1	2000	0.400
10	160	0.625
27.12	113	0.612
40.68	97.3	0.693
100	71.7	0.889
200	56.5	1.28
300	54	1.37
433	53	1.43
750	52	1.54
915	51	1.60
1500	49	1.77
2450	47	2.21
3000	46	2.26
5000	44	3.92
5900	43.3	4.73
8000	40	7.65
10000	39.9	10.3

In addition to the data presented in the above tables, more details can be seen in [2-5].

26.3 Electromagnetic Phantom Materials: Synthesizing Concepts

Basically an EM phantom material is a lossy dielectric material constituted by appropriate lossy/loss-less substances with the end result of emulating the complex dielectric characteristics of a given biological medium at a specified temperature and frequency. The complex permittivity of a medium is specified by the Debye expression, namely:

$$\begin{aligned} \varepsilon &= \varepsilon_\infty + [(\varepsilon_s - \varepsilon_\infty)/(1 + j\omega\tau)^{1-\alpha}] - (\sigma/\omega\varepsilon_o) \\ &= \varepsilon'_b - j\varepsilon''_b \end{aligned} \tag{26.1}$$

where

ε_∞	Dielectric constant of the material at infinity frequency
ε_s	Static dielectric constant of the material
τ	Relaxation time of the material in second
ω	$2\pi f$, with f frequency in Hertz
α	Empirical parameter
σ	Ionic conductivity of the material (siemen/meter)
ε_o	8.854×10^{-12} farads/meter (free-space permittivity)

A phantom is designed to exhibit the similar dielectric properties as dictated by Equation 26.1. That is, if the complex permittivity of a biological medium, namely, $(\varepsilon'_b - j\varepsilon''_b)$, is known, the corresponding phantom material should have the permittivity values $\varepsilon'_p = \varepsilon'_b$ and $\varepsilon''_p = \varepsilon''_b$. In the following sections, the methods of emulating such dielectric properties in phantoms are addressed.

26.4 Saline Solution as a Phantom Material

The simplest way to realize the lossy biological characteristics (such as that of a tissue material) is to use saline solution as the phantom material. Water with the addition of NaCl becomes a lossy dielectric whose dielectric permittivity can then be expressed by the following Debye formula [6]:

$$\varepsilon_W = (\varepsilon_\infty)_W + [(\varepsilon_s)_W - (\varepsilon_\infty)_W]/[1 + j\omega\tau_W]^{1-\beta} - j[\sigma_W/\omega\varepsilon_o] \tag{26.2}$$

where

$(\varepsilon_\infty)_W$	Dielectric constant of the material at infinity frequency = 4.9
$(\varepsilon_s)_W$	Static dielectric constant of the water
τ_W	Relaxation time of the material in second
ω	$2\pi f$, f frequency in hertz
β	Empirical parameter ≈ (0.02 ± 0.007)
σ_W	Ionic conductivity of the material (siemen/meter)
ε_o	8.854×10^{-12} farads/meter (free-space permittivity)

If T indicates the temperature in °C and S is the salinity (in parts per thousand) of the salt water, then,

$$(\varepsilon_s)_W(T) = 88.045 - 0.4147T + 6.295 \times 10^{-4}\,T^2 + 1.075 \times 10^{-5}\,T^3 \tag{26.3}$$

$$\sigma_W(T,S) = \sigma_W(25,S)\,\exp(-\Delta\gamma) \tag{26.4}$$

with

$$\begin{aligned} \Delta &= (25 - T), \\ \gamma &= 2.033 \times 10^{-2} + 1.266 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2 \\ &\quad - S(1.849 \times 10^{-5} - 2.551 \times 10^{-7}\Delta + 2.551 \times 10^{-8}\Delta^2) \end{aligned} \tag{26.5}$$

and

$$\begin{aligned} \sigma_W(25,S) &= S(0.182521 - 1.46192 \times 10^{-3}S + 2.09324 \times 10^{-5}S^2 \\ &\quad - 1.28205 \times 10^{-7}S^3) \end{aligned} \tag{26.6}$$

Further,

$$\tau_W(T,S) = \tau_W(T,O)\, b(S,T) \tag{26.7}$$

where

$$\tau_W(T,O) = 1.768 \times 10^{-11} - 6.086 \times 10^{-13}T + 1.104 \times 10^{-14}T^2 - 8.11 \times 10^{-17}T^3$$

and

$$\begin{aligned} b(S,T) &= 1.000 + 2.282 \times 10^{-5}ST - 7.638 \times 10^{-4}S - 7.760 \times 10^{-6}S^2 \\ &\quad + 1.105 \times 10^{-8}S^3 \end{aligned}$$

The *salinity factor (S)* is related to the percentage concentration of the salt content by the following relation:

$$S = (1.805 \times \text{chlorinity} + 0.030) \tag{26.8}$$

and

$$\text{Chlorinity} = \frac{(6.0657)}{(\text{Specific gravity of the solution})} \, \frac{(\text{Weight of NaCl} \times 100)}{(\text{Volume of the solvent})} \tag{26.9}$$

The specific gravity of NaCl solution for a given percentage concentration (that is, weight/volume %) can be extrapolated from the following data:

NaCl Concentration (Weight/vol)%	3.30	3.28	3.21	3.20	3.15	3.14	3.12	3.07	2.94	2.78	1.48
Specific gravity	1.0250	1.0249	1.0243	1.0242	1.0238	1.0238	1.0236	1.0232	1.0216	1.0209	1.0104

Though a saline solution offers a simple phantom synthesization, it is useful only for the representation of a simple biological medium (such as a simple structure to emulate the specific absorption rate (SAR) pertinent to human adult, etc.). The dielectric behavior of saline solution is highly temperature sensitive and also it is sensitive to the concentration of NaCl content. Further, being a fluid, its use in a compact geometry is rather futile. Nevertheless, columns of saline solution are being used as human phantoms to study their proximity effect in the performance of devices like pagers. Nonliquid (semisolid) phantoms *in lieu* of water are preferred in practice because of their moldability to required shapes. Various such semisolid phantoms developed and reported in [7-11] are briefly described in the following sections.

26.5 Polyacrylamide Gels as Phantom Materials

A convenient way of emulating biological materials such as tissues is to use the polyacrylamide gel which offers the following advantages as phantom materials: (i) Easily shaped into complex forms, (ii) an elasticsolid, (iii) readily prepared with a complete range of highly reproducible values of electrical parameters, (iv) optically transparent facilitating the insertion probes, and etc. (v) low cost material.

The base material to constitute a polyacrylamide phantom is acrylamide (C_3H_5NO) which with the addition of water becomes gel-like. NaCl is used to dope the gel to realize desired lossy characteristics. As reported in [9], the following are the techniques associated in realizing viable phantom materials using polyacrylamide:

Constitutents of the gel:

1. Base material: Polymeric acrylamide (C_3H_5NO)
2. Water
3. Polymerization catalysts:
    MBA (N, N'-methylene-bis-acrylamide, $C_7H_{10}N_2O_2$)
    TEMEDA (N, N, N', N'-tetramethyl-ethylene-diamine, $C_6H_{16}N_2$)
4. Primer: Ammonium persulfate (AP) $(NH_4)_2S_2O_8$

Recipe:

Phase 1: 15 grams of acrylamide
+0.1 gram of MBA
+0.5 gram of TEMEDA
plus water to make a total volume of 90 cm^3 + adequate amount of NaCl to acquire a specified electrical conductivity.

Phase 2: AP in water (1.3% by weight) to form 10 cm^3

Phase 3: Solutions of phase 1 and phase 2 mixed to set the polymerization

Conductivity control:

Electrical conductivity of the above material is primarily dictated by NaCl content. With no salt added the lower limit of conductivity is 0.15 siemen/meter.

Permittivity control:

This is accomplished by varying acrylamide content (maintaining the stoichiometric proportions of MBA and TEMEDA). Nominal dielectric constant ≈60. This value can be lowered by substituting water with low permittivity liquids such as dioxane, pyridine, or ethylene glycol. Stability of the composition is dependent on loss of water content *via* evaporation.

Thermal properties of these materials have also been assayed as reported in [9].

26.6 Other Semisolid Gels to Simulate Soft-Tissue Materials

Soft-tissue phantoms can be fabricated from the composition of a saline solution, polyethylene powder, and gelling agent. Resulting phantom materials are very viscous, pliable and putty-like and are suitable to simulate bisected phantoms for thermographic studies.

Another gel-like phantom material is constituted from hydroxethyl cellulose (HEC) and saline solution. For frequencies above 100 MHz, polyethylene or sugar is also added.

A moist gellied plastic to simulate muscle is formed as described below.

This material is constituted from 76.5% (by weight) of saline solution (equivalent to 12 grams of salt/liter), 15.2% (by weight) of powdered polyethylene, and 8.4% (by weight) of Super Stuff™ which is a gelling agent supplied by Whamo Manufacturing Company, San Gabriel, CA. The dielectric properties of this phantom material are: Dielectric constant ≈ 49-58 and loss tangent 0.33-1.7. The other physical properties are: Density ≈ 1.0 and specific heat 0.24-0.30.

26.7 Simulation of Bone and Fat Phantoms

Bone and adipose tissue (fat) have low water content. They can be simulated in dry plastic-like form using: 84.81% (by weight) of laminac polyester resin + 0.45% (by weight) of a catalyst (for example, methyl ethyl ketone peroxide 60%) + 0.24% (by weight) of acetylene black + 14.5% (by weight) of aluminum powder. The dielectric constant of this phantom is 4.6-6.2 and the loss tangent is 0.70-0.55. The density of the material is 1.3 and the specific heat is 0.24-0.30.

Other possible compositions of biological phantom materials are presented in Table 26.7.

Table 26.7 Composition of Typical Phantom Materials

Biological Media	Compositions in % by Weight				
	Aluminum Powder	Polyethylene Powder	Gel Agent	Water	NaCl
Brain (2450 MHz)		29.8	7.01	62.6	0.582
Muscle (2450 MHz)		15.2	8.45	75.4	0.907
Muscle (27 MHz)	13.7		9.49	76.6	0.153
	Aluminum Powder	XC–72*	Acetylene Black	Polyester Resin**	
Adipose (27 MHz)	29.46	0.94	0.30	69.3	

*XC–72 ("Fluffy") carbon powder, Cabot Corporation.
**Laminac 4110.

Table 26.8 Synthesis of Typical Biological Equivalent Phantoms

1. Muscle and brain equivalent phantom

Material	Percentage by Weight	
	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

2. Lung material

Material	Percentage by Volume
Muscle material (above)	47
Microspheres	53

3. Bone material (castable)

Material	Percentage by Weight
Two-ton epoxy	35.0
Epoxy	35.0
Hardener	28.0
KCl solution	–

4. Bone material (liquid)

Material	Percentage by Weight
TWEEN	57.0
n-Amyl alcohol	28.5
Paraffin oil	9.5
Water	4.5
Salt (NaCl)	0.5

26.8 Thermal Properties of Phantom Materials

In dosimetry applications, knowing the precise values of physical and thermal parameters of phantoms are rather essential. Typical values of these parameters *vis-a-vis* a variety of phantom materials as reported in [7-11] listed in the following table.

Table 26.9 Thermal Properties of Phantom Materials

Simulated Phantom	Thermal Conductivity (W/m-K)	Specific Heat ($\times 10^3$ J/kg-K)	Density ($\times 10^3$ kg/m^3)	Thermal Diffusivity ($\times 10^{-6}$ m^2/s)
Ethylene glycol	0.259 + 0.005	–	–	–
Brain (2450 MHz)	0.478 + 0.015	3.41	0.98 0.03	0.143
Muscle (2450 MHz)	0.535 0.003	3.70	1.00 0.02	0.145
Muscle (27 MHz)	0.657 0.028	3.58	1.00 0.01	0.167
Adipose tissue (27 MHz)	0.352 0.004	1.07	1.43 0.01	0.230

Actual biological substances have the following physical and thermal charcteristics as estimated on an average basis.

Table 26.10 Thermal Properties of Actual Biological Media

Material	Thermal Conductivity ([W/(m – °C)] $\times 10^3$)	Specific Heat [(J/kg – °C)] $\times 10^3$)	Thermal Diffusivity ([m^2/s] $\times 10^{-6}$)	Mass Density ([kg/m^3] $\times 10^3$)
Muscle *in vitro*	0.197–0.545	3.51	0.183	1.07
Brain *in vitro*	0.497–0.566	3.47	0.134–0.143	1.07
Fat tissue *in vitro*	0.132–0.371	1.21–1.55	0.230	1.06
Bone	–	1.26–2.97	–	1.25–1.79

It should be noted that the thermal properties of the phantom materials are also largely influenced by the conducting constitutents of the composite such as aluminum powder and/or NaCl. For example, if the weight fraction of aluminum is changed by a 1:4 ratio, thermal conductivity is increased more than twice and the specific heat is altered by about 22%.

26.9 Concluding Remarks

Tissue-equivalent electromagnetic phantoms offer a means to measure the extent of EM power deposition which manifests as the thermal power in the medium assessable through thermographic/thermometric methods. A variety of phantom materials have been designed for use, especially at radio and microwave frequencies. Electrical as well as physical/thermal properties of these materials have been evaluated.

One of the greatest problems associated in the practical use of these materials is maintaining the stable characteristics, both electrical and thermal. Presence of materials like water poses evaporation problems and growth of parasitic fungi is encouraged. Further, synthesizing phantoms to match the exact properties of biological substances is based more on trial and error basis rather than by algorithmic recipes.

In effect, phantoms are composite dielectrics. However, the heterogeneous nature of such materials is so complex, no simple analytic modeling is feasible. Development of appropriate algorithms using computer-aided design strategies, would lead to comprehensive and user friendly, ready-made mixture formulations. Also, conceiving new compositions with a variety of possible ingredients offers a wide scope for further research in EM phantom technology.

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Defining Terms

EM phantoms: Phantoms fabricated with materials that simulate the dielectric properties of various biological tissues (such as fat, muscle, brain, bone, or a body fluid).

Nonionizing radiations: Electromagnetic radiations in the radio/microwave frequency ranges which do not cause ionization of molecules in their transit across a medium like air, unlike ionizing radiation like X-ray, etc.

Subject Index