Electrical Properties of Biological Materials: A Bibliographic Survey

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Abstract

A bibliographic survey of the electrical properties of biological tissues and of phantoms is provided. A phantom is, for these purposes, any material, structure, or system that is intended to emulate the electrical properties of biological tissues, biological systems, or of a whole organism. Phantoms are considered for 1) the evaluation of interference in medical electronic devices due to exposure to the electromagnetic fields generated by hand-held and walk-through metal detectors, and 2) the development of standard tests to evaluate the accuracy, reliability, and sensitivity of hand-held and walk-through metal detectors. The following subjects are included in this bibliography: measurements of the electrical properties of biological tissues, phantom materials, and materials that may hold potential use as a phantom material; the description and evaluation of phantoms; and techniques for measurement of electrical properties.

Keywords

biological tissue, dielectric relaxation, dispersion, phantom

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1 Introduction

There is a plethora of electronic devices found in medical applications. These devices include, for example, cardiac defibrillators, cardiac pacemakers, infusion pumps, and spinal cord stimulators. Further, the number of people who rely on these devices to assist or supplant physiological function is steadily increasing.

Such personal medical electronic devices (PMEDs) are susceptible, in principle, to interference due to electromagnetic fields emitted by other electronic or electrical devices. The susceptibility of a device to electromagnetic interference may be influenced by form factors: Medical devices may be implanted in the body, located on the outer surface of the body, or a combination of both configurations. The functionality of the PMED may also influence its susceptibility to electromagnetic interference: PMEDs that are programmed magnetically may be highly susceptible to electromagnetic interference.

Regulations exist to restrict unwanted electromagnetic emissions from electrical and electronic devices; and most devices are not intentional radiators. However, the interaction of PMEDs with intentional radiators is of concern. Commonly encountered intentional radiators are the hand-held and walk-through metal detectors used in security applications. These detectors may emit electromagnetic fields that oscillate at frequencies close to those used by PMEDs.

Metal detectors are often used at courthouses, correctional facilities, airports, schools, governmental buildings, and at special events. Unlike air travel, which is a voluntary activity, many situations that require an individual to visit a courthouse or governmental building are not voluntary. Consequently, the safety of persons with medical electronic devices is not an avoidable issue. Unfortunately, there is little information, other than anecdotal, on the interaction of PMEDs with the fields emitted by metal detectors.

Biological phantoms, that is materials that are designed to emulate the electrical properties of biological tissues, have been widely used to evaluate the effects of electromagnetic radiation on human tissues. Such materials have been used, for example, in studies of the clinical application of hyperthermia for treatment of cancer and to estimate the hazard to biological tissues due to exposure to electromagnetic fields. In that biological phantoms may simulate the penetration of electromagnetic fields into the human body, these materials may provide means to estimate the interaction of PMEDs with the fields emitted by metal detectors.

Another potential application of phantom materials is in the evaluation of metal detectors. Standards of the National Institute of Justice for hand-held and walk-through metal detectors [68, 139] include tests for body cavity concealment of contraband. Although the tests are representative of actual use in the field, they have not been shown to be reproducible or accurate. The use of phantoms may improve this situation.

The preparation of this bibliography was undertaken to survey the published materials on phantoms. For the purposes of this report, a phantom is any material, structure, or system that is intended to emulate the electrical properties of biological tissues, biological systems, or of whole organisms. The following subjects are included in this bibliography: the results of electrical measurements of biological tissues, phantom materials, and materials that may hold potential use as phantom materials; the specific description and evaluation of phantoms; and techniques for measurement of electrical properties.

2 Electrical properties

We begin with a highly abridged review of the electrical properties of materials. A more complete discussion of these topics can be found in [16, 113], for example. This introduction is included largely to motivate the use and interpretation of the Debye, Cole-Cole, and Davidson-Cole dispersion equations, which describe the frequency dependence of the electrical permittivity. These dispersion equations are, further, the basis of the phenomenological models for the electrical properties of biological materials presented below in section 4. The terms dielectric relaxation and dispersion are often used interchangeably to denote the frequency dependence of the electrical permittivity: we follow this practice here as well.

The discussion presented in this section relies on results obtained from differential geometry and topology. These results are not derived in this report: References [40, 44, 51, 97] may be helpful in providing a more rigorous treatment of this material. A few concepts are
briefly defined: A manifold may be viewed as an object on which integration is defined and an exterior differential form or differential form as the object integrated \( [4] \). Vectors are an example of a differential form. Vectors tangent to a manifold have a unique expansion of the form,

\[
\alpha = \sum \alpha \left( \frac{\partial}{\partial x^j} \right) dx^j = \sum a_i dx^i,
\]

where \( a_i \) is in the space of smooth real functions on the manifold and \( \left( \frac{\partial}{\partial x^j} \right) \) is in the space of exterior 1-forms on the manifold. Differential forms comprise a vector space.

For the purposes of this discussion, Maxwell’s equations are considered to be axiomatic. In vectorial form, Maxwell’s equations,

\[
\begin{align*}
\text{curl } \mathbf{E} + \frac{1}{\epsilon} \frac{\partial}{\partial t} \mathbf{B} &= 0 \\
\text{curl } \mathbf{H} - \frac{1}{\mu} \frac{\partial}{\partial t} \mathbf{D} &= \mathbf{J} \\
\text{div } \mathbf{B} &= 0 \\
\text{div } \mathbf{D} &= \rho_0,
\end{align*}
\]

are stated in terms of the magnetic induction, \( \mathbf{B} \); the electric displacement, \( \mathbf{D} \); the magnetic field strength, \( \mathbf{H} \); the electric field strength, \( \mathbf{E} \); and the current density, \( \mathbf{J} \).

The case at hand contemplates the interaction of electromagnetic fields with biological materials, which introduces the possibility of an exchange of energy between the electromagnetic field and the material. The electromagnetic field may, for example, polarize or heat the material. The equation of state for such a system must then properly include Maxwell’s equations together with the constituent equations:

\[
\mathbf{D} = \epsilon \mathbf{E} \quad \text{and} \quad \mathbf{B} = \mu \mathbf{H}.
\]

Here, \( \epsilon \) and \( \mu \) are the electrical permittivity and permeability tensors, respectively.

Solutions of Maxwell’s equations have values in a 4-dimensional space. This space is endowed with a metric, which essentially assigns a Euclidean coordinate frame to neighborhoods of each point in the space. The 4-dimensional space together with the collection of coordinate neighborhoods define a 4-manifold \( M \). We consider the case where the manifold \( M \) has a local decomposition \( U \times Y \): The spatial coordinates are associated with the 3-manifold \( U \), and time is associated with a 1-manifold \( Y = \{ t \mid t \in \mathbb{R} \} \).

As a general principle, quantities that are physically significant must be independent of their local coordinate representation. We presume the metric to be physically significant and select a system of local coordinates satisfying the condition,

\[
dx^2 + dy^2 + dz^2 - \frac{1}{c^2} dt^2 = 0,
\]

where \( c \) is a speed of propagation. For the case \( c = 1 \), the spatial coordinates describe points on a unit 3-sphere, \( S^3 - \{ 0 \} \). The sub-manifold \( U \) may then be associated, after normalization, with \( S^3 - \{ 0 \} \).

Maxwell’s equations, \( \text{div } \mathbf{B} = 0 \) and \( \text{div } \mathbf{D} = \rho_0 \), provide two significant constraints: Firstly, these conditions contain no explicit dependence on time: the vectors \( \mathbf{B} \) and \( \mathbf{D} \) are thus associated with \( T(U) \), the space of vectors tangent to \( U \), and may then be associated with 1-forms \( B \) and \( D \in T(U) \). Secondly, \( \mathbf{B} \) and \( \mathbf{D} \) are transverse: The exterior product \( D \wedge B \) therefore has values in the space of 2-forms on \( U \) and, further, defines a planar field. \( G \).

Again invoking our general invariance principle, \( D \) and \( B \) must be independent of their coordinate representations and are thus invariant under the group of rotations that leave the origin fixed. It follows then that \( G \) is a closed, integral surface in \( U \). The product \( D \wedge B \) on the 3-manifold \( U \) further defines a conjugate 1-form \( \omega \) transverse to \( G \) with values in \( Y \). The orientation of \( G \) may be chosen to coincide with that of \( Y \). The Reeb stability theorem \([40]\) then provides that the manifold \( U \) admits a product decomposition \( S^2 \times S^1 \). We associate \( G \) with \( S^2 \), \( \omega \) with \( S^1 \), and the product \( D \wedge B \) with a projection \( \pi : M \to G \).

We have then the product decomposition \( G \times \omega \times Y \) for the manifold \( M \). It can be shown that \( \omega \) and \( Y \) commute \([40]\) in this product. The conditions at \( t = 0 \) are identified by the zero-section, \( G \times 0 \), and we examine further the properties of the germs of vectors on \( G \times 0 \).

Let \( \Gamma \) be a path in \( G \) with end points \( p \) and \( q \). The connection \( \xi \) describing parallel transport along \( \Gamma \) is a holonomy diffeomorphism \( Y_p = \pi^{-1}(p) \to Y_q = \pi^{-1}(q) \). The curvature for this connection, \( \Omega = d\xi \), has values in the Lie algebra of vectors on \( Y \). Stokes theorem then provides that

\[
\int_{D,p} \Omega = \int_{\partial D,p} \xi,
\]

for a disk \( D \in G \) with boundary \( \partial D \) and \( p \in \partial D \). The second integral is by definition a holonomy diffeomorphism. We note that the surface \( G \simeq S^2 \) is without holonomy \([40]\), thus \( \Omega(D,B) = 0 \).

The second integral in (7) may be generalized to obtain an integral representation for the group of circularly ordered diffeomorphisms. The covering group for the manifold \( S^3 - \{ 0 \} \) may be parameterized by the Hopf
fibration [97], $S^2 \times s, s \in S^1$ with fiber
\[ \gamma(s) = \frac{1}{1 + i s}. \]  
(8)

which for $s = \omega t$ is a map $\mathbb{R} \to S^1$. This scenario is shown schematically in Figure 1, which describes a projection from a complex 3-space $C^3$ onto the complex projective plane $CP^2$. It may be noted, by way of (7) and the result $\Omega(D, B) = 0$, that
\[ \epsilon_\infty - \epsilon_0 = \int_{-1}^{1} \frac{1}{1 + (is)} ds. \]  
(9)

Here $\epsilon_0$ and $\epsilon_\infty$ are respectively the limiting values of permittivity at low and high frequencies, and the difference $\epsilon_0 - \epsilon_\infty$ is a normalization.

An expression for $\epsilon^*(is)$ is then provided by the projection
\[ \epsilon^*(is) - \epsilon_\infty = (\epsilon_\infty - \epsilon_0) \int_{-\infty}^{\infty} \frac{F(s)}{1 + (is)^{(1-\theta)}} ds \]  
(10)

onto the complex plane. $F(s)$ is here a distribution with values in $s$. We may then associate $\epsilon$ with a homeomorphism $S^2 \to \mathbb{T}^2$, which is a projection onto the complex plane.

![Figure 1 Schematic representation of the Hopf fibration and the projection $S^2 \times S^1 \to \mathbb{T}^2 \times S^1$ (adapted from [51]).](image)

2.2 The Cole-Cole equation

In general, the polarization and the electric field are not in equilibrium and the condition $\theta = 0$ does not hold. For the case where: 1) $\theta \neq 0$, and 2) the distribution $F(s) = \delta(s - s_0)$, equation 10 obtains the Cole-Cole equation:
\[ \epsilon^*(is) - \epsilon_\infty = \frac{\epsilon_0 - \epsilon_\infty}{1 + (is)^{(1-\theta)}}. \]  
(12)

Non-equilibrium effects are most significant in condensed materials and at frequencies above 1 MHz.

2.3 The Davidson-Cole equation

Certain classes of materials, such as composites [94] and biological tissues [36], may not exhibit a unique relaxation time, $\tau_0$. The relaxation time may be distributed due to the variability in the local composition and structure of the material. Dispersion in such materials is described by the Davidson-Cole equation [31, 109]:
\[ \epsilon^*(i\omega\tau_0) - \epsilon_\infty = (\epsilon_0 - \epsilon_\infty) \int_{-\infty}^{\infty} \frac{F(\tau/\tau_0)}{1 + i\omega\tau} d\ln(\tau/\tau_0). \]  
(13)

Specific solutions for the distribution $F(\tau/\tau_0)$ are discussed in [16, 31, 109].

2.4 Interpretation

The Debye, Cole-Cole, and Davidson-Cole dispersion equations are integrations based on a $S^2 \times s, s \in S^1$ fibration of the compact manifold $U$. These equations describe projections from a complex 3-space $C^3$ onto the complex projective plane $CP^2$ that are identified by coordinate pairs $(\omega_0, \theta_0) \in CP^2$. A series approximation for the dispersion in terms of these coordinate pairs is suggested. The phenomenological models for biological tissues presented below are indeed based on such series approximations. In recommending these models, measured dispersion data, normalized by a factor $(\epsilon_0 - \epsilon_\infty)$, are fit by parameters $\omega_i$ and $\theta_i$, to obtain reasonable agreement with measurement over the desired range of frequencies. It is also common to use equivalent circuit parameters, corresponding to the specific resistivity and capacity, to obtain series approximations for the electrical permittivity [19, 36, 91].

The permittivity $\epsilon^*$ is by construction holomorphic; and a complex conductivity, $\sigma^* = i\omega\epsilon^*$, and resistivity, $R^* = 1/\sigma^*$, are therefore well defined. Here $\omega$ is the radian frequency. The real part of the permittivity, $\epsilon'$, is a measure of the capacity of the material to
store energy while the imaginary part, $\epsilon''$, is a measure of the dissipation of energy. For losses that are purely resistive $R^s = R^p$, which gives rise to a resistive term, $\sigma'' / \omega$, in the dispersion equations.

3 Measurement techniques

Three strategies are generally employed to describe the interaction of an electromagnetic field with a material:

1. measurement of the attenuation of the incident electromagnetic field,

2. measurement of the change of state of the material upon exposure to an electromagnetic field, or

3. measurement of the transformation of the electromagnetic field upon propagation through the material.

It is assumed, in each case, that the incident electromagnetic field is well characterized.

Time averaging techniques are often employed at frequencies where the electric and magnetic fields are difficult to resolve. Time averaging techniques essentially track the disposition of the available energy and do not require detailed knowledge of the wave shape or the relationship in phase between the electric and magnetic fields.

Coaxial probe techniques [3, 22, 73, 100] and electrodeless measurement techniques [41] are based on measurement of the attenuated electromagnetic field. Measurements based on a change of state of the material typically monitor a change in temperature of the material and thus require accurate determinations of such thermal properties as the specific heat and the thermal diffusion coefficient of the material.

Under appropriate conditions, the measured circuit parameters may be associated with the electrical properties of a material. For an ideal capacitor, the electric field in the fill material is determined by a geometrical factor and by the voltage across the capacitor. Measurements of the voltage and current may thus determine the electrical permittivity of the fill material. Capacitance bridge techniques [12, 24] are based on this principle.

Measurements based on transmission line techniques are discussed in [6-9] and other techniques are discussed in [23, 28, 72, 74, 96, 140].

Electrode polarization is an instrumental problem typically encountered at low frequencies in capacitive bridge measurements [27, 91, 102, 104, 118, 120]. This effect is due to the distribution of charge at the interface between dissimilar materials [37, 38], which is sometimes called the Debye layer or the charged double layer [39]. The presence of charge at the interface between an electrode and the sample effectively introduces a series impedance in the measurement circuit. The effects of electrode polarization may be reduced by choice of electrode material, platinum black is often used, and by decreasing the surface to volume ratio. Corrections for electrode effects have also been developed [116].

![Figure 2 Dispersion in biological tissues.](image)

The real part of permittivity, $\epsilon'$, for a typical tissue is plotted as a function of frequency, $f$. The $\alpha$, $\beta$, and $\gamma$-dispersions [121] are indicated. The range of frequencies utilized by metal detectors, i.e. 80 Hz to 10 MHz, is indicated in halftone.

4 Biological materials

The electrical properties of biological tissues are known to depend on tissue type and to be influenced by such factors as cellular structure and composition. It is essential therefore to consider tissue type when evaluating the effects of electromagnetic fields. In assessing the effects of radio frequency fields, for example, biological tissues are often differentiated by water content due to the predominant role of water in energy absorption at radio frequencies: High water content tissues include, for example, muscle and brain tissues; and low water content tissues include bone and fat.

A qualitative model of dielectric relaxation in biological tissues is suggested by Schwan [121]. The model consists of spherical cells that are immersed in a conducting fluid: The cell interior is itself conducting and is separated from the conducting bath by a nonconducting membrane. Dispersion in such a system falls into three broad categories, which are commonly designated $\alpha$, $\beta$, and $\gamma$ [119, 121], as depicted in Figure 2.
$\alpha$-dispersion: The dispersion occurring at frequencies below approximately $10^2$ Hz is commonly referred to as $\alpha$-dispersion. This dispersion is attributed to the conduction of charge associated with the Debye layer [11]. Biological molecules such as DNA, for example, contribute to dispersion at audio frequencies by counter-ion diffusion polarization [47, 49, 58, 69, 91]. This effect is due the diffusion of charged molecules near a charged surface.

The effects of electrode polarization and $\alpha$-dispersion typically occur over the same range of frequencies, thus it is particularly difficult to obtain meaningful data for the analysis of $\alpha$-dispersion. $\alpha$-dispersion has been studied most widely by examination of model systems such as suspensions of colloidal particles [59] and membranes [21, 90–92].

$\beta$-dispersion: The dispersion attributed to interfacial polarization due to ion blocking at inter- and intra-cellular membranes is commonly referred to as $\beta$-dispersion [19]. This phenomena is sometimes also referred to as the Maxwell-Wagner effect. $\beta$-dispersion ranges in frequency from tens of kHz to tens of MHz [91]. Relaxation is by conduction across the membrane. Investigations of $\beta$-dispersion are reported in [18, 20] where water content is shown to influence $\beta$-dispersion. The relative water content is thought to influence the inter-membrane spacing. $\beta$-dispersion is also discussed in [49, 50, 90].

$\gamma$-dispersion: This dispersion is primarily due to the molecular polarization of water, bound water, and polar subgroups. It occurs at frequencies above a few hundred MHz [91]. Counter-ion diffusion polarization may also contribute to the dispersion at radio frequencies [14, 15, 49, 54].

4.1 Measurements and models

Biological tissues may depart from the Schwan model in significant ways: cells are not spherical, indeed some tissues have no cellular structure; membranes are not perfect insulators; and tissues are often intercalated with conductive networks such as vascular and neural systems. As a consequence, phenomenological models for biological tissues are often more complex than indicated by the Schwan model: Hurt [78] uses five Debye terms to model the effects of radio frequency fields; and, as discussed below, Gabriel [52] and Gabriel, Lau, and Gabriel [56] use four Cole-Cole terms to model tissues.

Comprehensive reviews of the electrical properties of biological tissues can be found in [49, 50, 52, 53, 55, 56, 79, 91]. We note, in particular, the compilations by Gabriel [52] and Hurt [79], which are the basis of the data base file described in [4]. The Gabriel data and the sequel [56] are most relevant to the subject at hand, as the models suggested in [56] are intended to include frequencies ranging between 10 Hz and 100 GHz.

Gabriel et al. [56] present parametric models for seventeen tissue types including: heart, bone, fat, lung, and muscle tissues. Each tissue type is modeled by a series approximation of the form

$$\varepsilon^*(\omega) - \varepsilon_\infty = \sum_{\alpha=1}^{i} \frac{\Delta\varepsilon_{\alpha}}{1 + (i\omega\tau_{\alpha})^{(1-\theta_{\alpha})}} + \frac{\sigma_{i}}{i\omega\varepsilon_{0}},$$

(14)

The effects of ionic conductivity are included by the final term where $\varepsilon_0$ is the permittivity of free space. The difference $(\varepsilon_\infty - \varepsilon_\infty)_n$ for each dispersive term is given by $\Delta\varepsilon_{\alpha}$. The data presented in Figure 3 are based on the parameters suggested by these authors for heart tissue.

Gabriel et al. are confident in the calculated electrical properties for frequencies greater than 1 MHz. They note, however, that the models should be used with caution for frequencies below 1 MHz due the paucity of data and measurement uncertainties at these frequencies. Indeed, by examination of the data presented in [56], it appears that low frequency data were not available for several of the tissue types.

5 Phantoms

A phantom is considered here to be any material, structure, or system that emulates the electrical properties
of biological tissues, biological systems, or of whole organisms.

The suitability of a material to a specific application may be based on such factors as:

1. cost and availability,
2. the ability to form the material,
3. safety in handling,
4. chemical and physical stability, e.g., resistance to corrosion, resistance to bacterial attack, resistance to desiccation,
5. thermal properties,
6. the type of tissue to be emulated, and
7. the frequency range of interest.

5.4 Gels

Gels have been widely used as phantom materials [26, 64, 66, 99]. The advantages of gel type phantoms include: low cost, relative ease of forming, and the ability to implant probes directly in the material. However, these materials have several disadvantages: Gels are typically fragile and may require encapsulation. They tend to desiccate, which shortens the useful life of the phantom and may introduce variability in measurements based on the use of the phantom. Gels are also subject to bacterial and fungal attack; gel recipes often include preservatives to retard decomposition.

Gel type phantom materials are discussed in the review article by Stuchly and Stuchly [129] and in [103]. Recipes for polyacrylamide based gels are given in [5].

5.5 Solid and dry materials

Solid materials are sometimes preferred over the gel based materials due to the disadvantages noted above. Solid and dry type phantoms are typically composites of a polymeric material and some combination of carbon black, graphite, carbon fiber, or ceramic powder [107, 108, 133, 141].

Composite materials are inhomogeneous mixtures of two or more dissimilar materials. These materials may be designed to essentially mimic the structure of biological tissues and thereby match dielectric dispersion over a broad range of frequencies. We note two examples: Broadhurst, Chiang, and Davis [19] were able to simulate $\alpha$- and $\beta$-dispersions in a single composite material by essentially mimicking the micro structure of biological tissues. Hartsgrove et al. [71] developed a lung tissue phantom by admixing hollow silica microspheres to mimic alveoli in the lung tissue.

The electrical properties of binary mixtures of insulating and conducting materials have been widely studied [30, 45, 46, 81, 83]. These materials are of interest due to their novel electrical properties [19] and have been extensively studied in the evaluation of percolation theory [86]. Although these materials were not developed or evaluated as phantom materials, the range of frequencies examined, see for example [42], and the similarity of these materials to solid and dry type phantom materials suggests that these results may provide guidance in recommending and evaluating phantom materials.

One problem encountered in the use of composite materials is the variability in composition based on the method of preparation. The outcome of electrical measurements is known to depend on the process by which the material is prepared.
6 Discussion

The phantom materials discussed in the literature are primarily developed to simulate the effects of electromagnetic fields that oscillate at frequencies above 100 MHz. The range of frequencies significant to the evaluation of hand-held and walk-through metal detectors is 80 Hz to 10 MHz. As such, the criteria used in the design and evaluation of suitable phantom materials differ substantially from those discussed in the literature. In particular, α- and β-dispersion are significant in this range of frequencies and phantom materials developed for purposes of evaluating metal detectors should mimic these behaviors. The results of Broadhurst, Chiang, and Davis [19] appear to hold promise in this regard.

The thermal properties of phantom materials are discussed at length in the literature due to the importance of these factors in modeling the temperature distribution and dosage in biological tissues. These issues are less significant to the evaluation of metal detectors. The attenuation of the electromagnetic field should be considered, however the intensity of the electromagnetic fields used in metal detectors is probably not sufficient to heat biological tissues significantly. The thermal stability of the phantom material is of concern, in that a temperature dependence in the electrical properties may introduce variability in measurements based on the use of the phantom.

The induction of eddy currents in the body may be of concern. Computer based models [33] suggest that the induced current densities are greatest at the interface between dissimilar tissues. Thus anatomical factors, such as organ morphology and the placement and configuration of the device in the body may play a role in the evaluation of medical devices.

The models for biological tissues appear to be well developed and to differentiate adequately between tissue types. There is, however, some question as to the accuracy and reliability of these models at frequencies below 1 MHz.

7 The bibliography

The following bibliography includes references to: journal articles, books, conference reports, technical reports, standards, and product data. Bibliographic entries are listed alphabetically by author or by sponsoring organization, where authorship is not indicated. The “Annotation” field is included for the purposes of this survey and is intended to provide a concise summary of the contents of the entry.
References


**KEY:** ALL75

**Annotation:** The phantom consisted of a Lucite vessel filled with Ringer’s solution. Ringer’s solution is an aqueous solution of NaCl, KCl, and CaCl₂. The phantom was exposed to continuous wave radiation oscillating at frequencies of 10 MHz, 20 MHz, and 30 MHz. The absorbed power was determined by measurement of the incident, reflected, and transmitted power.


**KEY:** ALLKAN88

**Annotation:** This article describes the phantom developed to evaluate a system for clinical use of hyperthermia. The phantom consisted of a shell composed of a material that simulated fat filled with a muscle tissue phantom material. The shell was composed of Laminac 4110, aluminum powder, Shawinigan black, carbon powder, and peroxide. The gel was composed of hydroxyethylcellulose, Dowicil 75, NaCl, and water. The phantom was instrumented with temperature probes. Very little information is provide on the nature of the RF radiation.


**KEY:** ANDGAJ86


**KEY:** ANDROW98

**Annotation:** This Microsoft Excel file is based on the compilations of Gabriel [52] and Hurt [79]. The file is available over the internet at http://www.radhaz.com/files/tissues3.xls. The Gabriel tissue model covers frequencies ranging between 10 Hz and 100 GHz. The parameters used in the Gabriel models are also presented in [55].


**KEY:** ANDBIN88

**Annotation:** Recipes are presented for preparation of gel type phantom material based on polyacrylamide. Salt (NaCl) is added to the material to increase the conductivity. Low water content tissues are simulated be the addition of ethylene glycol in place of water. The electrical properties of the phantom material are compared with results obtained in muscle tissue. The range of frequencies studied is 0.75 GHz to 5.5 GHz.


**KEY:** BAK90


**KEY:** BAKGEY90

Key: BAKJAN91


Key: BAKVAN90


Key: BANHiS96

Annotation: Dielectric relaxation in the leaf tissue of six different plants is obtained over the frequency range of $10^{-3}$ Hz to $10^4$ Hz. The dispersion observed at high frequencies is attributed to the bulk properties of the tissue, dispersion at intermediate frequencies is attributed to leaf-interfacial impedance, and low frequency dispersion is thought to be due to electrode-leaf interfacial impedance. This is an extension of methods discussed in [76].


Key: BARBAR97

Annotation: Experimental investigation over the frequency range 20 Hz to $10^6$ Hz.


Key: BERHAN76

Annotation: A detailed description is provided of a four-electrode capacitance cell and comparator bridge. The apparatus is used to obtain very-low-frequency measurements of conductivity and dielectric loss in ionic solutions. The cell was used to measure dielectric relaxation in solutions of DNA. The range of frequencies examined is 0.1 Hz to 500 Hz.


Key: BINIGN84

Annotation: A gel type phantom material composed of polyacrylamide is described. Recipes are provided for preparation of the gel. The gel is doped with NaCl to obtain the desired conductivity. The material is transparent, which is an advantage in the placement and manipulation of probes. Formulas are provided for calculation of the required salt concentration to achieve a specified conductivity as a function of temperature at 13.6 MHz, 27 MHz, and 40.7 MHz.


Key: BONCAN91


Key: BONCAN89

KEY: BOTBOR78
ANNOTATION: This is a classic reference on dielectric materials.


KEY: BRIISK93


KEY: BRO70


KEY: BROCHI87
ANNOTATION: This report describes the development and evaluation of phantom materials for use in simulating heating effects in human tissue due to high frequency electromagnetic radiation. The range of frequencies considered is 1 MHz to 1000 MHz, although data are presented for frequencies ranging between 100 Hz and 1000 MHz. The phantom materials were composed of a 50/50 solution of ethylene carbonate and propylene carbonate, an organic salt, flakes of polyethylene terephthalate, and a gelling agent. Particular attention is given to simulation of β-dispersion, i.e., Maxwell-Wagner polarization. This work was done at NIST. The paper appears to be based on an NBS Interagency Report 86-3355 [21]. One of the authors, C. K. Chiang, is still a NIST employee.


KEY: BROCHI87a
ANNOTATION: This article contains a discussion of dielectric relaxation in plant leaf tissue. The electrical properties of jade leaf tissue were measured as a prototype material for the development and evaluation of phantom materials. The jade leaf tissue was measured for frequencies ranging between 10⁻² Hz and 10⁶ Hz. Both α- and β-dispersions were noted. A NBS Interagency Report [21] is cited for a description of the phantom material.


KEY: BROCHI86
ANNOTATION: This report provides a detailed account of the development and evaluation of phantom materials for use in simulating heating effects in human tissue due to high frequency electromagnetic radiation. The range of frequencies considered is 10 MHz to 100 MHz. The phantom materials were composed of a 50/50 solution of ethylene carbonate and propylene carbonate, an organic salt, flakes of polyethylene terephthalate, and a gelling agent. Particular attention is given to simulation of Maxwell-Wagner polarization. The report is cited by [20].


KEY: BUS80


KEY: CACLES73

**Key:** CHARAO66


**Key:** CHEKOO76

**Annotation:** A discussion is provided of the development of phantom materials for use in the X-band, that is, at frequencies on the order of 9 GHz. The application of the phantom materials to scale model studies is briefly discussed. Recipes for phantom materials intended to simulate muscle, brain, fat, and bone tissues are discussed. The real part of the permittivity, $\epsilon'$, conductivity, and loss tangent $\epsilon''/\epsilon'$ of these materials are measured at 8.5 GHz and 10.0 GHz. The specific heats of the materials is also provided. Phantom materials for high water content tissues are composed of water, NaCl, polyethylene, and a gelling agent referred to as “Super Stuff” [93]. Low water content tissues are simulated by compositions of acetylene black, aluminum powder, and Laminex 4110. The authors refer to [66] for a detailed description of the component materials.


**Key:** CHOCHES81

**Annotation:** A gel-type phantom material is described. Measurements of the real part of the permittivity, $\epsilon'$, and conductivity are presented for frequencies ranging between 13.56 MHz and 2,450 MHz. The temperature dependence of these electrical properties is evaluated for temperatures ranging between 15° C and 30° C. The phantom material is intended to simulate muscle tissue for RF hyperthermia treatment. The recipes for frequencies below 100 MHz consisted of TX150, which is a commercially available gelling agent [93], water, NaCl, and aluminum powder. The content of aluminum powder ranged between 2.12 percent and 9.15 percent by weight. The authors recommend a useful life of two weeks for the phantom material. The gelling agent, TX150, is no longer available; a similar product, TX151, is available from Oil Research Center, Lafayette, LA [93].


**Key:** CIRVAN97


**Key:** CLA73


**Key:** COLC041

**Annotation:** The Cole-Cole dispersion equation is derived in this paper. Several modifications of the dispersion equation are discussed, including the case where the relaxation times are distributed.

KEY: CONROY98
ANNOTATION: The electrical properties of a composite of carbon-black filled polyethylene are described. The temperature dependence of the dc conductivity was measured and found to be consistent with thermal fluctuation induced tunneling for temperatures above 45° K. The electrical conductivity is measured over frequencies ranging between dc and 10^9 Hz and for various carbon-black fills. The conductivity is evaluated in terms of percolation theory.


KEY: DAVCOL51
ANNOTATION: Formulas are derived for the dielectric constant of a system having a distribution of relaxation times. Discussion of the Debye formula for dispersion is also provided. The authors also note that relaxation time, \( \tau_0 \), and the viscosity have the same temperature dependence. This paper is cited by [109].


KEY: DERSTAA83
ANNOTATION: The results of a Monte Carlo calculation of the conductivity exponent, \( t \), are discussed. In percolation theory, the conductivity is given by a power law, \( \sigma = (\rho - \rho_c)^t \), for values of the volume fraction, \( \rho \), near the percolation threshold, \( \rho_c \). The value given for the conductivity exponent for a 3-dimensional system is 1.94 ± 0.1.


KEY: DIM98
ANNOTATION: A computational model is described. The model is developed to simulate induced currents in human tissues due to exposure to electromagnetic fields. An anatomical model of the human body is developed to include the electrical properties of various tissues. Calculation of induced current is based on a scalar potential finite difference method. The article provides a tabulation of the conductivity of various human tissues. References are provided to various exposure limit standards.


KEY: DIM00
ANNOTATION: The current induced in the body by exposure to a 50 Hz electric field is calculated. The calculations are based on a geometric model of the human body. The model differentiates biological tissue type. The electrical properties of tissue types is based on Gabriel et al. [53, 55, 56].


KEY: DISHIL89


KEY: DIS90
ANNOTATION: Refinements of the model suggested by Schwan [121] are presented. Schwan treated biological tissue as a uniform, isotropic media, thus ignoring conductive networks, such as the vascular system, that interface biological tissues. These conductive networks are modeled as fractal structures; and the frequency dependence of the real part of the permittivity, \( \epsilon' \), is considered. Recent results obtained for liver, muscle, and brain tissues are discussed. \( \alpha- \)
and $\beta$-dispersions are shown to be influenced by tissue structure and to be consistent with the predicted behavior in each case.


**KEY:** DUK93


**KEY:** DUK95


**KEY:** DUKSHI74


**KEY:** ELITHU98

**ANNOTATION:** This book contains a mathematical treatment of dynamical systems. It includes discussions of foliations, i.e. interval systems, contact structures, and the generalization of these objects to confoliations.


**KEY:** ENDMCG60


**KEY:** EZQKUL91

**ANNOTATION:** The electrical properties of carbon-black filled polyethylene are examined. The real part of the permittivity, $\varepsilon'$, and conductivity are examined as a function of carbon fill for frequencies ranging between $10^{2}$ Hz and $10^{9}$ Hz. The paper gives the power law exponent for the dielectric constant.


**KEY:** FANSTA90


**KEY:** FLA89

**ANNOTATION:** The book provides an introduction to differential forms and differential geometry. The application of differential forms to Maxwell’s equations is presented.


**KEY:** FLABRE99

**ANNOTATION:** A RC model is presented for the electrical properties of a binary composite of a conducting polymer (polypyrrole) and an insulating latex (styrene-butyl acrylate copolymer). The real and imaginary parts of the electrical conductivity are measured for filler volume fractions ranging between 0.03 and 0.25. Data are obtained for frequencies ranging between 1000 Hz and 1 MHz.

**Key:** FLAPRA99  
**Annotation:** The electrical properties of a carbon black filled epoxy composite are described. Evidence for nonisotropic distribution of carbon black is presented. The distribution of particles is thought to be influenced by static charge carried on the carbon black particles. The frequency dependence of the conductivity is measured for frequencies ranging between 100 Hz and 1 MHz. Experimental results are compared with the predicted electric properties based on statistical percolation theory.


**Key:** FOSEPS87


**Key:** FOSSAU92  
**Annotation:** A review of the electrophoretic forces on particles is presented. Formulas for the dispersion of spherical and non-spherical particles are provided. The effect of surface conductivity is briefly discussed. Hydrodynamical effects, i.e. effects due to the coupling of the charge density and fluid flow, are thought to be most significant at low frequencies and in non-conducting media.


**Key:** FOSSCH86  
**Annotation:** This article presents a comprehensive review of the electrical properties of biological tissues. The topics covered include: basic concepts, relaxation mechanisms, distributed relaxation times, etc. A discussion of counter ion diffusion polarization is provided with references to key papers. The low frequency dispersion associated with counter ion diffusion polarization is attributed in part to the hydrodynamic coupling of the particle motion.


**Key:** FOSSCH89


**Key:** FRA97  
**Annotation:** This book provides general background material on differential geometry.


**Key:** GAB96  
**Annotation:** This report is available from NTIS (703-605-6000), reference number AD-A309764. The report is 268 pages in length and the current price is $54.


**Key:** GABGAB96

KEY: GABGRA87


KEY: GABLAU96


KEY: GABLAU96a

ANNOTATION: Parametric models for seventeen tissue types are presented. These models are based on a recent compilation of electrical measurements in biological tissues by Gabriel [52]. A four term Cole-Cole dispersion model is given for each tissue type. The model is intended for frequencies ranging between 10 Hz and 100 GHz. The authors state that the model is most reliable for frequencies above 1 MHz.


KEY: GAJSTU79

ANNOTATION: The use of an electric field probe to characterize energy deposition in biological tissues is described. The field probe is used to characterize microwave diathermy applicators. A phantom material composed of glycerol and water was used. The frequency of the applied microwave field was 2.45 GHz.


KEY: GRASHE78


KEY: GROFOS87


KEY: GROTI98


KEY: GROBAR92


KEY: GROSH96


KEY: GUSBAH99


KEY: GUYCHO86

**KEY: GUYWEB76**


**KEY: GUY71**

**Annotation:** The development of phantom materials intended to simulate muscle, fat and bone is described. Low water content tissues are simulated by a composite of “laminae” polyester resin, catalyst, acetylene black and aluminum powder. High water content tissues are simulated by a composite of water, salt, polyethylene powder, and “Super Stuff,” which is a commercial gelling agent. The real part of the permittivity, $\varepsilon'$, and loss tangent of the phantom materials are measured for frequencies ranging between 200 MHz and 2,000 MHz.


**KEY: HAGLEV92**

**Annotation:** The development of aqueous solutions for use as phantom material is described. The phantom material is a transparent solution. The real part of the permittivity, $\varepsilon'$, and conductivity are measured at 13.56 MHz, 27.12 MHz and 40.68 MHz. The solutions are nondispersive over the frequency range between 1 MHz and 1 GHz. The conductivity of the material is adjusted by varying concentration. The use of gelling agents is discussed.


**KEY: NIJHH**

**Annotation:** The test for concealed metal objects entails testing for standard objects concealed under the arm of a person.


**KEY: HANBER73**


**KEY: HARCOL93**


**KEY: HARKRA87**

**Annotation:** Preparation of gel type phantom materials is described. The phantom materials are based on the use of hydroxyethylcellulose (HEC), which was available under the trade name Natrosol. The HEC was mixed with water, NaCl, sucrose, and a bactericide. The phantom materials simulate brain, lung, muscle, and bone tissue. The lung tissue phantom was prepared by admixing hollow silica micro-spheres to mimic alveoli in human lung tissue. A castable bone tissue phantom, which was based on epoxy and KCl, is also described. The frequency range investigated was 100 MHz to 1000 MHz.


**KEY: HAYKAN75**

Key: HEW85

Annotation: This measurement method is referred to as the coaxial line S-parameter method.


Key: HILGRED82


Key: HILDIS91


Key: HILDIS86

Annotation: This article reports measurements of the real and imaginary parts of the complex dielectric permittivity of jade leaf. These data are obtained for frequencies ranging between $10^{-3}$ Hz and $10^9$ Hz. $\alpha$ and $\beta$ dispersions [121] were noted. $\alpha$ dispersion is attributed to a reduction in the region of charge to membranes next to the electrodes. $\beta$ dispersion is attributed to charging of cell walls.


Key: HONNIC95


Key: HUR85


Key: HUR96


Key: ICR92

Annotation: A comprehensive history of the development and use of phantoms is presented. Information on commercially available phantoms is provided.


Key: ISHIL99

Annotation: The electrical and mechanical properties of a series of conductor-polymer composites were evaluated. The filler materials evaluated include metal powders, graphite, and conducting ceramics. The polymers used were epoxy, polypropylene, and polyethylene. The resistivity of the composites was measured for varying filler content up to and above the percolation threshold.


Key: JENHOD90

**Key:** KARME96

**Annotation:** The electrical properties of composites of carbon black and styrene butadiene rubber are examined. The conductivity, the real part of the real part of the permittivity, $\epsilon'$, and the imaginary part of the permittivity, $\epsilon''$, are measured for frequencies ranging between 1 kHz and 13 MHz.


**Key:** KATHIR86

**Annotation:** The phantom material was composed of agar powder, NaCl, NaN₃, and water. The material was used to construct a free standing model of a human torso, which remained stable for one year. The phantom was wrapped in polyethylene film to prevent dessication. The conductivity and the real part of the permittivity, $\epsilon'$, of the phantom material were measured as a function of NaCl concentration for frequencies ranging between 1 MHz and 40 MHz.


**Key:** KATISH87

**Annotation:** A gel type phantom material is described. The material is composed of agar, NaN₃, polyvinyl chloride powder, and water. The conductivity and the real part of the permittivity, $\epsilon'$, of the phantom material were measured as a function of NaN₃ concentration for frequencies ranging between 1 MHz and 40 MHz.


**Key:** KIR73


**Key:** KOBNOJ93


**Key:** KOP80

**Annotation:** A muscle tissue phantom was used to simulate the temperature distributions obtained during clinical use of hyperthermia. The phantom material is composed of NaCl, polyethylene powder, “Super Stuff” [93], and water; and was based on Guy [66]. Data were obtained at frequencies of 915 MHz to 2450 MHz.


**Key:** KRASTU84

**Annotation:** The specific absorption rate is determined by use of an implanted field probe. The electric field was determined at low intensity thus eliminating thermal effects. The phantom consisted of a hollow styrofoam form that was filled with a solution of water, sugar, and salt.

KEY: KUA96


KEY: KUANEL98
Annotation: This is a general review of low frequency dispersion in biological tissues. The origins of the electrical double layer are presented. The Debye and Cole-Cole dispersion equations are discussed. A discussion of physical mechanisms contributing to $\alpha$, $\beta$, and $\gamma$-dispersion is presented. Electrode effects are discussed.


KEY: KUANEL97
Annotation: The low frequency dispersion of a porous membrane was examined. Saran and Mylar membranes were used. The membranes were punctured to yield 50 $\mu$m circular pores on average. The membrane was immersed in an aqueous solution of NaCl. The conductance and capacitance of the membrane were measured for frequencies ranging between 5 Hz and $10^5$ Hz and for pores ranging in number between 0 and 1000.


KEY: LAU99
Annotation: The product TX150, which is a gelling agent used in gel type phantom materials, is no longer available and has been replaced by a similar product TX151. TX150 is apparently also be referred to as “Super Stuff” [88].


KEY: LEESON86
Annotation: Two systems were evaluated: The first consisted of a composite of metalized glass spheres and insulating Teflon powder. The second was a composite of indium and insulating glass spheres. The behavior of the first system was consistent with predictions based on statistical percolation theory. The second composite, however, departed from the theoretical predictions. The indium, being highly malleable, deformed to fill the voids around the insulating spheres and thus produced a complex conducting network connected by paths having a distribution of conductivities. Statistical percolation theory provides that the conductivity of a metal/insulator composite is given by $\sigma_{1f} = \sigma_e (p - p_c)^{\lambda}$, where the $p$ is the volume fraction of metal, $p_c$ is the percolation threshold, $\sigma_e$ is the conductivity of the metal, and $\lambda$ is the conductivity exponent. Statistical percolation theory predicts a value for $\lambda$ of 1.9 for a 3-dimensional conducting network. The conductivity exponent for the indium/glass composite was approximately 3.


KEY: LEFOSS4


KEY: LYN74


KEY: MADTOR97
Annotation: This is a reference book containing background material on manifolds and differential geometry.

KEY: MANODI84


KEY: MARNAD89

Annotation: A phantom material used to simulate muscle is described. The material is composed of gelatine, water, and sodium chloride. The material can be cast and is inexpensive. The material was evaluated at: 10 MHz, 27 MHz, and 50 MHz; and for temperatures ranging between 15° C and 50° C.


KEY: MAREVA87


KEY: MARGRI98


KEY: MCAJOS94


KEY: MIYTAK95

Annotation: Gellan gum and polyacrylamide gel type phantom materials are evaluated. The gel phantom material is doped with a thermally sensitive material to provide a 3-dimensional map of RF absorption. The dopant becomes opaque at elevated temperatures. The mechanical properties of these materials and issues of fabrication are discussed. Measurements of the conductivity and dielectric constant of a polyacrylamide gel based phantom material are reported over the frequency range of 1 MHz to 3 GHz. These data were obtained using a coaxial probe technique.


KEY: MOUSCH94


KEY: NANBAG98


KEY: NEEZWA70

The phantom material is composed of carbon black and carbon fibers imbedded in silicone rubber. Different tissue types, e.g., fat and muscle, were simulated by changing the mixture. The frequency range over which the material was evaluated was 10 MHz to 3 GHz.


**Key: NIKCH96**

**Annotation:** Data for two phantom materials simulating high and low water content tissue are presented. The phantom material is composed of silicone rubber impregnated with carbon fibers. The electrical measurements are obtained using the reflection method. The materials are evaluated at frequencies ranging between 430 MHz and 2450 MHz.


**Key: NIK93**

**Annotation:** Solutions of a generalized diffusion equation for conduction on fractal structures are considered. Conduction due to quasi-free charge and due to bound charge are treated. Conduction on a finite fractal aggregate is an example of conduction of a bound charge. Conduction of bound charge leads to the Cole-Cole equation for the complex susceptibility $\chi(s) = \chi_0/(1 + (sr)^{-\beta})$. Conduction of quasi-free charges leads to the Davidson-Cole equation for the complex resistance $\rho(s) = \rho_0/(1 + sr)^{\nu}$. The case where two processes having different cut-off times occurs in the same material is also considered.


**Key: NOJKOB91**

**Annotation:** Development of a phantom of the human head is described. The composition of the material is not clearly described; it appears to be a ceramic material. Data are obtained for the specific absorption rate at 900 MHz. A longer version of this paper was later published [87].


**Key: PACGAR93**


**Key: PET79**


**Key: POS97**

**Annotation:** This is a classic reference on electromagnetics. It was originally published in 1962.


**Key: ROSBAY92**


**Key: SAH**

**Key:** SCH75


**Key:** SCHSTI77


**Key:** SCH92


**Key:** SCH93

**Annotation:** This paper outlines the mechanisms for dispersion in biological tissues. $\alpha$-, $\beta$-, and $\gamma$-dispersions are discussed. The mechanisms for $\alpha$-dispersion include: counterions, tubular cell structure, glycocalyx, and membrane ion channels. The mechanisms for $\beta$-dispersion include: membrane blocking, organelles, and proteins. The mechanisms for $\gamma$-dispersion include: water, bound water, and polar subgroups.


**Key:** SCH99


**Key:** SCH57


**Key:** SCOSMI86


**Key:** SONNOH86

**Annotation:** This paper gives the power law exponent for the dielectric constant.


**Key:** STI78


**Key:** STRWIE93


**Key:** STUGAN00


22

KEY: STUKRA85


KEY: STUSTU80

ANNOTATION: Tabulations of electrical measurements in biological and phantom materials is provided. Values of ε' and ε'' are given for biological tissues for frequencies ranging between $10^2$ Hz to $10^6$ Hz. The data on phantom materials ranges between $10^6$ Hz and $10^{10}$ Hz.


KEY: STUKRA85a


KEY: STUSTU86


KEY: TAK89


KEY: TAMISH97

ANNOTATION: The phantom material was composed of ceramic and graphite powders imbedded in polyvinylidene fluoride (PVDF) resin. The ceramic powder is a BaTiO$_3$ type material with particle size of 30 µm. The graphite particle size was 30 µm. The phantom material was evaluated at frequencies ranging between 50 MHz and 5 GHz. The method used to measure the dielectric constant was the coaxial line S-parameter method.


KEY: TOULAX57


KEY: TUNMOL77


KEY: VANMAN74


KEY: VEROVE48


KEY: VON54

   Key: NJJWT
   Annotation: The test for concealed metal objects entails testing for standard objects concealed under the arm of a person.


   Key: WES50


   Key: WUSFAH98
   Annotation: Phantom materials developed to simulate hyperthermia are evaluated. The materials studied include: polyester resins, epoxy resin, polyurethane, and silicone rubber. Additives included: aluminium, graphite, and brass powders. Formulations for phantom materials to simulate water, 2/3 muscle, muscle, bone and fat are provided. The frequency range studied was 10 MHz to 400 MHz.


   Key: YAMYAM76