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Electrical Properties of Biological Materials: A Bibliographic Survey

K. L. Stricklett

Electricity Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8113

J. Baker-Jarvis

Radio-Frequency Technology Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Boulder, CO 80303

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U.S. DEPARTMENT OF COMMERCE
Norman Y. Mineta, Secretary

TECHNOLOGY ADMINISTRATION
Dr. Cheryl L. Shavers, Under Secretary
of Commerce for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Raymond G. Kammer, Director

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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Electrical Properties of Biological Materials: A Bibliographic Survey

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 functionally 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 connote 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 [44]. Vectors are an example of a differential form. Vectors tangent to a manifold have a unique expansion of the form,

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

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,

$$\text{curl } \mathbf{E} + \frac{\partial}{\partial t}\mathbf{B} = 0 \quad (1)$$

$$\text{curl } \mathbf{H} - \frac{\partial}{\partial t}\mathbf{D} = \mathbf{J} \quad (2)$$

$$\text{div } \mathbf{B} = 0 \quad (3)$$

$$\text{div } \mathbf{D} = J_0, \quad (4)$$

are stated in terms of the magnetic induction, **B**; the electric displacement, **D**; the magnetic field strength, **H**; the electric field strength, **E**; and the current density, **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:

$$\mathbf{D} = \epsilon\mathbf{E} \text{ and } \mathbf{B} = \mu\mathbf{H}. \quad (5)$$

Here, ϵ and μ 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,

$$dx^2 + dy^2 + dz^2 - \frac{1}{c^2}dt^2 = 0, \quad (6)$$

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, div $\mathbf{B} = 0$ and div $\mathbf{D} = J_0$, provide two significant constraints: Firstly, these conditions contain no explicit dependence on time: the vectors **B** and **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, **B** and **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 ω 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, ω with S^1, and the product $D \wedge B$ with a projection $\pi : M \longrightarrow G$.

We have then the product decomposition $G \times \omega \times Y$ for the manifold M. It can be shown that ω 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 Γ be a path in G with end points p and q. The connection ξ describing parallel transport along Γ is a holonomy diffeomorphism $Y_p = \pi^{-1}(p) \longrightarrow Y_q = \pi^{-1}(q)$. The curvature for this connection, $\Omega = d\xi$, has values in the Lie algebra of vectors on Y. Stokes theorem then provides that

$$\int_{\mathcal{D},p} \Omega = \int_{\partial\mathcal{D},p} \xi, \quad (7)$$

for a disk $\mathcal{D} \in G$ with boundary $\partial\mathcal{D}$ and $p \in \partial\mathcal{D}$. 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

$$\gamma(s) = \frac{1}{1+is}, \tag{8}$$

which for $s = \omega t$ is a map $\mathbb{R} \longrightarrow S^1$. 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

$$\epsilon_\infty - \epsilon_0 = \int_{-1}^{1} \frac{1}{1+(is)} ds. \tag{9}$$

Here ϵ_0 and ϵ_∞ 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

$$\epsilon^*(is) - \epsilon_\infty = (\epsilon_\infty - \epsilon_0) \int_{-\infty}^{\infty} \frac{F(s)}{1+(is)^{(1-\theta)}} ds \tag{10}$$

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

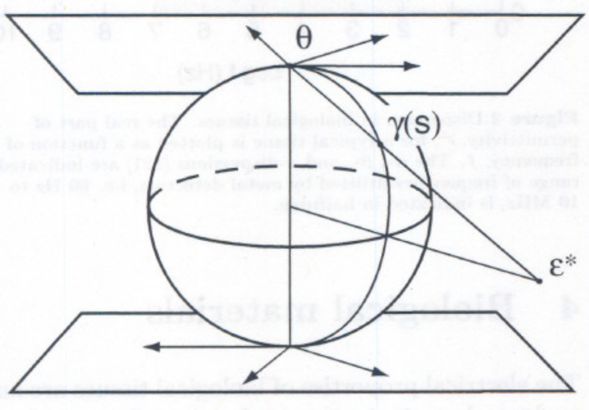

Figure 1 Schematic representation of the Hopf fibration and the projection $S^2 \times S^1 \longrightarrow T^2 \times S^1$ (adapted from [51]).

2.1 The Debye equation

Consider firstly solutions of equation 10 where: 1) $\theta = 0$, and 2) the distribution $F(s) = \delta(s - s_0)$. Equation 10 obtains, for these conditions, the Debye equation:

$$\epsilon^*(is) - \epsilon_\infty = \frac{\epsilon_0 - \epsilon_\infty}{1+is}. \tag{11}$$

The Debye equation corresponds physically to the case where the polarization and the electric field are in equilibrium and the relaxation time is uniquely defined. The Debye equation holds, to good approximation, for polar gases and dilute solutions of polar molecules at frequencies below approximately 1 MHz.

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:

$$\epsilon^*(is) - \epsilon_\infty = \frac{\epsilon_0 - \epsilon_\infty}{1+(is)^{(1-\theta)}}. \tag{12}$$

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, τ_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]:

$$\epsilon^*(i\omega\tau_0) - \epsilon_\infty = (\epsilon_0 - \epsilon_\infty) \int_{-\infty}^{\infty} \frac{F(\tau/\tau_0)}{1+i\omega\tau} d\ln(\tau/\tau_0). \tag{13}$$

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 $(\omega_i, \theta_i) \in CP^2$. 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 $(\epsilon_0 - \epsilon_\infty)_i$, are fit by parameters ω_i and θ_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 ϵ^* is by construction holomorphic; and a complex conductivity, $\sigma^* = i\omega\epsilon^*$, and resistivity, $R^* = 1/\sigma^*$, are therefore well defined. Here ω is the radian frequency. The real part of the permittivity, ϵ', is a measure of the capacity of the material to store energy while the imaginary part, ϵ'', is a measure of the dissipation of energy. For losses that are purely resistive $R^* = R''$, which gives rise to a resistive term, $\sigma''/i\omega$, 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].

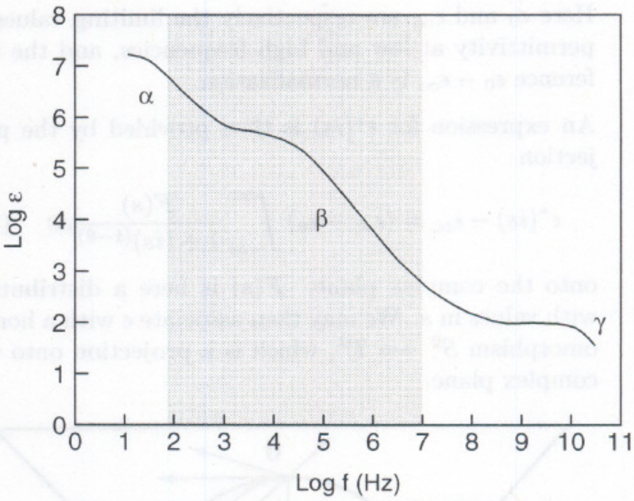

Figure 2 Dispersion in biological tissues. The real part of permittivity, ϵ', for a typical tissue is plotted as a function of frequency, f. The α-, β-, and γ-dispersions [121] are indicated. The range of frequencies utilized by metal detectors, i.e. 80 Hz to 10 MHz, is indicated in halftone.

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 α, β, and γ [119, 121], as depicted in Figure 2.

α-dispersion: The dispersion occurring at frequencies below approximately 10^4 Hz is commonly referred to as α-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 α-dispersion typically occur over the same range of frequencies, thus it is particularly difficult to obtain meaningful data for the analysis of α-dispersion. α-dispersion has been studied most widely by examination of model systems such as suspensions of colloidal particles [59] and membranes [21,90–92].

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

γ-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.

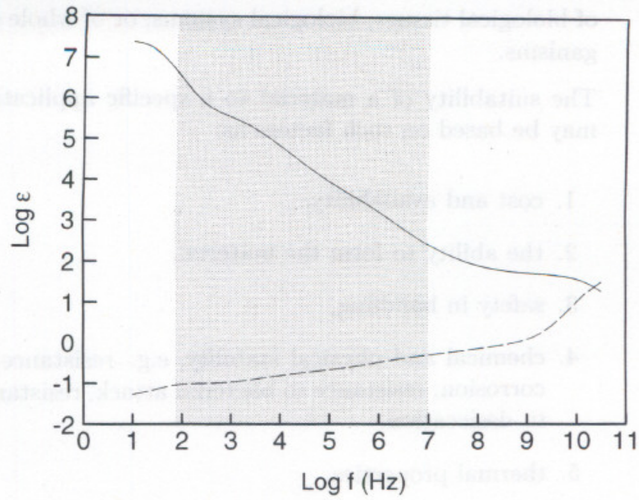

Figure 3 Dispersion in heart tissue. The real part of the dielectric constant (——) and the real part of the conductivity (- - -) are shown. These data are due to the model suggested in [56]. The range of frequencies utilized by hand-held and walk-through metal detectors is indicated in halftone.

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

$$\epsilon^*(\omega) - \epsilon_\infty = \sum_{n=1}^{4} \frac{\Delta\epsilon_n}{1 + (i\omega\tau_n)^{(1-\theta_n)}} + \frac{\sigma_i}{i\omega\epsilon_\circ}. \quad (14)$$

The effects of ionic conductivity are included by the final term where $\epsilon_\circ$ is the permittivity of free space. The difference $(\epsilon_0 - \epsilon_\infty)_n$ for each dispersive term is given by $\Delta\epsilon_n$. 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.

5.1 Computer models

A comprehensive review of computational phantoms is presented in a handbook prepared by International Commission on Radiation Units and Measurements [80]. These models are, however, primarily used to estimate dosimetry due to exposure to ionizing radiation.

High resolution geometric models of the human body have been, more recently, adapted to estimate the electrical currents induced in the body due to exposure to non-ionizing radiation [33, 34]. A comparative evaluation of these computational models is presented in [126].

5.2 Particles and membranes

Colloidal particles and membranes have been used as model systems to investigate the electrical properties of single cells and dilute suspensions of cells [48] and to evaluate low-frequency α-dispersion [90, 92].

5.3 Solutions

The use of aqueous solutions to simulate biological tissues is discussed in [67, 88, 89]. Solutions have several advantages in this application: Fluids are typically transparent and have excellent optical properties. Transparency can facilitate instrumentation in that probes can be readily positioned and manipulated. Solutions are uniform in composition and can be accurately and consistently prepared. Solutions can also be stirred to provide a uniform temperature distribution and for accurate measurement of thermal properties.

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 α- and β-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 phantoms 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

[1] S. J. Allen. Measurement of power absorption by human phantoms immersed in radio-frequency fields. *Ann. NY Acad. Sci.*, 247:494–498, 1975.

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 $CaCl_2$. 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.

[2] Stewart Allen, Gideon Kantor, Howard Bassen, and Paul Ruggera. CDRH RF phantom for hyperthermia systems evaluations. *Intern. J. Hypertheri.*, 4(1):17–23, January-February 1988.

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.

[3] L. S. Anderson, G. B. Gajda, and S. S. Stuchly. Analysis of open-ended coaxial line sensor in layered dielectric. *IEEE Trans. Inst. Meas.*, 35(1):13–18, March 1986.

KEY: ANDGAJ86

[4] Vitas Anderson and Jack Rowley. Tissue dielectric properties calculator. Telstra Research Laboratories, 770 Blackburn Rd., Clayton VIC 3168, Australia, May 15, 1998.

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].

[5] D. Andreuccetti, M. Bini, A. Ignesti, R. Olmi, N. Rubino, and R. Vanni. Use of polyacrylamide as a tissue-equivalent material in the microwave range. *IEEE Trans. Bio-Med. Eng.*, 35(4):275–277, April 1988.

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.

[6] James Baker-Jarvis. Transmission/reflection and short-circuit line permittivity measurements. Technical Note 1341, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce, July 1990.

KEY: BAK90

[7] James Baker-Jarvis, Richard G. Geyer, and Paul Domich. Improvements in transmission line permittivity and permeability measurements. In *CPEM'90 Digest*, pages 232–233. Conference on Precision Electromagnetic Measurements, 1990.

KEY: BAKGEY90

[8] James Baker-Jarvis, Michael Janezic, John Grosvenor, Paul D. Domich, and Richard G. Geyer. Transmission/reflection and short-circuit line methods for permittivity and permeability determination. Technical Note 1355, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce, 1991.

KEY: BAKJAN91

[9] James Baker-Jarvis, Eric Vanzura, and William Kissick. Improved technique for determining complex permittivity with the transmission/reflection method. *IEEE Trans. Microw. Theory Tech.*, 38(8):1096–1103, August 1990.

KEY: BAKVAN90

[10] N. Bano and R. A. Hashmi. Electrical studies of leaves over wide frequency range. *IEEE Trans. Electr. Insul.*, 3(2):229–232, April 1996.

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-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].

[11] S. T. Barsamian and T. K. Barsamian. Dielectric phenomenon of living matter. *IEEE Trans. Electr. Insul.*, 4(5):629–643, October 1997.

KEY: BARBAR97

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

[12] J. C. Bernengo and M. Hanss. Four-electrode, very-low-frequency impedance comparator for ionic solutions. *Rev. Sci. Instrum.*, 47(4):505–508, April 1976.

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 conductive 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.

[13] Marco G. Bini, Amleto Ignesti, Luigi Millanta, Roberto Olmi, Nicola Rubino, and Riccardo Vanni. The polyacrylamide as a phantom material for electromagnetic hyperthermia studies. *IEEE Trans. Bio-Med. Eng.*, 31(3):317–322, March 1984.

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.

[14] A. Bonincontro, R. Caneva, and F. Pedone. Dielectric relaxation at radio frequencies of DNA-protamine systems. *J. Non-crystalline Solids*, 131:1186–1189, June 1991. Part 2.

KEY: BONCAN91

[15] A. Bonincontro, R. Caneva, F. Pedone, and T. F. Romano. Complex dielectric constant of arginine-DNA and protamine-DNA aqueous systems at 10 GHz. *Phys. Med. Biol.*, 34(5):609–616, May 1989.

KEY: BONCAN89

[16] C. J. F. Böttcher and P. Bordewijk. *Theory of Electric Polarization*, volume II of *Dielectrics in time-dependent fields*. Elsevier Scientific Publishing Co., New York, NY, USA, 2nd edition, 1973.

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

[17] S. Bringhurst and M. F. Iskander. New metalized ceramic coaxial probe for high-temperature broadband dielectric properties of low permittivity materials. In *Microwaves: Theory and Application in Materials Processing II*, pages 503–510. Amer. Ceram. Soc.: Ceramics Trans., 1993.

KEY: BRIISK93

[18] M. G. Broadhurst. Complex dielectric constant and dissipation factor of foliage. Report 9592, National Bureau of Standards, U.S. Department of Commerce, Washington, DC, 1970.

KEY: BRO70

[19] M. G. Broadhurst, C. K. Chiang, and G. T. Davis. Dielectric phantoms for electromagnetic-radiation. *J. Mol. Liq.*, 36:47–64, September 1987.

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.

[20] M. G. Broadhurst, C. K. Chiang, K. J. Wahlstrand, R. M. Hill, L. A. Dissado, and J. Pugh. The dielectric-properties of biological tissue (crassula-portulacea) from 10^{-2} to 10^9 Hz. *J. Mol. Liq.*, 36:65–73, September 1987.

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 10^9 Hz. Both α- and β-dispersions were noted. A NBS Interagency Report [21] is cited for a description of the phantom material.

[21] Martin G. Broadhurst, C. K. Chiang, and G. Thomas Davis. A dielectric phantom material for electromagnetic radiation. NBSIR 86-3355, National Bureau of Standards, March 1986.

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].

[22] Howard E. Bussey. Dielectric measurements in a shielded open circuit coaxial line. *IEEE Trans. Inst. Meas.*, IM-29:120–124, June 1980.

KEY: BUS80

[23] H. Cachet, J. C. Lestrade, and J. P. Badiali. A measurement technique suited to the dielectric study of electrolyte solutions. In J. Chamberlain and G. W. Chantry, editors, *High frequency dielectric measurements*, pages 38–41. IPC Science and Technology Press, 1973.

KEY: CACLES73

[24] R. E. Charles, K. V. Rao, and W. P. Westphal. A capacitance bridge assembly for dielectric measurements. Laboratory for Insulation Research Technical Report 201, MIT, 1966.

KEY: CHARAO66

[25] Augustine Y. Cheung and David W. Koopman. Experimental development of simulated biomaterials for dosimetry studies of hazardous microwave radiation. *IEEE Trans. Microw. Theory Tech.*, 24:669–673, October 1976.

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 discribed. The real part of the permititivity, ϵ', conductivity, and loss tangent ϵ''/ϵ' 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 Laminac 4110. The authors refer to [66] for a detailed description of the component materials.

[26] C. K. Chou, G. W. Chen, A. W. Guy, and K. H. Luk. Formulas for preparing phantom muscle-tissue at various radiofrequencies. *Bioelectromagn.*, 5(4):435–441, 1984.

KEY: CHOCHE84
ANNOTATION: A gel-type phantom material is described. Measurements of the real part of the permittivity, ϵ', 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].

[27] P. A. Cirkel, J. P. M. van der Ploeg, and G. J. M. Koper. Electrode effects in dielectric spectroscopy of colloidal suspensions. *Physica A*, 235(1-2):269–278, January 15, 1997.

KEY: CIRVAN97

[28] R. N. Clarke. A re-entrant cavity method for the measurement of non-linear polarization in organic liquids. In J. Chamberlain and G. W. Chantry, editors, *High frequency dielectric measurements*, pages 56–59. IPC Science and Technology Press, 1973.

KEY: CLA73

[29] Kenneth S. Cole and Robert H. Cole. Dispersion and absorption in dielectrics I. Alternating current characteristics. *J. Chem. Phys.*, 9:341–351, April 1941.

KEY: COLCOL41
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.

[30] Saibal Connor, Marco T. Roy, Tiberio A. Ezquerra, and Francisco J. Baltá Calleja. Broadband ac conductivity of conductor-polymer composites. *Phys. Rev. B*, 57(4):2286–2294, January 15, 1998.

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.

[31] D. W. Davidson and R. H. Cole. Dielectric relaxation in glycerol, propylene glycol, and *n*-propanol. *J. Chem. Phys.*, 19(12):1484–1490, December 1951.

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, τ_o, and the viscosity have the same temperture dependence. This paper is cited by [109].

[32] B. Derrida, D. Stauffer, H. J. Herrmann, and J. Vannimenus. Transfer-matrix calculation of conductivity in 3-dimensional random resistor networks at percolation-threshold. *J. Phys. Lett. Paris*, 44(17):L701–L706, September 1, 1983.

KEY: DERSTA83
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, $\sigma = (p - p_c)^t$, for values of the volume fraction, p, near the percolation threshold, p_c. The value given for the conductivity exponent for a 3-dimensional system is 1.94 ± 0.1.

[33] P. J. Dimbylow. Induced current densities from low-frequency magnetic fields in a 2 mm resolution, anatomically realistic model of the body. *Phys. Med. Biol.*, 43(2):221–230, February 1998.

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.

[34] P. J. Dimbylow. Current densities in a 2 mm resolution anatomically realistic model of the body induced by low frequency electric fields. *Phys. Med. Biol.*, 45(4):1013–1022, April 2000.

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].

[35] L. A. Dissado and R. M. Hill. The fractal nature of the cluster model dielectric response functions. *J. Appl. Phys.*, 66(6):2511–2524, September 15, 1989.

KEY: DISHIL89

[36] Leonard A. Dissado. A fractal interpretation of the dielectric response of animal tissues. *Phys. Med. Biol.*, 35(11):1487–1503, November 1990.

KEY: DIS90
ANNOTATION: Refinements of the model suggested by Schwan [121] are presented. Schwan treated biological tissue a uniform, isotropic media, thus ignoring conductive networks, such as the vascular system, that interlace biological tissues. These conductive networks are modeled as fractal structures; and the frequency dependence of the real part of the permittivity, ϵ', is considered. Recent results obtained for liver, muscle, and brain tissues are discussed. α-

and β-dispersions are shown to be influenced by tissue structure and to be consistent with the predicted behavior in each case.

[37] S. S. Dukhin. Nonequilibrium electric surface phenomena. *Adv. Colloid Interfac.*, 44:1–134, May 24, 1993.
KEY: DUK93

[38] S. S. Dukhin. Electrochemical characterization of the surface of a small-particle and nonequilibrium electric surface phenomena. *Adv. Colloid Interfac.*, 61:17–49, November 10, 1995.

KEY: DUK95

[39] S. S. Dukhin and V. N. Shilov. *Dielectric Phenomena and the Double layer in Disperse Systems and Polyelectrolytes.* John Wiley and Sons, 1973.

KEY: DUKSHI74

[40] Yakov M. Eliashberg and William P. Thurston. *Confoliations*, volume 13 of *University Lecture Series.* American Mathematical Society, Providence, Rhode Island, 1998.

KEY: ELITHU98
ANNOTATION: This book contains a mathematical treatment of dynamical systems. In includes discussions of foliations, i.e. intergal systems, contact structures, and the generalization of these objects to confoliations.

[41] H. S. Endicott and E. J. McGowan. Measurement of dielectric constant and dissipation factor without electrodes. General Electric Technical Information Series 60GL214, General Electric, 1960.

KEY: ENDMCG60

[42] T. A. Ezquerra, M. Kulescza, and F. J. Baltá-Calleja. Electrical transport in polyethylene-graphite composite-materials. *Synthetic Met.*, 41(3):915–920, May 6, 1991.

KEY: EZQKUL91
ANNOTATION: The electrical properties of carbon-black filled polyethylene are examined. The real part of the permittivity, ϵ', 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.

[43] S. Fan, K. Staebell, and D. Misra. Static analysis of an open-ended coaxial line terminated by layered dielectric. *IEEE Trans. Inst. Meas.*, 39(2):435–437, April 1990.

KEY: FANSTA90

[44] Harley Flanders. *Differential Forms with Applications to the Physical Sciences.* Dover Publications, Inc., 31 East 2nd Street, Mineola, NY 11501 USA, 1989.

KEY: FLA89
ANNOTATION: The book provides an intoduction to differential forms and differential geometry. The applicaiton of differential forms to Maxwell's equations is presented.

[45] L. Flandin, Y. Brechet, G. R. Canova, and J. Y. Cavaille. AC electrical properties as a sensor of the microstructural evolution in nanocomposite materials: experiment and simulation. *Model. Sim. Mat. Sci. Eng.*, 7(5):865–874, September 1999.

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.

[46] L. Flanpdin, T. Prasse, R. Schueler, K. Schulte, W. Bauhofer, and J. Y. Cavaille. Anomalous percolation transition in carbon-black-epoxy composite materials. *Phys. Rev. B*, 59(22):14349–14355, June 1, 1999.

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.

[47] K. R. Foster, B. R. Epstein, and M. A. Gealt. Resonances in the dielectric absorption of DNA. *Biophys. J.*, 52:421–425, 1987.

KEY: FOSEPS87

[48] Kenneth R. Foster, Friedrich A. Saur, and Herman P. Schwan. Electrorotation and levitation of cells and colloidal particles. *Biophys. J.*, 63:180–190, July 1992.

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.

[49] Kenneth R. Foster and Herman P. Schwan. Dielectric properties of tissues. In Charles Polk and Elliot Postow, editors, *CRC Handbook of Biological Effects of Electromagnetic Fields*, pages 27–96. CRC Press, Inc., Boca Raton, FL, 1986.

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.

[50] Kenneth R. Foster and Herman P. Schwan. The dielectric properties of tissues and biological materials: A critical review. *Critical Reviews in Biomedical Engineering*, 17(1):25–104, 1989.

KEY: FOSSCH89

[51] Theodore Frankel. *The Geometry of Physics: An Introduction.* Cambridge University Press, 40 West 20th Street, New York, NY 10011-4211, USA, 1997.

KEY: FRA97
ANNOTATION: This book provides general background material on differential geometry.

[52] C. Gabriel. Compilation of the dielectric properties of body tissues at RF and microwave frequencies. Technical Report AL/OE-TR-1996-0037, Brooks Air Force Base, 1996.

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.

[53] C. Gabriel, S. Gabriel, and E. Corthout. The dielectric properties of biological tissues: I. Literature survey. *Phys. Med. Biol.*, 41:2231–2249, 1996.

KEY: GABGAB96

[54] C. Gabriel, E. H. Grant, R. Tata, P. R. Brown, B. Gestblom, and E. Noreland. Microwave absorption in aqueous solutions of DNA. *Nature*, 328:145–146, 1987.

KEY: GABGRA87

[55] S. Gabriel, R. W. Lau, and C. Gabriel. The dielectric properties of biological tissues: II. Measurments in the frequency range of 10 Hz to 20 GHz. *Phys. Med. Biol.*, 41:2251–2269, 1996.

KEY: GABLAU96

[56] S. Gabriel, R. W. Lau, and C. Gabriel. The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. *Phys. Med. Biol.*, 41:2271–2293, 1996.

KEY: GABLAU96a
ANNOTATION: Parametric models for seventeen tissue types are presented. These models are base 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.

[57] G. Gajda, M. A. Stuchly, and S. S. Stuchly. Mapping of the near-field pattern in simulated biological tissues. *Electron. Lett.*, 15(4):120–121, February 15, 1979.

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.

[58] E. H. Grant, R. J. Sheppard, and G. P. South. *Dielectric behavior of biological molecules in solution.* Clarendon Press, 1978.

KEY: GRASHE78

[59] C. Grosse and K. R. Foster. Permittivity of a suspension of charged spherical-particles in electrolyte solution. *J. Phys. Chem.*, 91(11):3073–3076, May 21, 1987.

KEY: GROFOS87

[60] C. Grosse, M. Tirado, W. Pieper, and R. Pottel. Broad frequency range study of the dielectric properties of suspensions of colloidal polystyrene particles in aqueous electrolyte solutions. *J. Colloid Interf. Sci.*, 205(1):26–41, September 1, 1998.

KEY: GROTIR98

[61] Constantino Grosse and Raquel Barchini. The influence of diffusion on the dielectric properties of suspensions of conductive spherical particles in an electrolyte. *J. Phys. D: Appl. Phys.*, 25:508–515, 1992.

KEY: GROBAR92

[62] Constantino Grosse and Vladimir N. Shilov. On the possibility of inductive properties in suspensions of ion exchange resin particles. *J. Colloid Interf. Sci.*, 178:18–28, 1996.

KEY: GROSHI96

[63] F. Gustrau, A. Bahr, M. Rittweger, S. Goltz, and S. Eggert. Simulation of induced current densities in the human body at industrial induction heating frequencies. *IEEE Trans. Electromag. Comp.*, 41(4):480–486, November 1999. Part 2.

KEY: GUSBAH99

[64] A. W. Guy and C. Chou. Specific absorption rates of energy in man models exposed to cellular UHF mobile-antenna fields. *IEEE Trans. Microw. Theory Tech.*, 34(6):671–680, June 1986.

KEY: GUYCHO86

[65] A. W. Guy, M. D. Webb, and C. C. Sorensen. Determination of power absorption in man exposed to high frequency electromagnetic fields by thermographic measurements of scale models. *IEEE Trans. Bio-Med. Eng.*, 23:361–391, 1976.

KEY: GUYWEB76

[66] Arthur W. Guy. Analyses of electromagnetic fields induced in biological tissues by thermographic studies on equivalent phantom models. *IEEE Trans. Microw. Theory Tech.*, 19(2):205–214, February 1971.

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 "laminac" 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, ϵ', and loss tangent of the phantom materials are measured for frequencies ranging between 200 MHz and 2,000 MHz.

[67] M. J. Hagmann, R. L. Levin, L. Calloway, A. J. Osborn, and K. R. Foster. Muscle-equivalent phantom materials for 10–100 MHz. *IEEE Trans. Microw. Theory*, 40(4):760–762, 1992.

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, ϵ', 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.

[68] Hand-held metal detectors for use in concealed weapon and contraband detection. National Institute of Justice Standard 0602-01, August 2000.

KEY: NIJHH
ANNOTATION: The test for concealed metal objects entails testing for standard objects concealed under the arm of a person.

[69] M. Hanss and J. C. Bernengo. Dielectric relaxation and orientation of DNA molecules. *Biopolymers*, 12:2151–2159, 1973.

KEY: HANBER73

[70] F. X. Hart and W. H. Cole. Dielectric-properties of apples in the range 0.1–100 kHz. *J. Mater. Sci.*, 28(3):621–631, February 1, 1993.

KEY: HARCOL93

[71] G. Hartgrove, A. Kraszewski, and A. Surowiec. Simulated biological materials for electromagnetic radiation absorption studies. *Bioelectromagn.*, 8:29–36, 1987.

KEY: HARKRA87
ANNOTATION: Preparation of gel type phantom materials is described. The phantom materials are based on the use of hydroxyetheylcellulose (HEC), which was available under the trade name Natrosol. The HEC was mixed with water, NaCl, sucrose, and a bacteriacide. 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.

[72] Reinosuke Hayakawa, Hiroshi Kanda, Masanori Sakamoto, and Yasaku Wada. New apparatus for measuring the complex dielectric constant of a highly conductive material. *Japan. J. Appl. Phys.*, 14(12):2039–2052, 1975.

KEY: HAYKAN75

[73] Measuring dielectric constant with the HP 8510 network analyzer, 1985.

KEY: HEW85

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

[74] P. N. Hill and H. E. Green. *In situ* measurement of soil permittivity and permeability. *J. Elect. Electr. Eng., Australia*, 2(4):205–209, December 1982.

KEY: HILGRE82

[75] R. M. Hill, L. A. Dissado, and R. R. Nigmatullin. Invariant behavior classes for the response of simple fractal circuits. *J. Phys.: Condens. Matter*, 3(48):9773–9790, December 2, 1991.

KEY: HILDIS91

[76] R. M. Hill, L. A. Dissado, J. Pugh, M. G. Broadhurst, C.K. Chiang, and K. J. Wahlstrand. The dielectric response of portulacaceae (jade) leaves over an extended frequency range. *J. Bio. Phys.*, 14:133–135, 1986.

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. α and β dispersions [121] were noted. α dispersion is attributed to a reduction in the region of charge to membranes next to the electrodes. β dispersion is attributed to charging of cell walls.

[77] Barry Honig and Anthony Nicholls. Classical electrostatics in biology and chemistry. *Science*, 268:1144–1149, 1995.

KEY: HONNIC95

[78] W. D. Hurt. Multiterm Debye dispersion-relations for permittivity of muscle. *IEEE Trans. Bio-Med. Eng.*, 32(1):60–64, 1985.

KEY: HUR85

[79] W. D. Hurt. Radiofrequency radiation dosimetry workshop. Technical Report AL/OE-SR-1996-0003, Brooks Air Force Base, 1996.

KEY: HUR96

[80] International Commission on Radiation Units and Measurements, 790 Woodmont Ave., Bethesda, MD, USA. *Phantoms and computational model in therapy, diagnosis and protection*, June 15, 1992. ICRU Report 48.

KEY: ICR92

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

[81] Y. Ishigure, S. Iijima, H. Ito, T. Ota, H. Unuma, M. Takahashi, Y. Hikichi, and H. Suzuki. Electrical and elastic properties of conductor-polymer composites. *J. Mater. Sci.*, 34(12):2979–2985, January 15, 1999.

KEY: ISHIIJ99

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.

[82] S. Jenkins, T. E. Hodgetts, R. N. Clarke, and A. W. Preece. Dielectric measurements on reference liquids using automatic network analyzers and calculable geometries. *Meas. Sci. Tech.*, 1:691–702, 1990.

KEY: JENHOD90

[83] Luděk Karásek, Bohumil Meissner, Shigeo Asai, and Masao Sumita. Percolation concept: Polymer-filler gel formation, electrical conductivity and dynamic electrical properties of carbon-black-filled rubbers. *Polym. J.*, 28(2):121–126, 1996.

KEY: KARMEI96

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, ϵ', and the imaginary part of the permittivity, ϵ'', are measured for frequencies ranging between 1 kHz and 13 MHz.

[84] Hirokazu Kato, Masahiro Hiraoka, and Tetsuya Ishida. An agar phantom for hyperthermia. *Med. Phys.*, 13(3):396–398, May-June 1986.

KEY: KATHIR86

ANNOTATION: The phantom material was composed of agar powder, NaCl, NaN_3, 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 desiccation. The conductivity and the real part of the permittivity, ϵ', of the phantom material were measured as a function of NaCl concentration for frequencies ranging between 1 MHz and 40 MHz.

[85] Hirokazu Kato and Tetsuya Ishida. Development of an agar phantom adaptable for simulation of various tissues in the range 5–40 MHz. *Phys. Med. Biol.*, 32(2):221–226, February 1987.

KEY: KATISH87

ANNOTATION: A gel type phanom material is described. The material is composed of agar, NaN_3, polyvinyl chloride powder, and water. The conductivity and the real part of the permittivity, ϵ', of the phantom material were measured as a function of NaN_3 concentration for frequencies ranging between 1 MHz and 40 MHz.

[86] S. Kirkpatrick. Percolation and conduction. *Rev. Mod. Phys.*, 45:574–588, 1973.

KEY: KIR73

[87] Takehiko Kobayashi, Toshio Nojima, Kenji Yamada, and Shinji Uebayashi. Dry phantom composed of ceramics and its application to SAR estimation. *IEEE Trans. Microw. Theory Tech.*, 41(1):136–140, January 1993.

KEY: KOBNOJ93

[88] Walter J. Kopecky. Using liquid dielectrics to obtain spatial thermal distributions. *Med. Phys.*, 7(5):566–570, September/October 1980.

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.

[89] Andrzej Kraszewski, Maria A. Stuchly, Stanislaw S. Stuchly, George Hartsgrove, and Daniel Adamski. Specific absorption rate distribution in a full-scale model of man at 350 MHz. *IEEE Trans. Microw. Theory*, 32(8):779–783, 1984.

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.

[90] W. Kuang. Low-frequency dielectric properties of biological tissues: Electrical double layer on membranes and ionic conduction through membrane pores. Master's thesis, The University of Georgia, Athens, GA, 1996.

KEY: KUA96

[91] W. Kuang and S. O. Nelson. Low-frequency dielectric properties of biological tissues: A review with some new insights. *Trans. ASAE*, 41(1):173–184, 1998.

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 α-, β-, and γ-dispersion is presented. Electrode effects are discussed.

[92] Wensheng Kuang and Stuart O. Nelson. Low-frequency dielectric dispersion from ion permeability of membranes. *J. Colloid Interf. Sci.*, 193(2):242–249, September 15, 1997.
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 μm 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.

[93] Terry Laudry, December 1999. Personal communication with Terry Landry, Oil Center Research, 616 West Pont Des Mouton Road, Lafayette, LA (TEL: 318-232-2496, FAX: 318-235-2907).

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].

[94] Sung-Ik Lee, Yi Song, Tae Won Noh, and James R. Gaines. Experimental observation of nonuniversal behavior of the conductivity exponent for three-dimensional continuum percolation systems. *Phys. Rev. B*, 34(10):6719–6724, November 15, 1986.
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 $\sigma_{eff} = \sigma_o(p - p_c)^t$, where the p is the volume fraction of metal, p_c is the percolation threshold, σ_o is the conductivity of the metal, and t is the conductivity exponent. Statistical percolation theory predicts a value for t of 1.9 for a 3-dimensional conducting network. The conductivity exponent for the indium/glass composite was approximately 3.

[95] J. B. Leonard, K. R. Foster, and T. W. Athey. Thermal-properties of tissue equivalent phantom materials. *IEEE Trans. Bio-Med. Eng.*, 31(7):533–536, 1984.

KEY: LEOFOS84

[96] A. C. Lynch. Precise measurement of complex permittivity and permeability in the millimeter region by a frequency domain technique. *IEEE Trans. Inst. Meas.*, 23:425–430, 1974.

KEY: LYN74

[97] Ib Madsen and Jørgen Tornehave. *From calculus to cohomology: De Rham cohomology and characteristic classes.* Cambridge University Press, 1997.

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

[98] M. Mandel and U. Odijk. Dielectric properties of polyelectrolyte solutions. In *Ann. Rev. Phys. Chem.*, pages 75–108. Annual Reviews, Inc., 1984.

KEY: MANODI84

[99] C. Marchal, M. Nadi, A. J. Tosser, C. Roussey, and M. L. Gaulard. Dielectric-properties of gelatine phantoms used for simulations of biological tissues between 10 and 50 MHz. *Intern. J. Hypertheri.*, 5(6):725–732, November-December 1989.

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

[100] T. P. Marsland and S. Evans. Dielectric measurements with an open-ended coaxial probe. *IEE Proceedings H*, 134(4):341–349, August 1987.

KEY: MAREVA87

[101] Orjan G. Martinsen, Sverre Grimmes, and Jan Karlsen. Low frequency dielectric dispersion of microporous membranes in electrolyte solution. *J. Colloid Interf. Sci.*, 199:107–110, 1998.

KEY: MARGRI98

[102] E. T. McAdams and J. Jossinet. Physical interpretation of Schwan's limit voltage of linearity. *Med. Biol. Eng. Comput.*, 32(2):126–130, March 1994.

KEY: MCAJOS94

[103] Michio Miyakawa, Naoki Takahashi, and Shinichiroh Hoshina. A method for observing the 3-dimensional patterns of electromagnetic power absorbed by the human-body—The gel phantom of the human-body used to study the electromagnetic environmental problem. *Electron. Comm. Jpn. Part 1*, 78(8):99–111, August 1995.

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.

[104] M. Moussavi, H. P. Schwan, and H. H. Sun. Harmonic distortion caused by electrode polarization. *Med. Biol. Eng. Comput.*, 32(2):121–125, March 1994.

KEY: MOUSCH94

[105] Nilashis Nandi and Biman Bagchi. Anomalous dielectric relaxation of aqueous protein solutions. *J. Phys. Chem. A*, 102:8217–8221, 1998.

KEY: NANBAG98

[106] Tsu-Wei Nee and Robert Zwanzig. Theory of dielectric relaxation in polar liquids. *J. Chem. Phys.*, 52:6353–6363, June 1970.

KEY: NEEZWA70

[107] Yoshio Nikawa. Study on dry phantom model to evaluate SAR distribution in human tissue. In *7th International Conference on Microwave and High Frequency Heating*, pages 383–386, 1999.

KEY: NIK99
ANNOTATION: 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.

[108] Yoshio Nikawa, Masaru Chino, and Kazuo Kikuchi. Soft and dry phantom modeling material using silicone rubber with carbon fiber. *IEEE Trans. Microw. Theory Tech.*, 44(10):1949–1953, October 1996.

KEY: NIKCHI96
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.

[109] G. A. Niklasson. A fractal description of the dielectric response of disordered materials. *J. Phys.: Condens. Matter*, 5(25):4233–4242, June 21, 1993.

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. Charge 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 $\chi(s) = \chi_0/(1 + (s\tau)^{1-n})$. Conduction of quasi-free charges leads to the Davidson-Cole equation for the complex resistance $\rho(s) = \rho_o/(1 + s\tau)^n$. The case where two processes having different cut off times occurs in the same material is also considered.

[110] T. Nojima, T. Kobayashi, K. Yamada, and S. Uebayashi. Ceramic dry-phantom and its application to SAR estimation. In *Microwave Symposium Digest*, MTT-S International, pages 189–192. IEEE, 1991.

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 are at 900 MHz. A longer version of this paper was later published [87].

[111] George R. Pack, G. A. Garrett, Linda Wong, and Gene Lamm. The effect of a variable dielectric coefficient and finite ion size on Poisson-Boltzmann calculations of DNA-electrolyte systems. *Biophys. J.*, 65:1363–1370, 1993.

KEY: PACGAR93

[112] Ronald Pethig. *Dielectric and Electronic Properties of Biological Materials.* John Wiley and Sons, New York, 1979.

KEY: PET79

[113] E. J. Post. *Formal structure of electromagnetics: general covariance and electromagnetics.* Dover Publications, Inc., Mineloa, NY, 1997.

KEY: POS97
ANNOTATION: This is a classic reference on electromagnetics. It was origanally published in 1962.

[114] L. A. Rosen, J. C. Baygents, and D. A. Saville. The interpretation of dielectric response measurements on colloid dispersions using the dynamic Stern layer model. *J. Chem. Phys.*, 98:4183–4194, 1992.

KEY: ROSBAY92

[115] Muhammad Sahimi. *Applications of Percolation Theory.* Taylor and Fransic, Ltd., 1994.
KEY: SAH

[116] Walter Schelder. Theory of the frequency dispersion of electrode polarization. Topology of networks with fractional power frequency dependence. *J. Chem. Phys.*, 79(2):127–136, 1975.

KEY: SCH75

[117] John A. Schellman and Dirk Stigter. The double layer, zeta potential, and electrophoretic charge of double-stranded DNA. *Biopolymers*, 16:1415–1434, 1977.

KEY: SCHSTI77

[118] H. P. Schwan. Linear and nonlinear electrode polarization and biological-materials. *Ann. Biomed. Eng.*, 20(3):269–288, 1992.

KEY: SCH92

[119] H. P. Schwan. Mechanisms responsible for electrical-properties of tissues and cell-suspensions. *Med. Prog. Technol.*, 19(4):163–165, 1993.

KEY: SCH93

ANNOTATION: This paper outlines the mechanisms for dispersion in biological tissues. α-, β-, and γ-dispersions are discussed. The mechanisms for α-dispersion include: counterions, tubular cell structure, glycocalyx, and membrane ion channels. The mechanisms for β-dispersion include: membrane blocking, organelles, and proteins. The mechanisms for γ-dispersion include: water, bound water, and polar subgroups.

[120] H. P. Schwan. The practical success of impedance techniques from an historical perspective. *Ann. NY Acad. Sci.*, 873:1–12, 1999.

KEY: SCH99

[121] Herman P. Schwan. Electrical properties of tissue and cell suspensions. *Advances in Biological and Medical Physics*, 5:147–209, 1957.

KEY: SCH57

[122] Waymond R. Scott and Glenn S. Smith. Error analysis for dielectric spectroscopy using shielded open-circuited coaxial lines of general length. *IEEE Trans. Inst. Meas.*, IM-35:130–137, June 1986.

KEY: SCOSMI86

[123] Y. Song, T. W. Noh, S. I. Lee, and J. R. Gaines. Experimental-study of the 3-dimensional ac conductivity and dielectric-constant of a conductor-insulator composite near the percolation-threshold. *Phys. Rev. B*, 33(2):904–908, January 15, 1986.

KEY: SONNOH86

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

[124] Dirk Stigter. A comparison of Manning's polyelectrolyte theory with the cylindrical Guoy model. *J. Chem. Phys.*, 82:1603–1606, 1978.

KEY: STI78

[125] P. Strating and F. W. Wiegel. Distribution of ions around a charged sphere. *Physica A*, 193:413–420, 1993.

KEY: STRWIE93

[126] M. A. Stuchly and O. P. Gandhi. Inter-laboratory comparison of numerical dosimetry for human exposure to 60 Hz electric and magnetic fields. *Biophys.*, 21(3):167–174, April 2000.

KEY: STUGAN00

[127] M. A. Stuchly, A. Kraszewski, and S. S. Stuchly. Exposure of human models in the near and far field—A comparison. *IEEE Trans. Bio-Med. Eng.*, 32(8):609–616, 1985.

KEY: STUKRA85

[128] M. A. Stuchly and S. S. Stuchly. Coaxial line reflection methods for measuring dielectric properties of biological substances at radio and microwave frequencies-A review. *IEEE Trans. Inst. Meas.*, IM-29:176–183, 1980.

KEY: STUSTU80a

[129] M. A. Stuchly and S. S. Stuchly. Dielectric properties of biological substances—Tabulated. *J. Microwave Power*, 15(1):19–26, 1980.

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 10^3 Hz to 10^9 Hz. the data on phantom materials ranges between 10^6 Hz and 10^10 Hz.

[130] S. S. Stuchly, A. Kraszewski, M. A. Stuchly, G. Hartsgrove, and D. Adamski. Energy deposition in a model of man in the near-field. *Bioelectromagn.*, 6(2):115–129, 1985.

KEY: STUKRA85a

[131] S. S. Stuchly, M. A. Stuchly, A. Kraszewski, and G. Hartsgrove. Energy deposition in a model of man—Frequency-effects. *IEEE Trans. Bio-Med. Eng.*, 33(7):702–711, July 1986.

KEY: STUSTU86

[132] Shiro Takashima. *Electrical Properties of Biopolymers and Membranes.* Adam Hilger, Bristol; Philadelphia, 1989.

KEY: TAK89

[133] Hiroshi Tamura, Youhei Ishikawa, Takehiko Kobayashi, and Toshio Nojima. A dry phantom material composed of ceramic and graphite powder. *IEEE Trans. Electromag. Comp.*, 39(2):132–137, May 1997.

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.

[134] R. A. Toupin and M. Lax. Lattice of partly permanent dipoles. *J. Chem. Phys.*, 27:458–464, August 1957.

KEY: TOULAX57

[135] M. S. Tung, R. J. Molinari, R. H. Cole, and J. H. Gibbs. Influence of temperature and ionic strength on the low-frequency dielectric dispersion of DNA solutions. *Biopolymers*, 16:2653, 1977.

KEY: TUNMOL77

[136] F. Van der Touw and M. Mandel. Dielectric increment and dielectric dispersion of solutions containing simple charged linear macromolecules. *Biophys. Chem.*, 2:218–241, 1974.

KEY: VANMAN74

[137] E. J. W. Verway and J. Th. G. Overbeek. *Theory of the Stability of Lyophobic Colloids.* Elsevier Publishing Company, Inc., New York, NY, USA, 1948.

KEY: VEROVE48

[138] A. R. Von Hippel. *Dielectric Materials and Applications.* M.I.T. Press, Cambridge, MA, 1954.

KEY: VON54

[139] Standard for walk through metal detectors for use in concealed weapon and contraband detection. National Institue of Justice Standard 0601-01, August 2000.

KEY: NIJWT

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

[140] W. P. Westphal. Techniques of measuring the permittivity and permeability of liquids and solids in the frequency range 3 c/s to 50 kMc/s. Laboratory for Insulation Research Technical Report XXXVI, MIT, 1950.

KEY: WES50

[141] P. Wust, H. Fähling, J. Berger, A. Jordan, G. Mönich, and R. Felix. Solid materials with high dielectric constants for hyperthermia applications. *Intern. J. Hypertheri.*, 14(2):183–193, March-April 1998.

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.

[142] T. Yamamoto and Y. Yamamoto. Electrical properties of the epidermal stratum corneum. *Med. Biol. Eng.*, 14:151–158, 1976.

KEY: YAMYAM76