RF/Microwave Interaction with Biological Tissues

ANDRÉ VANDER VORST
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Preface

This book addresses the unique needs of today's engineering community with an interest in radio frequency (RF)/microwaves in public health and in medicine as well as those of the medical community. Our decision to embark on this project was made during the time in which the authors served as Members of the IEEE Microwave Theory and Techniques (MTT) Subcommittee on Biological Effects and Medical Applications of Microwaves.

We were even more enthusiastic about writing the book after editing two special issues of *IEEE MTT Transactions* named "Medical Applications and Biological Effects of RF/Microwaves," one in 1996 and the second in 2001. The number of excellent papers accepted for publication in those two special issues required that two volumes be allocated to the subject each year. We then realized that we had the obligation, and the opportunity, to develop a new biomedical course that would encourage further research and produce new researchers in the unique area of RF/microwave interaction with tissue. Thus the book.

The material is divided into six chapters. Chapter 1 summarizes fundamentals in electromagnetics, with the biological mechanisms in mind. Special attention is paid to penetration in biological tissues and skin effect, relaxation effects in materials and the Cole–Cole display, the near field of an antenna, blackbody radiation with the various associated laws, and microwave measurements.

Chapter 2 discusses RF/microwave interaction mechanisms in biological materials. The word *interaction* stresses the fact that end results not only depend on the action of the field but also are influenced by the reaction of the living system. Cells and nerves are described, as well as tissue characterization, in particular dielectric, and measurements in tissues and biological liquids are included. A section is devoted to the fundamentals of thermodynamics, including a discussion on energy and entropy.

Biological effects are the subject of Chapter 3. Dosimetric studies attempt to quantify the interactions of RF fields with biological tissues and bodies. A variety of effects are described and discussed; they include those on the nervous system, the brain and spinal cord, the blood–brain barrier, cells and membranes, effects at the molecular level, influence of drugs, and effects due to extremely low frequency components of signal modulation. Thermal considerations, related to absorption, are the subject of a significant part of this chapter. The possibility of nonthermal effects is also discussed. This leads to a discussion on radiation hazards and exposure standards.

Chapter 4 is devoted to thermal therapy. Thermotherapy has been used as medical treatment in, for example, rheumatism and muscle diseases. In this chapter, the reader will find a description of applicators and an extensive discussion on the foundation of dielectric heating and inductive heating as well as a variety of technological information. Hyperthermia is also discussed as a noninvasive method, and practical thermometry methods are described.

Recently, electromagnetic (EM) environments have become very complex because of the wide and rapid spread of a number of electric or electronic devices, including recent progress and the increase in use in the area of cellular telephony. As a countermeasure, wave absorbers are being used for protecting biological and medical environments, and knowledge about these absorbers has become important. In Chapter 5, we investigate materials for EM wave absorbers, both from a theoretical and an application point of view. Special attention is paid to ferrite absorbers, for which it has long been a challenge to develop an EM wave absorber at the desired matching frequency. The chapter ends with the description of a method for improving the distribution of RF fields in a small room.

Chapter 6 begins with some of the fundamental aspects of major components used in RF/microwave delivery systems for therapeutic applications. The authors have chosen to detail the research done on the subject of cardiac ablation. The chapter also covers new ideas and research done on the use of RF/microwaves in the development of future measurement techniques, such as blood perfusion, for example, and the use of microwaves in therapeutic applications. New inventions would reduce further the need for surgical or invasive procedures, substituting noninvasive and minimally invasive techniques.

The authors acknowledge the enthusiastic help received during the preparation of the manuscript.

Andre Vander Vorst acknowledges the numerous conversations he has had over the years with two past doctoral students, D. Vanhoenacker-Janvier on a variety of microwave issues, more specifically microwave propagation, and Benoît Stockbroeckx about exposure measurements and radiation hazards. The stimulating environment created by some Ph.D. students is also acknowledged, especially Jian Teng, who participated in the investigation of the effect of microwaves on the nervous system of rabbits, and Dirk Adang, who in 2004 started a one-year epidemiological study on rats exposed to microwaves. This author also benefited from conversations with Jacques Vanderstraeten about

the effect of microwaves on DNA and with his colleagues of the Belgian Health Council.

Arye Rosen acknowledges the enthusiastic help that he received from then Ph.D. student, now colleague at Drexel University, M. Tofighi, who helped in the preparation of some of the problems included in the book and who, together with Yifei Li, reviewed part of the book. He also wishes to recognize Renee Cohen and Melany Smith, who helped to organize and type part of the material, and Rong Gu, who helped with some of the drawings. He acknowledges that selected, relevant parts, included with permission, have been published previously in *IEEE Transactions* and include contributions by Stuart Edwards, Paul Walinsky, and Arnold Greenspon. He also thanks his son, Harel Rosen, and his wife, Danielle Rosen, both of whose assistance is sincerely appreciated.

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André Vander Vorst
Arye Rosen
Youji Kotsuka

Introduction

Rapid technological advances in electronics, electro-optics, and computer science have profoundly affected our everyday lives. They have also set the stage for an unprecedented drive toward the improvement of existing medical devices and for the development of new ones. In particular, the advances in radio-frequency (RF)/microwave technology and computation techniques, among others, have paved the way for exciting new therapeutic and diagnostic methods. Frequencies from RF as low as 400 kHz through microwave frequencies as high as 10 GHz are presently being investigated for therapeutic applications in areas such as cardiology, urology, surgery, ophthalmology, cancer therapy, and others and for diagnostic applications in areas such as cancer detection, organ imaging, and more.

At the same time, safety concerns regarding the biological effects of electromagnetic (EM) radiation have been raised, including those at a low level of exposure. A variety of waves and signals have to be considered, from pure or almost pure sine waves to digital signals such as those of digital radio, digital television, and digital mobile phone systems.

In this book, we restrict ourselves to a discussion of the applications and effects of RF and microwave fields. These cover a frequency range from about 100 kHz to 10 GHz and above. This choice seems appropriate, although effects at RF and microwaves, respectively, are of a different nature. It excludes low-frequency (LF) and extremely low frequency (ELF) effects. It also excludes ultraviolet (UV) and X-rays, termed "ionizing radiation" because of their capability of disrupting molecular or atom structures. The RF/microwave frequency range covered here may be called "nonionizing."

For many years, hyperthermia and the related radiometry have been a major subject of interest in investigating biological effects of microwaves.

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Numerous publications are available on the subject, with [1–5] as examples. More recently, however, other subjects have received as much attention, in particular EM energy absorption in human subjects, especially in the human head and neck [6], interaction of microwaves with the nervous system [7], influence of the fields of mobilophony on membrane channels [8], and molecular effects [9].

An increasing amount of evidence, derived from in vitro and in vivo studies, indicates that microwaves affect living systems directly. With microwave absorption, however, when experimenting with animals or humans, there are ambiguities concerning the relative contributions to physiological alterations of indirect thermal effects, microwave-specific thermal effects, and possibly direct nonthermal interactions. In spite of these ambiguities, results of in vivo experiments conducted at low specific absorption rates indicate direct microwave effects. Furthermore, unambiguous evidence of direct effects of microwave fields has been provided by the results of in vitro studies. These studies were conducted under conditions of precise and accurate temperature control, revealing direct effects at various frequencies and intensities on a number of cellular endpoints, including calcium binding, proliferation, ligand–receptor-mediated events, and alteration in membrane channels. Interactions occurring at the microscopic level are related to the dielectric properties of biomacromolecules and large molecular units such as enzyme complexes, cell-membrane receptors, or ion channels.

The classical book by Michaelson and Lin [9], which reviews the biological effects of RF radiation, is still recommended to those who want to acquire a solid knowledge of the field. A more recent book by Thuery [10] reviews industrial, scientific, and medical applications of microwaves and lists a number of sources that offer basic information on the interaction between microwave fields and the nervous system. Another handbook by Polk and Postow, published in 1996 [11], reviews the biological effects of EM fields. Specific European research was reviewed in 1993 [12].

In this book, the reader will not find a review in the usual sense of the word, but rather will find an ensemble of aspects, which, in the authors' opinion, are highlights on specific subjects. Although a number of uncertainties about the biological effects of microwaves still persist, there exists today a substantial database on the subject of biological effects of thermal nature, and research is underway on new issues. As a consequence, there are now many applications at RF/microwaves of heating through absorption. Chapter 6 reviews most of those applications in the medical field. It must be emphasized that the application of RF/microwaves in medicine, essentially in cardiology, urology, and surgery, has been made possible due to the enormous amount of research carried out through many years and devoted to the understanding and modeling of microwave absorption in living materials [13].

Investigation of the interaction of EM fields with biological tissues requires a good physical insight and a mathematical understanding of what fields are. A field is associated with a physical phenomenon present in a given region of space. As an example, the temperature in a room is a field of temperature composed of the values of temperature in a number of points in the room. Chapter 1 summarizes fundamentals in electromagnetics, while bearing in mind the biological mechanisms. It emphasizes the fact that, at RF and microwave frequencies, the electric and magnetic fields are simultaneously present: If there is an electric field, then there is a coupled magnetic field and vice versa. If one is known, the other can be calculated.

Special attention is paid to some aspects that are not often handled in a book on electromagnetics but that are of importance as they pertain to biological effects, such as penetration in biological tissues and skin effect, relaxation effects in materials and the Cole–Cole display, the near field of an antenna, blackbody radiation with the various associated laws, and microwave measurements.

Chapter 2 is devoted to RF/microwave interaction mechanisms in biological materials. This is important basic material because the effects of this interaction are the result of the penetration of the EM waves into the living system and their propagation into it, their primary interaction with biological tissues, and the possible secondary effects induced by the primary interaction. The word *interaction* is important. It stresses the fact that end results not only depend on the action of the field but also are influenced by the reaction of the living system. Living systems have a large capacity for compensating for the effects induced by external influences, in particular EM sources. There can, however, be physiological compensation, meaning that the strain imposed by external factors is fully compensated and the organism is able to perform normally; or pathological compensation is possible, meaning that the imposed strain leads to the appearance of disturbances within the functions of the organism, and even structural alterations may result. The borderline between these two types of compensation is obviously not always easy to determine.

Cells and nerves are described as well as tissue characterization, in particular dielectric characterization, and measurements in tissues and biological liquids are included. A section is devoted to the fundamentals of thermodynamics and a discussion on energy and entropy.

Biological effects are treated in Chapter 3. The fact is stressed that only the fields inside a material can influence it, so that only the fields inside tissues and biological bodies can possibly interact with these: The biological effects of RF/microwaves do not depend solely on the external power density; they depend on the dielectric field inside the tissue or the body. Hence, the internal fields have to be determined for any meaningful and general quantification of biological data obtained experimentally. Dosimetric studies that attempt to quantify the interactions of RF fields with biological tissues and bodies are reported.

A variety of effects are described and discussed, such as those affecting the nervous system, the brain, and spinal cord. Special attention is given to effects on cells and membranes, effects at the molecular level, and effects due to ELF components of signal modulation as well as effects on the blood–brain barrier with report on the results of recent studies and the influence of drugs.

Thermal considerations are the subject of a significant part of this chapter. They are related to absorption, and the specific absorption rate is defined and discussed. The possibility of nonthermal effects is also discussed, more specifically as microthermal effects—where microwaves act as a trigger—and isothermal effects—where thermodynamics are a necessary tool. In the latter case, entropy is considered simultaneously with energy. This leads quite naturally to a discussion of radiation hazards and exposure standards, which the reader will find at the end of the chapter.

Chapter 4 is devoted to thermal therapy. The use of heat for medical treatment is not new: Heat has been used to treat lesions for more than 2000 years. Thermotherapy has been used as medical treatment for rheumatism, muscle diseases, and so on. In this chapter the reader will find the description of applicators and an extensive discussion on the foundation of both dielectric heating and inductive heating.

Hyperthermia is discussed in the second part of the chapter. Some reasons for which hyperthermia is effective for treating tumors are described in simple terms, based on biological results on culture cells and tumors of laboratory animals. It is shown that the development of accurate thermometry technology is an important challenge. Temperature measurement methods are generally classified into invasive methods and noninvasive methods, and practical thermometry methods are described.

Recently, EM environments have become very complex because of the rapid spread and wide use of a number of electric and electronic devices, including recent widespread use of cellular telephones. These devices have created an increasing number of EM wave interference problems. Also, there is a growing concern in the population about the possible biological effects induced by such radiation. As a countermeasure, wave absorbers are being used for protecting biological and medical environments, and familiarity with these absorbers has become important. In Chapter 5, materials ideal for use as EM wave absorbers are investigated both from a theoretical and an application point of view.

The absorbers are classified according to constituent material, structural shape, frequency characteristics, and application, and the fundamental theory is established for single- as well as multilayer wave absorbers. Special attention is paid to the ferrite absorbers, for which it has long been a challenge to develop an EM wave absorber at the desired matching frequency. A new method for the effective use of ferrite for microwave absorbers has therefore been proposed where small holes are punched through a rubber ferrite [14]. It is described in detail in this chapter. Such a method is termed an equivalent transformation method of material constant. The chapter ends with a method for improving the distribution of RF fields in a small room.

We have chosen to start Chapter 6 with some of the fundamental aspects of major components used in RF/microwave delivery systems for therapeutic applications. The components treated in detail are transmission lines, such as coaxial cable terminated in a simple antenna, and circular waveguide—both currently used in cardiology, urology, endocrinology, and obstetrics, to name just a few.

Although some of the applications are discussed in this chapter, the authors have chosen to detail the research done on the subject of cardiac ablation. The use of RF/microwaves has become the method of choice in the treatment of supraventricular tachycardia and benign prostatic hyperplasia worldwide. The engineering community should be proud of this accomplishment.

The chapter also covers new ideas and research done on the use of RF/microwaves in the development of future measurement techniques, such as blood perfusion.

In addition, the authors discuss a number of subjects for possible research in the use of microwaves in therapeutic medicine. Hopefully, with the understanding of the fundamentals of RF/microwave interaction with tissue and familiarity with the techniques already in use, these new ideas will encourage the student to become an inventor. New inventions would then reduce further the need for surgical or invasive procedures, substituting noninvasive and minimally invasive techniques.

The authors have organized the material as a textbook, and the reader will find problems at the end of each chapter.

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CHAPTER ONE

Fundamentals of Electromagnetics

1.1 RF AND MICROWAVE FREQUENCY RANGES

The rapid technological advances in electronics, electro-optics, and computer science have profoundly affected our everyday lives. They have also set the stage for an unprecedented drive toward the improvement of existing medical devices and the development of new ones. In particular, the advances in radio-frequency (RF)/microwave technology and computation techniques, among others, have paved the way for exciting new therapeutic and diagnostic methods. Frequencies, from RF as low as 400 kHz through microwave frequencies as high as 10 GHz, are presently being investigated for therapeutic applications in areas such as cardiology, urology, surgery, ophthalmology, cancer therapy, and others and for diagnostic applications in cancer detection, organ imaging, and more.

At the same time, safety concerns regarding the biological effects of electromagnetic (EM) radiation have been raised, in particular at a low level of exposure. A variety of waves and signals have to be considered, from pure or almost pure sine waves to digital signals, such as in digital radio, digital television, and digital mobile phone systems. The field has become rather sophisticated, and establishing safety recommendations or rules and making adequate measurements require quite an expertise.

In this book, we limit ourselves to the effects and applications of RF and microwave fields. This covers a frequency range from about 100 kHz to 10 GHz and above. This choice is appropriate, although effects at RF and microwaves,

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respectively, are of a different nature. It excludes low-frequency (LF) and extremely low frequency (ELF) effects, which do not involve any radiation. It also excludes ultraviolet (UV) and X-rays, called *ionizing* because they can disrupt molecular or atom structures. The RF/microwave frequency range covered here may be called *nonionizing*.

Radiation is a phenomenon characterizing the RF/microwave range. It is well known that structures radiate poorly when they are small with respect to the wavelength. For example, the wavelengths at the power distribution frequencies of 50 and 60 Hz are 6.000 and 5.000 km, respectively, which are enormous with respect to the objects we use in our day-to-day life. In fact, to radiate efficiently, a structure has to be large enough with respect to the wavelength λ. The concepts of radiation, antennas, far field, and near field have to be investigated.

On the other hand, at RF and microwave frequencies, the electric (E) and magnetic (H) fields are simultaneously present: if there is an electric field, then there is a coupled magnetic field and vice versa. If one is known, the other can be calculated: They are linked together by the well-known Maxwell's equations. Later in this book, we shall be able to separate some biological effects due to one field from some due to the other field. We need, however, to remember that we are considering the general case, which is that of the complete field, called the EM field. Hence, we are not considering direct-current (DC) and LF electric or magnetic fields into tissue.

Because we limit ourselves to the RF/microwave range, we may refer to our subject of interaction of electric and magnetic fields with organic matter as *biological effects of nonionizing radiation*. It should be well noticed that, by specifically considering a frequency range, we decide to describe the phenomena in what is called the *frequency domain*, that is, when the materials and systems of interest are submitted to a source of sinusoidal fields. To investigate properties over a frequency range, wide or narrow, we need to change the frequency of the source. The frequency domain is not "physical" because a sinusoidal source is not physical: It started to exist an infinite amount of time ago and it lasts forever. Furthermore, the general description in the frequency domain implies complex quantities, with a real and an imaginary part, respectively, which are not physical either. The frequency-domain description is, however, extremely useful because many sources are (almost) monochromatic.

To investigate the actual effect of physical sources, however, one has to operate in what is called the *time domain*, where the phenomena are described as a function of time and hence they are real and physically measurable. Operating in the time domain may be rather difficult with respect to the frequency domain. The interaction of RF/microwave fields with biological tissues is investigated mostly in the frequency domain, with sources considered as sinusoidal. Today numerical signals, such as for telephony, television, and frequency-modulated (FM) radio, may, however, necessitate time-domain analyses and measurements.

There is an interesting feature to note about microwaves: They cover, indeed, the frequency range where the wavelength is of the order of the size of objects of common use, that is, meter, decimeter, centimeter, and millimeter, depending of course on the material in which it is measured. One may, hence, wonder whether such wavelengths can excite resonance in biological tissues and systems. We shall come back later to this question.

1.2 FIELDS

Investigating the interaction of EM fields with biological tissues requires a good physical insight and mathematical understanding of what are *fields*. A field is associated with a physical phenomenon present in a given region of space. As an example, the temperature in a room is a field of temperature, composed of the values of temperature in a number of points of the room. One may say the same about the temperature *distribution* inside a human body, for instance. We do not see the field, but it exists, and we can for instance visualize constant-temperature or isothermal surfaces.

There are fields of different nature. First, fields may be either *static* or *time dependent*. Considering, for instance, the temperature field just described, the room may indeed be heated or cooled, which makes the temperature field time dependent. The human body may also be submitted to a variety of external sources or internal reasons which affect the temperature distribution inside the body. In this case, the isothermal surfaces will change their shapes as a function of time.

Second, the nature of the field may be such that one parameter only, such as magnitude, is associated with it. Then, the field is defined as *scalar*. The temperature field, for instance, inside a room or a human body, is a scalar field. One realizes that plotting a field may require skill, and also memory space, if the structure is described in detail or if the observer requires a detailed description of the field in space. This is true even in the simplest cases, when the field is scalar and static.

On the other hand, in a *vector* field, a vector represents both the magnitude and the direction of the physical quantity of interest at points in space, and this vector field may also be static or time dependent. When plotting a static scalar field, that is, one quantity, in points of space already requires some visualization effort. On the other hand, plotting a time-dependent vector field, that is, three time-varying quantities, in points of space obviously requires much more attention. A vector field is described by a set of *direction lines*, also known as *stream lines* or *flux lines*. The direction line is a curve constructed so that the field is tangential to the curve in all points of the curve.

1.3 ELECTROMAGNETICS

1.3.1 Electric Field and Flux Density

The electric field E is derived from Coulomb's law, which expresses the interaction between two electric point charges. Experimentally, it has been shown that

1. Two charges of opposite polarity attract each other, while they repel when they have the same polarity, and hence a charge creates a field of force.
2. The force is proportional to the product of charges.
3. The force acts along the line joining the charges and hence the force field is vectorial.
4. The force is higher when the charges are closer.
5. The force depends upon the electric properties of the medium in which the charges are placed.

The first observations showed that the force is about proportional to the square of the distance between them. In 1936, the difference between the measured value and the value 2 for the exponent was of the order of 2×10^{-9} [1]. It is admitted as a postulate that the exponent of the distance in the law expressing the force between the two charges is exactly equal to 2. It has been demonstrated that this postulate is necessary for deriving Maxwell's equations from a relativistic transformation of Coulomb's law under the assumption that the speed of light is a constant with respect to the observer [2, 3]. Hence, Coulomb's law is

$$\bar{f} = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}\bar{a}_r \qquad \text{N} \tag{1.1}$$

where $\bar{f}$ is the force; q_1 and q_2 the value of the charges, expressed in *coulombs* (C), including their polarity; the factor 4π is due to the use of the rationalized meter-kilogram-second (MKS) system, exhibiting a factor 4π when the symmetry is spherical; and ε_0 measures the influence of the medium containing the charges, equal to approximately $10^{-9}/36\pi$ *farads per meter* (F m^{-1}) in vacuum.

If a test charge Δq is placed in the field of force created by a charge q, it undergoes a force

$$\bar{f} = \frac{q_1(\Delta q)}{4\pi\varepsilon_0 r^2}\bar{a}_r \qquad \text{N} \tag{1.2}$$

The test charge Δq is small enough to avoid any perturbation of the field of force created by q. The intensity of the *electric field*, in *volts per meter* (V m^{-1}), is then defined as the ratio of the force exerted onto q by the charge Δq, which for the electric field created by a charge q in vacuum yields

$$\overline{E} = \frac{q}{4\pi\varepsilon_0 r^2}\overline{a}_r \qquad \text{V m}^{-1} \tag{1.3}$$

Ideally, the electric field is defined in the limit that Δq tends to zero. It is a vector field, radial in the case of a point charge. It comes out of a positive charge and points toward a negative charge. The lines of electric field are tangential to the electric field in every point. Equation (1.3) is linear with respect to the charge. Hence, when several charges are present, one may vectorially add up the electric fields due to each charge, which yields what is often called the generalized Coulomb's law.

The electric charge may appear in four different forms:

1. It can be punctual, as in Eqn. (1.2). It is then usually denoted q and measured in *coulombs*.
2. It can be distributed in space along a line (material of not). It is then usually denoted ρ_l and measured in *coulombs per meter* (C m^{-1}).
3. It can be distributed in space over a surface (material of not). It is then usually denoted ρ_s and measured in *coulombs per square meter* (C m^{-2}).
4. It can also be distributed in a volume. It is then usually denoted ρ and measured in *coulombs per cubic meter* (C m^{-3}).

When a material is submitted to an applied electric field, it becomes polarized, the amount of which is called the *polarization vector* $\overline{P}$. This is due to the fact that, in many circumstances, electric dipoles are created or transformed into the material, which corresponds to what is called the dielectric properties of the material. Hence, the polarization is the *electric dipole moment per unit volume*, in *coulombs per square meter*.

The total electric field in a dielectric material is the sum of the applied electric field and of an induced electric field, resulting from the polarization of the material. As a simple example, a *perfect electric conductor* is defined as an equipotential material. If the points in the material are at the same electric potential, then the electric field must be zero and there can be no electric charges in the material. When a perfect electric conductor is submitted to an applied field, this applied field exists in all points of the material. To have a vanishing *total electric field*, the material must develop an induced electric field such that the sum of the applied field and the induced field vanishes in all points of the material. The induced field is calculated by taking into account the geometry of the problem and the boundary conditions, which can of course be complicated. As another example, a human body placed in an applied electric field develops an induced electric field such that the sum of the applied field and the induced field satisfies the boundary conditions at the surface of the body. The total field in the body is the sum of the applied field and of the induced field.

A new vector field $\overline{D}$ is then defined, known as the *displacement flux density* or the *electric flux density*, in *coulombs per square meter* similarly to the polarization, defined as

$$\overline{D} = \varepsilon_0 \overline{E} + \overline{P} \qquad \mathrm{C\,m^{-2}} \tag{1.4}$$

This definition is totally general, applying to all materials, in particular to all biological materials. It indeed holds for materials in which [3]:

1. The polarization vector has not the same direction as the vector electric field, in which case the material is *anisotropic*.
2. The polarization can be delayed with respect to the variation of electric field, as is the case in *lossy materials*. All physical materials are lossy, so this is a universal property. It is neglected, however, when the losses are reasonably small, which is not always the case in biological tissues.
3. The polarization is not proportional to the electric field, in which case the material is *nonlinear*.

In all other cases, that is, when the material is *isotropic*, *lossless*, and *linear*, the definition (1.4) can be written

$$\overline{D} = \varepsilon_0 \varepsilon_r \overline{E} = \varepsilon \overline{E} \tag{1.5}$$

which combines the applied and induced fields, hence the external source field and the induced polarization, into the definition of ε ($\mathrm{F\,m^{-1}}$), permittivity of the material, product of the permittivity of vacuum ε_0 ($\mathrm{F\,m^{-1}}$) and the relative permittivity ε_r (dimensionless) of the material. The *electric susceptibility* χ_e is related to the relative permittivity by the expression

$$\varepsilon_r = 1 + \chi_e \tag{1.6}$$

It should be stressed that the use of permittivity, relative permittivity, and susceptibility is limited to isotropy, losslessness, and linearity, which is far from being always the case, in particular in biological tissues.

Dielectric polarization is a rather complicated phenomenon [4]. It may be due to a variety of mechanisms, which can be summarized here only briefly. The simplest materials are gases, especially when they are rarefied. The simplest variety is formed of *nonpolar gases*, in which the molecules have no electric dipole at rest. When an electric field is applied, an electric dipole is induced. This is a simple case for which a simple model can be used for correctly calculating the polarization. The next category is that of *polar gases*, in which an electric dipole does exist at rest. When an external electric field is applied, the dipole orientation is modified; it essentially rotates. For such a polar rarefied gas, which is still a very simple case, the relationship between polarization and applied field is already found to be nonlinear. When the density increases, modeling becomes much more difficult, and classical physics yields wrong models for compact gases, liquids, and of course solids, in particular conductors, semiconductors, and superconductors. Classical physics almost completely fails when trying to establish quantitative models. It can however yield some very illuminating insight on the phenomena involved with the dielectric character of materials, in particular about the influence of frequency, as will be shown now.

The *dipolar polarization*, resulting from the alignment of the molecule dipolar moment due to an applied field, is a rather slow phenomenon. It is correctly described by a first-order equation, called after Debye [5]: The dipolar polarization reaches its saturation value only after some time, measured by a time constant called *relaxation time* τ. The ability to polarize, called the *polarizability*, is measured by the parameter

$$\alpha_d = \frac{\alpha_0}{1 + j\omega\tau} + C \tag{1.7}$$

where constant C takes into account the nonzero value of the polarizability at infinite frequency. The relative permittivity related to this phenomenon is

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{1.8}$$

where N is the number of dipoles per unit volume. It should be observed that the permittivity is a complex quantity with real and imaginary parts. If ε_{r0} and $\varepsilon_{r\infty}$ are the values of the real part of the relative permittivity at frequencies zero and infinity, respectively, one can easily verify that the equations can be written as

$$\varepsilon_r' = \frac{\varepsilon_{r0} - \varepsilon_{r\infty}}{1 + \omega^2\tau^2} + \varepsilon_{r\infty} \qquad \varepsilon_r'' = \frac{(\varepsilon_{r0} - \varepsilon_{r\infty})\omega\tau}{1 + \omega^2\tau^2} \tag{1.9}$$

The parameter $\varepsilon_{r\infty}$ is in most cases the value at optical frequencies. It is often called the *optical dielectric constant*.

Dipolar polarization is dominant in the case of water, much present on earth and an essential element of living systems. The relative permittivity of water at 0°C is

$$\varepsilon_r = 5 + \frac{83}{1 + j0.113f\,(\text{GHz})} \tag{1.10}$$

with $1/\tau = 8.84\,\text{GHz}$. The real part of the relative permittivity is usually called the *dielectric constant*, while the imaginary part is a measure of the dielectric losses. These are often expressed also as the tangent of the *loss angle*:

$$\tan\ \delta_e = \frac{\varepsilon''}{\varepsilon'} \tag{1.11}$$

Table 1.1 shows values of relaxation times for several materials. A high value of the relaxation time is indicative of a good insulator, while small values are typical of good conductors.

TABLE 1.1 Relaxation Time of Some Materials

Material	Relaxation Time
Copper	1.51^{-19} s
Silver	1.31^{-19} s
Sea water	2.01^{-10} s
Distilled water	10^{-6} days
Quartz	10 days

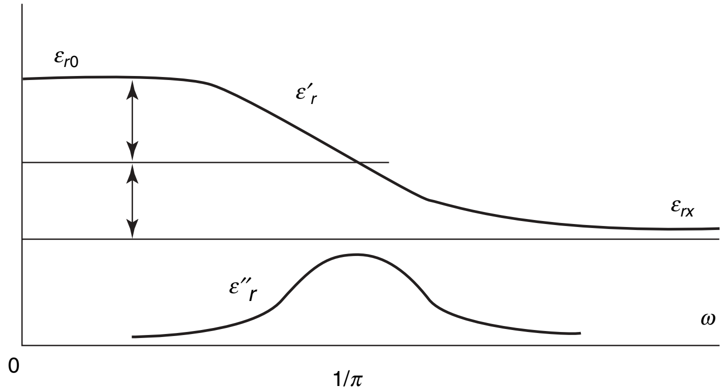

FIGURE 1.1 Relaxation effect.

Figure 1.1 represents the typical evolution of the real and imaginary parts of a relative permittivity satisfying Debye's law, where ε_{r0} and $\varepsilon_{r\infty}$ are the values at frequencies zero and infinity, respectively. It shows the general behavior of the real and imaginary parts of permittivity: The imaginary part is nonzero only when the real part varies as a function of frequency. Furthermore, each part can be calculated from the variation of the other part over the whole frequency range, as indicated by the Kramer and Kronig formulas [6]:

$$\varepsilon'(\omega) = \varepsilon_0 + \frac{2}{\pi}\int_0^\infty \frac{x\varepsilon''(x)}{x^2 - \omega^2}dx$$

$$\varepsilon''(\omega) = -\frac{2\omega}{\pi}\int_0^\infty \frac{\varepsilon'(x) - \varepsilon_\infty}{x^2 - \omega^2}dx \tag{1.12}$$

It can easily be seen that $\varepsilon'' = 0$ if ε' is frequency independent. The variable of integration x is real. The principal parts of the integrals are to be taken in the event of singularities of the integrands. The second equation implies that $\varepsilon''(\infty) = 0$. The evaluation of Eqn. (1.12) is laborious if the complex $\varepsilon(\omega)$ is not a convenient analytical function. It is interesting to observe that the formulas are

Chapter 2: RF/Microwave Interaction Mechanisms in Biological Materials is a collection of sub-topics that largely describe the mechanisms that occur when fields interact with tissues. Sub-topics such as polarization and relaxation are introduced. Descriptions of conductivity and permittivity, and typical values measured in various tissues are presented. The chapter ends with a description of the fundamentals of thermodynamics and a discussion of energy and entropy. Chapter 3: Biological Effects presents a description of the methods and metrics used to describe exposure of RF/Microwave energy t RF Microwave Interaction with Biological Tissues (Wiley Series in. 346 PagesÂ·2006Â·7.56 MBÂ·20 Downloads. of temperature in a number of points in the room. Chapter of RF/microwaves do not depend solely on the RF/Microwave Interaction with Biological Tissues. 346 PagesÂ·2006Â·7.56 MBÂ·38 Downloads. RF/Microwave Interaction with Biological Tissues ANDRÃ‰ VANDER VORST ARYE ROSEN YOUJI RF/Microwave Interaction with Biological Tissues. 346 PagesÂ·2006Â·7.56 MBÂ·5 Downloads. 6.5 Perfusion Chamber. 279 6.9.1 Microwave Tissue Welding. 294 . The stimulating environment Act like a Lady, Think like a Radio Frequency And Microwave Effects On Biological Tissues. 2019-11-14. Jitendra Behari. CRC Press. Focussing on engineering aspects of RF/Microwave interaction with biological tissues This book discusses the a. ISBN10 : 036725459X , ISBN13 : 9780367254599. Page Number : 352. Read Online Download Full. Principles And Applications Of Rf Microwave In Healthcare And Biosensing. 2016-10-05. Changzhi Li.