Preface

The topic of interactions of electromagnetic fields with biological systems is not only drawing attention from research scientists but also capturing interest from members of the general public. In the United States, the National Center for Complementary and Alternative Medicine, which is part of the National Institutes of Health, conducts and supports research that is generally not considered part of conventional or western medicine. The scope of research conducted by the Center is very broad and includes a group of diverse medical and health-care practices and treatments. In particular, the institution has provided research support for several projects investigating the therapeutic effectiveness of electromagnetic energy in the millimeter wavelength (mmW) region.

The use of nonionizing electromagnetic energy (in the mode of fields, waves, or radiation) for medical purposes dates back to the late 1800s. Shortly after Heinrich Hertz's confirmation of James C. Maxwell's prediction of the existence of electromagnetic waves, Arsene d'Arsonval applied the newly discovered high-frequency (10 kHz) current on himself and found that it produced warming of muscles without any accompanying sensation of muscular contraction. Indeed, the application of electromagnetic fields in biology and medicine has a long and illustrious history of research that continues to this date. Perhaps the most prominent application today is its use in medicine for magnetic resonance imaging and spectroscopy.

Moreover, interest in wireless communication and widespread use of wireless communication devices such as cellular mobile telephones have grown significantly all over the world during the past two decades. As a consequence, for the first time in human history a source of electromagnetic radiation has come to be located right next to the head or the body. This trend will likely continue and it promises to expand at a greater rate in the near future. Almost all human beings will soon become immersed a vast milieu of electromagnetic fields, waves, and radiation generated by human activity. Aside from cellular mobile telephones, such fields may come from, among others, the hubs (base stations) that enable wireless connections of all mobile and location-fixed devices, smart grids associated with the distribution and delivery of electricity, and global positioning systems (GPSs) employed for navigation to enable and facilitate mobility with safety and reliability.

Without question, human-made electromagnetic radiation will increase both in strength and in the spread of the frequency spectrum. The fact that electromagnetic fields and radiation can interact with biological systems is beyond debate. For instance, nuclear magnetic resonance takes place in biological medium under the influence of a radiofrequency (RF) field to allow imaging and spectroscopy of tissues inside the human body. Clearly, a biological effect is a prerequisite to any potential medical application of electromagnetic fields. However, an unintended or deleterious biological effect of electromagnetic fields and radiation may indicate grounds for health and safety precautions in the communication, industrial, scientific, and medical use of electromagnetic fields and radiation. Regardless, to help advance knowledge of the biological effects of such fields and to exploit their potential medical applications, it is essential to describe the characteristics of not only the applied electromagnetic fields and radiation but also the resulting electromagnetic fields and radiation inside the biological system.

A quantitative relationship between applied and induced electromagnetic fields and radiation would relate them to specific responses of the biological system. It should also facilitate an understanding of the biological responses. The induced field is the primary source of energy driving the interaction of electromagnetic energy with the biological system. Although it may contribute to the formulation of mechanisms of interaction, it is independent of any mechanism of interaction. Moreover, knowledge of applied and induced fields would aid in analyzing relationships among various observed biological effects in different experimental models and subjects. It could also serve as an index for comparison and extrapolation of experimental results from cell to cell, tissue to tissue, and tissue to animal, and from animal to animal, animal to human, and human to human exposures.

Experiments designed to study the interaction of electromagnetic fields and radiation with biological systems and the possible effects of such fields on the systems can be divided into three categories: (1) *in vitro* biological experiments, (2) *in vivo* animal experiments, and (3) laboratory or epidemiological studies on humans. *In vitro* biological experiments typically involve biological entities constituted by cells contained within flasks or petri dishes and exposed to well-defined electromagnetic fields and radiation. These experiments are most suited to study the possible effects of exposure on specific biological targets or to study postulates and verify proposed interaction mechanisms aimed toward explaining observed biological responses. Epidemiological studies can offer the most direct evidence on the health effects of human exposure to electromagnetic fields and radiation. Apart from the difficulties faced in exposure assessment, that is, the quantification of levels of applied and induced electromagnetic fields and radiation, which is rather difficult if not impossible to obtain with a high degree of accuracy, the major limitation of epidemiological studies is the prolonged period of time typically required for observation in most cases and the related confounding factors.

Moreover, the implications of any effect obtained at the cellular level from *in vitro* investigations are not always obvious in terms of health effects on the whole organism. Thus, it is often necessary to conduct *in vivo* experiments, where whole animals, such as mice and rats, are directly exposed to electromagnetic fields and radiation and the potential for induction of specific health effects is studied. *In vivo* experiments are not only important in assessing possible health effects of electromagnetic fields and the thresholds for their induction but also useful in allowing extrapolation of animal observations to human subjects, provided knowledge is available to specify the relationship between applied and induced electromagnetic fields and radiation.

The objective of this book is to provide a comprehensive discussion of the interactions of electromagnetic fields and radiation with biological systems, spanning a variety of topics from static fields to terahertz waves in seven chapters. Each chapter includes materials written by scientists who have made major contributions to the relevant subjects. Particular emphasis is placed on the coupling of electromagnetic fields and radiation into biological systems. Each chapter focuses on induced fields and absorbed energy from applied or exposure fields, and a review of the literature is included to explain the motivation for writing the chapter. The relevant literature is summarized so that the reader can understand why the topic is of interest or importance and this summary discusses current progress on the subject. The aim is to achieve a quantitative understanding of the relationships between the applied and induced electromagnetic fields and radiation that cause biological effects and enable medical applications.

A wide range of analytical techniques, computational algorithms, and/or experimental methods may be employed to determine the coupling of electromagnetic fields and radiation into biological systems. Hybrid approaches involving both analytical and numerical methods have been used. Although this book spotlights advanced experimental and computational techniques and current results on isolated cells and realistic anatomical models, it begins with a brief introduction of Maxwell's equations, which is the fundamental mathematical statement of the physical laws that govern all electromagnetic phenomena. It is significant to note that although most theories of classical physics were fundamentally modified as a result of the introduction of Albert Einstein's special theory of relativity, Maxwell's equations have remained consistent and intact over the years in describing the known physical phenomena over the entire experimentally observed nonionizing electromagnetic spectrum.

Knowledge of internal electric and magnetic fields, induced current densities, and specific absorption rates (SAR) inside the biological medium is fundamental in studying biological responses to, health effects of, and medical applications of electromagnetic fields and radiation. The discussions in Chapter 1 provide a basic understanding of essential interactions and field coupling phenomena to facilitate better appreciation and understanding of their use and importance. Electromagnetic energy at both high and low frequencies can be transmitted into a biological medium. Using canonical geometries, phantom models, and anatomically based representations of the human body, results obtained from closed-form analytical solutions and computer methods to predict the internal fields and their distributions are discussed and salient features are summarized. Specifically, they include induced static electric and magnetic fields, transmission of low-frequency and quasistatic electric and magnetic fields, transmission and reflection of RF fields at planar interfaces, RF coupling to bodies with curvature and in the near field, dosimetry and energy absorption from handheld cell phones in anatomical human models, SAR in childlike head models, fields from body-worn devices, and whole-body exposure from cell phone base stations. The coupling of short (narrow-width) and ultra-wideband (UWB) pulses into the human body is analyzed for planar, spherical, and full-scale anatomical models. Recent advances in mmW technologies and beyond have motivated a wide range of telecommunication, industrial, medical, and scientific applications including security screening in the form of whole-body image scanning. The chapter concludes with a summary of available information on transmitted, reflected, and distributed mmW energy in skin tissues.

Short electric pulses can extend deeply into the cell interior (see Chapter 2) and have been briefly discussed in Chapter 1. The classical understanding of a majority of the electric field induced biological effect is the induction of a potential difference across the cell membrane by the external electric field. For example, the electric field strength required to achieve electroporation depends on the duration of the applied pulse, because this process involves the gradual charging of the cell membrane followed by rearrangement of the lipid molecules. The typical pulses range from tens of milliseconds (ms) with amplitudes in the 10 kV/m ranges to pulses of a few microseconds (ms) or less at field strengths of several 100 kV/m. More recently, the electrical pulses in the nanosecond (ns) duration range and pulse amplitudes as high as 30,000 kV/m have been investigated for triggering purely electrically driven responses without any thermal heating. Such fast processes as electron transfers between molecules, electrophoretic separation and self-organization, or field induced changes in reaction kinetics are being explored. Chapter 2 presents many potential applications based on intracellular effects produced by the use of nanosecond, pulsed electric fields (nsPEF) of high-intensity. It is anticipated that nsPEF may provide versatile non-thermal tools capable of producing cellular electroporation, intra-cellular calcium release, shrinkage of tumors and cellular apoptosis, temporary blockage of action potential propagation in nerves, activation of platelets, and release of growth factors for accelerated wound healing.

Exposure to naturally occurring and human-made static, low-frequency, and pulsed magnetic fields in biological systems forms the topic of Chapter 3. It is of interest because changes in the strength and distribution of such fields have been found to be biologically effective; many questions have been raised as to whether exposure to these fields may be linked to adverse health effects, and a wide range of biomedical applications have been developed to take advantage of the interaction of magnetic fields with biological systems. In addition to discussing the coupling of static, low-frequency, and pulsed magnetic fields into biological systems, the chapter summarizes more recent information on biological effects and medical applications of such fields and discusses mechanisms by which biological systems sense and respond to magnetic fields.

During the past few decades, the interaction of extremely low frequency (ELF) electromagnetic fields with biological systems has become a major source of health concern, especially for the 50 and 60 Hz frequencies used by electric power distribution systems. An essential aspect of health investigations has been the evaluation of induced electric fields and current densities inside human subjects and phantom models of human and animal bodies. Chapter 4 is devoted to dosimetry or coupling of ELF fields into biological systems. It provides a description of the historical developments and recent trends in numerical dosimetry. It also includes a comprehensive review of research efforts from Japan on induced electric fields and current densities inside phantom models resulting from ELF exposures.

Cellular communication has evolved into one of the most successfully commercialized technologies. Today, the immense popularity of cell phones is beyond debate. Worldwide, there are more people who own and use cell or mobile phones than any other electronic device, regardless of whether the country is rich or poor, developed or developing. Some predict that the entire world population will soon be exposed to RF electromagnetic fields or radiation from sources located near the human body that enable wireless communication. The coupling or dosimetry of RF radiation into the body in presented in Chapter 5. It discusses numerical tools and experimental methods that may be used to model and assess the interaction of mobile communication devices with the human body. Given the proximity of the cell phone handset to the human head in common use, the interaction between the cell phone and the user's head has been extensively studied. Moreover, there is increasing scientific interest in assessing human exposure to base station antennas, local area networks, and newly emerging mobile communication technologies. These scenarios suggest continuous and simultaneous exposure to multiple sources of RF and microwave radiation over an extended period of time or even the entire lifetime of the world population.

Electromagnetic fields and waves are widely used in medicine, and they are playing progressively more important roles in health care each day. The medical applications are based on either the direct interaction of the field with biological tissues to illicit functional responses or the conversion of field energy to heat through the delivery of electromagnetic energy into the treatment region. They enable the acquisition of diagnostic information such as distribution and binding status of nuclei in magnetic resonance imaging or spectroscopy. The applications encompass a wide range of electromagnetic frequencies, ranging from static to ELF and RF fields. In addition, they may involve rapidly changing field transients and spatial gradients, depending on the specific application. The exposure and dosimetry associated with these medical devices and systems are explained in Chapter 6. This chapter also includes discussions on the unintentional exposure of patients or staff or both through the coupling of stray electromagnetic fields from medical devices.

An emerging area of significant research activity over the past decade has been the terahertz region of the electromagnetic spectrum because of the development of high-power terahertz sources. While there is a paucity of biological studies at terahertz frequencies, information on exposure and dosimetry is even scarcer. However, terahertz sources are aggressively being explored for practical medical, military, and security applications. Current examples include early cancer detection and diagnosis; identification of concealed explosives, drugs, and weapons; and terahertz imaging and sensing techniques for security screening. Chapter 7 reviews available data on the biological effects of terahertz radiation and discusses the current understanding of the physical events that transpire when terahertz radiation interacts with biological tissues, cells, and organelles.

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