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Preface

The unique microwave auditory effect has been widely recognized as one of the most interesting and significant biological phenomena from microwave exposure. Its potential applications are just now beginning to be seriously explored.

The microwave auditory effect is defined as the auditory perception of microwave radiation or simply hearing microwaves. This description may seem surprising, and one might even question whether such sensation could exist. It is indeed a unique exception to the acoustic energy normally encountered by humans in auditory perception of sound. Although mammalian hearing apparatus responds to acoustic or sound pressure waves in the audio-frequency range (up to 20 kHz for humans), frequencies above 35 kHz are considered as ultrasound for humans (beyond the range of audible frequencies). The hearing of microwave pulses involves electromagnetic radiation whose frequency is in the much higher megahertz (MHz) to gigahertz (GHz) range. As electromagnetic waves (such as sunlight and optical radiation) can normally be seen but not heard, the auditory sensation of microwave pulses is obviously surprising, and initially, its authenticity was widely questioned.

The microwave auditory effect involves a cascade of events. Minuscule but rapid rise in tissue temperature (~10^{-6} °C) resulting from the absorption of short microsecond (μs) wide pulses of microwave energy creates a thermoelastic expansion of brain matter. This small theoretical temperature elevation is undetectable by any currently available temperature sensors, and at threshold levels, it cannot be felt as a thermal sensation or heat. Nevertheless, it can launch an acoustic wave of pressure that travels inside the head to the inner ear. It then activates the nerve cells in the cochlea and relays it to the central auditory nervous system for perception via the same process involved for normal hearing. Thus, the discovery of microwave thermoelastic pressure wave generation in biological tissues by deposition of short microwave pulses in tissue came about as the result of an intense effort in search of a mechanism to help understand the observed auditory response to microwave radiation. Furthermore, identification of the propagation nature of the acoustic wave of pressure in biological tissues has prompted the exploration of its potential for applications in biomedical imaging, specifically a new dual modality diagnostic imaging system – microwave thermoacoustic tomography (MTT).

It is interesting to note the U.S. State Department's disclosure that Havana-based US diplomats were experiencing health issues associated with hearing loud buzzing or what was described as bursts of sound in 2017. A similar announcement was made by the Government of Canada. The staff of both embassies had reported symptoms of hearing loss, ringing in the ears, headaches, nausea, and problems with balance or vertigo, which are suggestive of a connection to the inner ear apparatus within the human head, where the cochlea and vestibular organs are located.

Government officials had difficulty pinning down the source of sound. There are speculations that the diplomats may have been attacked with an advanced sound weapon. Assuming reported accounts are reliable, the microwave auditory effect may be the scientific explanation. It is plausible that the loud buzzing, burst of sound, or acoustic pressure waves could have been covertly delivered using high-power pulsed microwave radiation, rather than blasting the subjects with conventional sonic sources. Indeed, many have come to believe that the microwave auditory effect – induced by a targeted beam of high peak-power pulsed microwave radiation – may be the most likely scientific explanation for the sonic attack. Of course, until the truth is revealed, this specific matter will remain somewhat of a mystery.

The objective of this volume is to bring together in a comprehensive book the multidisciplinary research investigation leading to a scientific understanding of the microwave auditory effect and related applications, especially the emerging microwave thermoacoustic tomography (MTT) imaging modality. The analysis and discussions in the chapters of this book pertain to relevant physical laws, exposure and dosimetry, anatomy and physiology, psychophysics and behavior, theories and models, mechanisms of interaction, computer analysis and simulation, applications in biology and medicine, and other applied aspects. Another purpose of this volume is to expand and update existing knowledge and understanding of microwave auditory effects and applications, which was the title of an earlier research monograph. A considerable amount of scientific knowledge, data, and information have been generated since then through theoretical study, laboratory experimentation, numerical analysis, and computer simulation.

As this may be the readers' first encounter to this material and the treatment is multidisciplinary, after the Introduction, the four chapters that follow each begins with basic background information that may appear as elementary to some readers but is essential to understanding the discussions on microwave auditory effect and applications for those from a different discipline. There is a chapter on the principles of microwave and RF exposure and one on brain anatomy and auditory physiology. The succeeding two chapters present the microwave property of biological materials and its influence on dosimetry and microwave absorption in biological tissues. They are intended to facilitate a fuller understanding of discussions in the ensuing five chapters about microwave auditory effect and applications.

The focus of Chaps. 6, 7, 8, and 9 is all on the microwave auditory effect. In Chap. 6, neurophysiological evidence and psychophysical and behavioral observations from laboratory studies involving animals and humans as experimental subjects are discussed in detail. The objective is to provide a complete account of what is scientifically known about the microwave auditory effect. The possible mechanisms that have been suggested whereby auditory responses might be induced by pulse-modulated microwave radiation are analyzed in Chap. 7 with the conclusion of the microwave thermoelastic theory being the favored.

Solving partial differential equations may be mathematically fun and satisfying. However, some of the ramifications of mathematical solutions can be hidden if there is little knowledge of their parametric dependence, such as on peak power or pulse width or the values they may take at various frequencies. Also, because long uninterrupted strings of formulas tend to become dull, computational and experimental results are interspersed throughout these chapters when appropriate.

Chapter 8 presents rigorous multidisciplinary, mathematical analyses of the thermoelastic pressure waves generated in canonical or spherical human and animal head models exposed to pulsed microwave radiation. The results include variations of induced sound pressure frequency and strength on microwave pulse characteristics. They also correctly predict the attributes of sound waves generated in the head as perceived by humans. More precise computer simulations of the properties of microwave-pulse-induced sound pressure waves using realistic anatomic human head structures are presented in Chap. 9. The simulation confirmed by experimental results clearly indicates that the microwave auditory effect or the hearing of microwave pulse-induced sound involves a cascade of events that start from microwave absorption in the brain, where it is converted into an acoustic pressure wave.

Chapter 10 discusses the important diagnostic imaging application of microwave thermoelastic pressure wave interaction including a summary of early investigations and current developments in microwave thermoacoustic tomography (MTT) and imaging. It also describes some applied aspects of the microwave auditory effects in directed messaging, mind control, and its possible role in the recently reported covert personnel attacks at some diplomatic missions (the Havana syndrome) and fighter pilot disorientations.

An extensive list of references is provided in this book at the end of each chapter to furnish the knowledge base to put the materials in proper perspective, and to overcome potential misunderstanding. The guiding principles throughout the book are that any description or conclusion must be consistent and compatible with physical laws, biological evidence, and experimental observations based on laboratory data and findings.

The many graduate students and colleagues whose contributions to various aspects covered in this book are acknowledged with appreciation. Instead of repeating their names that are included in the reference citations, I would like to direct the readers to the references. It is with gratitude and love that I thank my family for their support and encouragement and especially my wife, Fei Mei, for her patience and forbearance during the writing of this book.

Chicago, USA James C. Lin

Contents

Chapter 1
Introduction

Humans have been living in a milieu of natural electromagnetic radiation for millennia. The natural electromagnetic radiation originates from terrestrial and extraterrestrial sources such as lightning and electrical discharges in the Earth's atmosphere and radiant energies from the solar system and outer space. Indeed, the discovery and measurement of 3 K microwave background radiation are the crucial steps leading to the standard "Big Bang" model of universe [Grandin, 2007; Lundqvist, 1992]. Furthermore, scientific and technological advances have ushered in a myriad of artificial electromagnetic sources through semiconductor and vacuum tube processes that are unique in each case and have given rise to devices and systems that enable applications to benefit human endeavors and embellish our daily lives. Examples are found in a wide variety of commercial, communication, industrial, scientific, residential, and medical applications.

1.1 Electromagnetic Radiation and Spectrum

The wide-ranging spectra of electromagnetic radiation span from cosmic gamma rays to static electric and magnetic fields. In between these are the well-known X-ray, ultraviolet (UV), visible light, infrared, microwave, and radio frequency (RF) waves (Fig. 1.1). Electromagnetic radiation may be described in terms of its wavelength, frequency, and energy, each with a different set of units of measures. The speed (v) of propagation of electromagnetic radiation in a material medium depends on the permittivity and permeability properties of the medium. It is related to the product of frequency (f) and wavelength (λ), such that

$$v = f \times \lambda \tag{1.1}$$

The highest speed of electromagnetic radiation can travel is 2.998×10^8 m/s in vacuum or free space.

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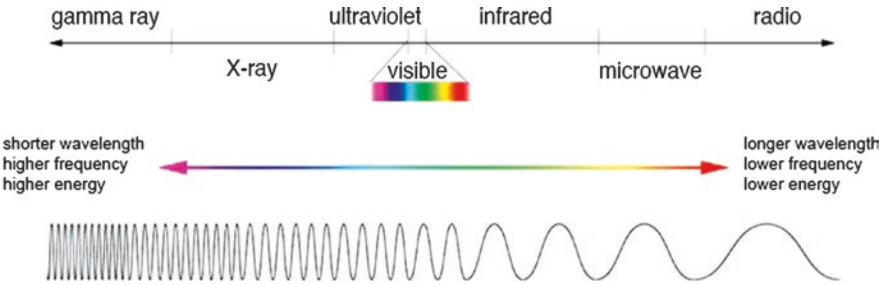

Fig. 1.1 A portion of the electromagnetic spectrum including microwave and radio frequency radiation (NASA)

Wavelength measures the closeness between any two successive peaks or valleys of the wave variations shown in Fig. 1.1 and uses meter (m) as the standard unit of measure. Frequency is measured in cycles per second (s) or Hertz (Hz). Energy is measured in Joules (J) or electron volts (eV). One eV is equal to 1.602×10^{-19} J. Gamma rays have shorter wavelength, higher frequency, and higher energy per quantum or photon, while microwave and RF radiation have longer wavelength, lower frequency, and lower energy per quantum or photon energy.

At shorter wavelength, electromagnetic radiation may be conceptualized as massless wave packets, referred to as photons, traveling at the speed of light in vacuum or free space with a finite amount of energy per packet or photon. Thus, the term photon energy is often used to describe the energy for various regions of electromagnetic radiation. The relationship among these quantities is specified by the equation

$$\varepsilon = h \times \mathrm{f} \tag{1.2}$$

where ε is energy per photon (J), h is Planck's constant (6.625×10^{-34} J-s), and f is frequency (Hz).

A list of the photon or quantum energy of common forms of electromagnetic radiation is provided in Table 1.1. The photon energy of Gamma ray is greater than 2×10^{-14} J, ultraviolet radiation has photon energy varying between 5×10^{-19} and 2×10^{-17} J, and those of optical radiation and microwaves are less than 5×10^{-19} J.

Depending on the photon energy carried by the electromagnetic radiation, some of them may be capable of ejection or promotion of orbital electrons from the atoms of materials through which the electromagnetic radiation travels and creating ions in the process. During ionization, the impinging electromagnetic radiation imparts a finite amount of photon energy to each ejected or promoted electron.

The minimum amount of photon energies required to produce ionization in water and atomic carbon, hydrogen, nitrogen, and oxygen is between 10 and 25 eV. Inasmuch as these atoms constitute the basic elements of living organisms, 10 eV is considered as the lower limit of ionization in biological systems. Although weak hydrogen bonds in biomolecules may involve energies less than 10 eV, photon energies below this value can generally be considered, biologically, as nonionizing.

Table 1.1 Approximate wavelength, frequency, and photon energy limits of the various regions of the electromagnetic spectrum

	Wavelength (m)	Frequency (Hz)	Energy (J)	Energy (eV)
Radio frequency (RF)	$>1 \times 10^{-1}$	$<3 \times 10^{9}$	$<2 \times 10^{-24}$	$<1.2 \times 10^{-5}$
Microwave	$1 \times 10^{-3} - 1 \times 10^{-1}$	3×10^{9}–3×10^{11}	$2 \times 10^{-24} - 2 \times 10^{-22}$	$1.2 \times 10^{-5} - 1.2 \times 10^{-3}$
Infrared	$7 \times 10^{-7} - 1 \times 10^{-3}$	3×10^{11}–4×10^{14}	$2 \times 10^{-22} - 3 \times 10^{-19}$	$1.2 \times 10^{-3} - 1.8$
Optical	$4 \times 10^{-7} - 7 \times 10^{-7}$	$4 \times 10^{14} - 7.5 \times 10^{14}$	$3 \times 10^{-19} - 5 \times 10^{-19}$	1.8–3.1
Ultraviolet (UV)	$1 \times 10^{-8} - 4 \times 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{16}$	$5 \times 10^{-19} - 2 \times 10^{-17}$	3.1–1.2×10^{2}
X-ray	$1 \times 10^{-11} - 1 \times 10^{-8}$	3×10^{16}–3×10^{19}	$2 \times 10^{-17} - 2 \times 10^{-14}$	$1.2 \times 10^{2} - 1.2 \times 10^{5}$
Gamma ray	$<1 \times 10^{-11}$	$>3 \times 10^{19}$	$>2 \times 10^{-14}$	$>1.2 \times 10^{5}$

1 eV = 1.602×10^{-19} J; 1 J = 6.242×10^{18} eV; 1 nm = 10^{-9} m

X-rays and Gamma rays have photon energies higher than 100 eV. The principal biological effects of the ionizing X-ray and Gamma radiation are therefore largely the result of ionization they produce, including their effect on deoxyribonucleic acid (DNA). It is important to know that ionizing radiation is also associated with thermal effects in biological systems through heat generation.

Terrestrial solar UV consists mainly of UV-A radiation (315–400 nm) and the balance UV-B (280–315 nm). Only artificial UV sources emit radiant energy within the UV-C spectral band (100–280 nm). Ultraviolet radiation is important for several biological processes and has been shown to have deleterious effects on certain biological systems, including carcinogenesis. One commonly known effect of UV radiation is sunburn. Aside from beneficial medical treatments, they are used in cellular and microbiology laboratories to kill bacteria and prevent bacterial growth and for public health applications as antiviral agents.

Ultraviolet radiation at wavelengths of less than 320 nm, especially the UV-B and UV-C bands, transfers their energies to atoms or molecules almost entirely by excitation, that is, by promotion of orbital electrons to some higher energy levels. Consequently, some of the effects produced by UV photons may resemble the changes resulting from ionizing radiation. In fact, the effects of UV share some aspects of effects of ionizing radiation such as effects on DNA. Also, since the advent of high-power lasers, some of the principal hazard recognized in the use of UV sources has been the potential for injury of the skin and eye from exposure to UV radiation at wavelengths of less than 320 nm. The widespread use of high-power UV in industry has been the cause of many corneal injuries. The UV rays can circumvent the natural defense of the body by allowing direct exposure of the cornea at normal angles of incidence, unshielded by the brow or eyelids.

Although the photons of visible light with relatively low energy levels, 1.8–3.1 eV, are not capable of ionization or excitation, they have the unique ability of producing photochemical effects or photobiological reactions. Through a series of biochemical reactions, green plants, for example, can use optical energy to fix carbon dioxide and split water such that carbohydrates and other chemicals are synthesized.

Because visible light is not very penetrating, the eye and the skin are the major organs of concern. Optical radiation is transmitted through the eye media without appreciable attenuation before reaching the retina. There it is absorbed by light-sensitive cells that initiate biochemical reactions whose end result is the sensation of vision. The leading acute effects are thermal and photochemical retinal injury for the eye and erythema and burns for the skin. Retinal injury and transient loss of vision may occur as a result of exposure to intense visible light. Delayed effects include cataract formation in the lens, retinal degeneration for the eye, and accelerated aging and cancer for the skin.

Infrared radiation of the sun is the major source of heat on the Earth and has wavelength varying from approximately 700 nm to 1 mm. It is also emitted by all hot bodies. With photon energies of 0.002–1.8 eV, it does not produce ionization. There is little evidence that photons in the infrared region can initiate photochemical reaction in biological systems. It is known that changes in vibrational modes are responsible for absorption in infrared region. The absorbed energy increases the kinetic energy in the system, which dissipates in heat. Thus, the main response of biological systems to an exposure to infrared radiation is thermal.

Microwave and RF radiation increases the kinetic energy of the system when it is absorbed by the biological media. In this case, the increase in kinetic energy is due to induced translation of electronic particles and change of rotational or vibrational energy levels; the latter ends up primarily in the form of increased system temperature while it may not be exclusively so. Microwave and RF radiation has low-energy photons; therefore, under ordinary circumstances, the photon energy is too low to affect excitation or ionization of a biological atom or molecule. However, the situation may be different in some cases, if multiple microwave photons imping on a single atom or molecule, or under intense bombardment, ionization may still occur. Simultaneous absorption of strong RF radiation, 8×10^5 greater than the low-energy microwave photons, could potentially produce ionization in biological materials. The point is that RF radiation has low energy photons, therefore under ordinary circumstances, RF radiation is too weak to affect ionization or cause significant damage to biological molecules such as DNA, which is especially renowned for its repair mechanism. Additional information and description on microwave and RF radiation are given in the following section and subsequent chapters.

1.2 Microwave Technology and Applications

In scientific, industrial, commercial, communication, medical, and security applications, common names such as RF, microwave, millimeter wave (mm-W), and Terahertz (THz) or T-wave are used to describe specific regions of the electromagnetic spectrum between 30 kHz and 3 THz (Table 1.2), using manufactured artificial sources. Also, for RF region, the LF, MF, HF, and VHF band designations are often employed to denote the low, medium, high, and very high frequency bands, respectively. Likewise, microwave radiation may be further divided into UHF (ultrahigh frequency) and SHF (super high frequency) bands.

Table 1.2 Commonly used frequency band designations of RF and microwave region of the electromagnetic spectrum

Common name	Band designation	Frequency
RF	Low frequency (LF)	30–300 kHz
	Medium frequency (MF)	300 kHz–3 MHz
	High frequency (HF)	3–30 MHz
	Very high frequency (VHF)	30–300 MHz
Microwave	Ultrahigh frequency (UHF)	300 MHz–3 GHz
	Super high frequency (SHF)	3–30 GHz
Millimeter wave (mm-W)	Extremely high frequency (EHF)	30–300 GHz
Terahertz wave (T-wave)	Terahertz (THz)	300 GHz–3 THz

Microwaves are generated as continuous-wave (CW) sinusoids or pulses of various forms and are transmitted in CW, baseband, amplitude- or frequency-modulated carrier waves, or pulse-amplitude modulated waves. In some high-power microwave applications, magnetron tubes are the generator of choice, although in some cases the multiple-beam klystron is favorite. However, in many current wireless communication and data transmission systems, solid-state semiconductor devices have replaced magnetron and klystron tubes.

Scenarios with sources of high levels of microwave and RF radiation are typically found in medical facilities such as magnetic resonance imaging (MRI) scanners, or specialized establishments with high-power radars. Some medical diagnostic imaging procedures may involve high levels of microwave and RF radiation at the patient's location or even inside a patient's body. Situations associated with personal use by the general public such as for wireless communication, data transmission, security operations, or food processing produce comparably much lower exposures at the position of the user.

In open medium or free space, these waves propagate or travel in straight line-of-sight path in the absence of obstacles. They may be reflected or refracted upon encountering any material bodies. It is interesting to note in this regard the moon's far side is continuously shielded from radio transmissions from the Earth. The recent touch down of China's Chang'e-4 lander on the lunar surface's far side in January 2019 involved the support of new technology-based relay platform at a location well beyond the moon [Greshko, 2019].

As a powerful but relatively compact microwave source for practical use, the magnetron tube was developed in the early 1940s under the stimulus of an intense war-time effort for military radars. It was reported that these microwave radars caused warmth sensation for radar operators in certain work environment. Furthermore, anecdotally, some radar personnel had stated that they were able to auditorily sense when radars were in active operation. However, microwave sources were unavailable for biological and medical research since they were reserved solely for military use during the war. Nonetheless, in response to the concerns over the biological effects and potential hazards of microwave radiation, the United States military services conducted some human studies to determine whether or not rumors such as sterilizing effects in males might have some factual ground. The available reports [Daily, 1943; Lidman and Cohn, 1945] failed to record any clinical (or hematological) changes resulting from exposure to radar microwave radiation.

Shortly after the war, magnetron sources capable of generating high power levels of microwaves were introduced into industrial and medical applications. Indeed, industrial microwave heating, drying, and curing systems are currently in widespread use in many industrial processes. They are found in agricultural, food processing, material treatment, pharmaceutics, waste management, and manufacturing facilities, to name a few. The following are some familiar applications of microwave and RF radiation beginning with microwave magnetrons operating under the CW mode.

1.2.1 Microwave Diathermy

In 1946, Mayo Clinic in Minnesota received two magnetron microwave generators for biomedical research, almost a decade after they had first become interested in the medical use of microwave radiation. They immediately embarked on their first studies of microwave diathermy, which means deep heating of tissues through the skin. Studies on animals showed that microwave diathermy could cause severe tissue burns within a short time of application. Nevertheless, with the proper selection of power and treatment duration, it was found that deep tissues could indeed be heated to therapeutically effective levels [Krusen et al. 1947]. It was noted that the initial temperature rise was greater in the skin and subcutaneous fat than in deeper musculatures. The final temperature in the muscle, however, was higher [Licht, 1965].

Research conducted at the Mayo Clinic had helped to establish the initial uses and limitations of microwave diathermy and led to its acceptance as a therapeutic instrument by the American Medical Association in 1947. Some early reports showed that microwave diathermy was effective in complete relieve of the pain of osteoarthritis in most cases. Microwave diathermy has been described as valuable in the management of disorders of the shoulder [Rae, et al., 1950]. Clinical studies found that microwave diathermy can be used to advantage in traumatic conditions such as sprains and strains, especially when combined with massage. Readers interested in this topic are referred to [Kotttke and Lehmann, 1990] for more detailed descriptions, indications, and contraindications and its use in the current practice of physical and sports medicine.

There are two related topics in medical applications of RF and microwave heating: ablation and hyperthermia treatments.

1.2.2 Microwave Ablation Therapy

Since 1987, percutaneous transluminal microwave [Beckmann, et al., 1987; Lin and Wang, 1987] and RF [Huang and Wilber, 2000] catheter technologies have been developed for cardiac ablation treatment of arrhythmia or abnormal heart rhythm [Lin, 1999, 2004]. Within a few years, it has become the method of choice for treatment of cardiac arrhythmias. Catheter ablation for atrial fibrillation and ventricular tachycardia is expanding; it stems in part from the nonpharmacological approach and the minimally invasive nature of these procedures. In cardiac ablation, endocardia conducting tissue responsible for causing arrhythmia is destroyed by a burst of microwave or RF energy applied through a catheter to the cardiac tissue to effect thermal coagulation. The field of catheter cardiac ablation has progressed with the development of new methods and tools [Lopresto et al., 2017] and with the publication of large clinical trials [Calkins et al. 2018; Cronin et al., 2019]. Catheter ablation of atrial fibrillation is widely available and is now the most performed catheter ablation procedure.

For ablation of atrioventricular junction to treat supraventricular arrhythmia, the catheter antenna or electrode is inserted percutaneously through the femoral vein, first to record electrograms from the His bundle using the catheter as electrode and then to apply heating energy to destroy the atrioventricular conduction tissue. For microwave catheters, (2-mm diam and operating at 2450 MHz), an average energy of 200 joules is required for tissue temperatures of 65 °C [Lin, 1999; Lin et al., 1996]. In the RF technique, a 500-kHz current is induced to flow from an electrode inside the heart to a large patch reference electrode on the body surface. The resulting resistive heating, which is the highest at the electrode-tissue interface, produces desiccation of the cardiac tissue to aid ablation.

The development of coagulative ablation therapy over the past decades has revolutionized not only the practice of cardiac electrophysiology but also oncology, especially in using microwave or RF energy to ablate tumors. For many of the diseases, surgical intervention has been the principal method of treatment, although alternatives to surgery have been sought to reduce the cost and morbidity of treatment. Minimally invasive catheter ablation offers several potential benefits: long incisions are replaced with a puncture wound, and the need for postoperative intensive care is significantly reduced and, in many cases, offers a complete or lasting cure. It also has important advantages over drugs that are merely palliative. It avoids the side effects, expense, and inconvenience of chronic drug therapy, often with only partial success.

Percutaneous microwave and RF ablation is considered a prime therapy for early hepatocellular carcinomas with improved rates of local tumor control and survival. However, RF current relies on a conductive or resistive heating process. It is limited to contact heating and is not successful in treating large tumors and tumors in regions of tissue with high blood perfusion. As a result, RF end up with an undesirably high rate of local tumor progress in larger tumors. In contrast, microwave energy at 915 or 2450 MHz is radiated from the catheter antenna into the tissue volume surrounding the antenna and can reach a larger tumor mass. Also, microwave technology affords better power control and has greater capacity to overcome perfusion-mediated tissue cooling associated with large vessels. A contraindication is the increased power can result in vascular thrombosis of the portal vein in patients with reduced portal venous flow rate. Note that blood flow velocity within the inferior vena cava, hepatic arteries, and major hepatic veins is usually sufficient to prevent significant vascular thrombosis [Wells et al., 2015].

1.2.3 Hyperthermia Treatment of Cancer

Hyperthermia cancer therapy is a treatment in which tumor temperatures are elevated to the range of 40–45 °C. The cytotoxic effects of some antitumor drugs are enhanced, and the cell-killing ability of ionizing radiation is potentiated by hyperthermia serving as a sensitizing agent. Moreover, the synergism between the beneficial effects of local or regional hyperthermia combined with chemotherapy and radiotherapy has been postulated for some time, and it has been well documented [Dewhirst et al., 2018; Issels, 2008; van der Zee et al., 2000]. Clinical and laboratory results from various investigators have indicated a promising future for hyperthermia. Its efficacy depends on the induction of a sufficient temperature rise throughout the tumor volume. Many external and implanted antennas and applicators have been designed to produce therapeutic heating of localized tumors of different volumes in a variety of anatomical sites [Burfeindt et al., 2011; Hand 1989; Lin et al., 2000; Nguyen et al., 2017]. Clearly, each modality has its own advantages and liabilities. Monitoring and control of tumor temperature in real time during hyperthermia treatment is essential for effective treatment. While progress in temperature sensing in vivo has been dramatic, considerable advance is needed along with appropriate treatment planning to support routine clinical application of hyperthermia for cancer. Nevertheless, hyperthermia is gaining wider use in clinical practice in treating a variety of malignant tumors [Cheng et al., 2019; Dooley et al., 2010; Yamamoto et al., 2014]. Also, hyperthermia as a multifaceted therapeutic modality represents a potent radiosensitizer, interacts favorably with a host of chemotherapeutic agents, and, in combination with radiotherapy, enforces immunomodulation akin to in situ tumor vaccination [Datta et al., 2020].

Whole-body hyperthermia has been employed to enhance the effectiveness of chemotherapy for patients with systemic metastatic cancer. A variety of conductive and convective heating techniques such as warm air, water, wax, radiant heating techniques, and heating the blood via extracorporeal circulation have been applied. Mild whole-body hyperthermia at 40 °C for as long as 10 hours in rats has shown promising therapeutic potentials on a metastatic primary tumor. Studies in pigs have shown body-core temperature elevations to 41.5–42.0 °C for 60 min are safe and associated with acceptable toxicity rates using radiant heat sources [Hildebrandt et al., 2015]. While clinical results remain guarded, a recent pig study reported on thermal distribution, pathophysiological effects, and safety of whole-body hyperthermia [Lassche et al., 2020].

1.2.4 Microwave Ovens

The search for new applications for the magnetron microwave-generating technology alighted on the idea of heating food with microwaves [Osepchuk, 1984, 2002]. Concerted efforts were directed toward a microwave oven for commercial and residential use, perhaps aided by prior accounts of warmth sensations close to radiating microwave radars, as mentioned above. In 1946, Raytheon in Massachusetts unveiled its new “Radarange” microwave oven for heating and cooking food, introducing a new use for the company’s magnetron tubes and allowing it to avoid obsolescence instead, for a bright future.

The successful marketing of countertop microwave ovens for consumer use, in subsequent years, had not only launched an economically important technology-based business, but it enabled magnetrons to become one of the best-known sources of microwave power. It also assured the future of magnetrons in helping to fulfill the “promise” of a microwave oven in every kitchen. Microwave oven operates at the industrial, scientific, and medical (ISM) band frequency of 2450 MHz for heating and cooking food in the household or commercial establishment. It remains an essential appliance in state-of-the-art kitchens. Some of the technological and economic accomplishments, along the way, include achievement of close to 100% efficiency at 1 kilowatt (kW) of microwave power and cost and weight reductions by a factor of 100 or more since 1946.

It is noteworthy that a Radiation Control for Health and Safety Act (PL90-602) was adopted by the United States Congress in October 1968, to protect the public from unnecessary exposure to potentially harmful radiation, which includes microwaves emitted by electronic products. The Act prescribes different and individual performance standards, to the extent appropriate and feasible, for different electronic products, to recognize their different operating characteristics and uses. For microwave ovens, the performance standard limits radiation at any point 5 cm from the oven surface to 1 mW/cm^2 prior to purchase and 5 mW/cm^2 throughout their useful life (1 mW/cm^2 = 10 W/m^2).

A primary source for microwave oven emission comes from the leakage of microwave radiation from the door. There had been several designs to effectively limit microwave leakage from the door and seal to the specified levels. In fact, most of the microwave ovens currently on the market are based on designs developed, tested, and evaluated decades ago for their effectiveness in minimizing leakage radiation.

1.2.5 Magnetic Resonance Imaging

Advantages of magnetic resonance imaging (MRI) have made it the radiological modality of choice for many diagnostic medical procedures. MRI has become perhaps the most successful application of electromagnetic fields and waves in biology and medicine. MRI systems use strong static, spatially varying gradient, and RF magnetic fields to make images. The clinical successes have also heightened the desire for increased spatial resolution from MRI systems. This demand has prompted the exploration of ever higher strength static magnetic fields and the associated use of higher RF spectra and powers. Pulsed RF magnetic fields are used to elicit magnetic resonance signals from tissues, principally from the hydrogen protons in fat and water molecules. Many open designs for interventional and intraoperative procedures are increasingly being installed in healthcare sites and radiological imaging centers.

In a typical MRI procedure, the patient is exposed to numerous pulses of RF radiation. For the common 1.5 tesla (1.5 T) clinical MRI scanner, the associated RF frequency for proton imaging at 1.5 T is about 64 MHz. The new 3 T MRI scanners use 128-MHz RF energy for operation. In fact, higher field MRI systems are becoming more common. Furthermore, at present, several experimental ultra-high-field strength and ultra-fast MRI systems operate at 7.0 T, 9.4 T, or higher, with a corresponding 300-MHz, 400-MHz, or higher RF frequencies for proton imaging (see more discussions in Chap. 9.).

1.2.6 Modern Microwave Radars

While radars based on magnetrons were initially developed for military purposes, current uses of microwave radars have expanded to numerous civilian applications where information on relative location of objects of interest is crucial. Examples include air traffic control, weather monitoring, marine navigation, and autonomous vehicles (self-driving cars). Many of these radar applications involve high-power microwave radiation ranging from a few kilowatt (kW) to several megawatt (MW). There are installations operating at gigawatt (GW), but other radar devices use power that are at or below the milliwatt (mW) level. Moreover, many modern radar applications are based on solid-state systems for high and low power applications [Balanis, 2008]. Also, most of these operations involve use of pulse or frequency modulation techniques to acquire both location and speed information.

1.3 Auditory Effects from Pulsed Microwave Exposure

Exposure to microwave and RF radiation is comprised of electric field, magnetic field, and the electromagnetic power carried by microwave and RF radiation in these fields. The exposures generally vary with time and space (or location) because the electric and magnetic fields change with time and space and the relative position (and distance) of the exposed subject and source of microwave and RF radiation. Of concern here are principally the macroscopic phenomena in which bodies or volumes whose dimensions are larger than atomic dimensions. Moreover, the time intervals of observation are assumed to be long enough to allow for an averaging of atomic fluctuations.

The microwave and RF radiation exposure may be measured using appropriate instruments and systems or quantified through theoretical analysis and computer simulation based on Maxwell's equations which form the classic electromagnetics theory. Indeed, solution of Maxwell's equations leads to descriptions with mathematical vigor and computational exactness of the macroscopic characteristics of radio and microwave radiation and their interaction with biological systems.

For exposure durations that are suitably long and average applied field strengths or incident power densities of microwave radiation that are sufficiently high, appreciable temperature elevation including heating may occur in biological materials. The heating effects have been extensively studied, documented, and served as the foundation for therapeutic treatment in physical medicine and rehabilitation, in minimally invasive ablative interventions in cardiology and oncology, and in the use of microwave oven for heating and cooking food stuff.

The unique microwave auditory effect has been widely recognized as one of the most interesting and significant biological phenomena from microwave exposure. Its potential applications are just now beginning to be seriously explored. In contrast to heating using high average-power CW microwaves in the medical applications and industrial microwave heating, drying, and curing process described above, the report of microwave auditory effect was striking since it occurred for exposures to very low average-power levels of pulsed microwave radiation [Lin, 1978, 1980, 1990; Chou et al., 1982; Elder and Chou, 2003; Lin and Wang, 2007].

The microwave auditory effect is defined as the auditory perception of microwave radiation or simply hearing microwaves. This definition may seem surprising, and one might even question whether such sensation could exist. It is indeed a unique exception to the acoustic energy normally encountered by humans in auditory perception of sound. Although mammalian hearing apparatus responds to acoustic or sound pressure waves in the audio-frequency range of 0 to 20 kHz for humans, which could be up to 35 kHz or higher for some animals (cats and rats for example), frequencies above 35 kHz are considered as ultrasound for humans (beyond the range of audible frequencies). The hearing of microwave pulses involved electromagnetic waves whose frequency are much higher, ranging from 300 MHz to tens of gigahertz (GHz). Since electromagnetic waves (such as sun lights and optical radiation) are seen but not heard, the report of auditory sensation of microwave pulses was quite surprising, and initially its authenticity was widely questioned.

The earliest reports of the auditory perception of microwave pulses were provided anecdotally by radar operators during World War II [Airborne Instruments Laboratory, 1956]. They described an audible sound, a zip, click, or buzz that occurred at the repetition rate of radar when standing in front of radar antennas. These reports of the microwave auditory effect were initially documented in a technical report, in which several persons who had reported the sensation were interviewed and tested under field conditions [Frey, 1961]. It had been hypothesized that the microwave auditory effect involved direct electrical stimulation of the cochlear nerves or neurons at more central sites along the auditory nervous system pathway. However, skepticism of the microwave auditory effect and a responsible mechanism of interaction remained obscure for more than a decade.

Research conducted since has shown that a cascade of events take place when a beam of microwave pulses is aimed at a human or animal subject's head [Guy et al., 1975; Lin, 1978, 1980, 1990; Elder and Chou, 2003; Lin and Wang, 2007].

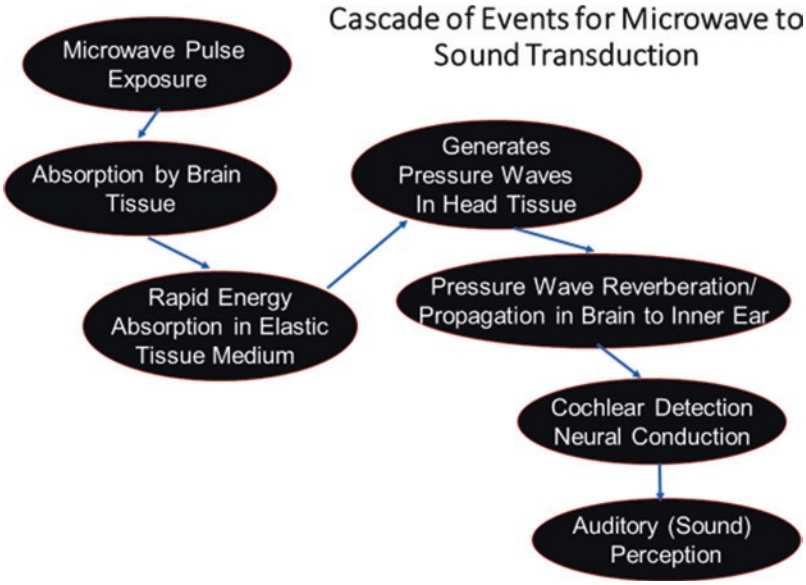

Fig. 1.2 The cascade of events illustrating the thermoelastic theory of auditory perception of pulsed microwaves

Absorption of pulsed microwave energy creates a rapid expansion of brain matter and launches an acoustic wave of pressure that travels inside the head to the inner ear. There, it activates the nerve cells in the cochlea, and the neural signals are then relayed through the central auditory system to the cerebral cortex for perception (Fig. 1.2). The center frequency of microwave pulse-induced acoustic pressure wave is about 8 kHz for human adults – well within the range of human auditory response.

However, if the average power and intensity of the impinging pulsed microwave is sufficiently high, the level of induced sound pressure could be considerably above the threshold of human auditory perception – to approaching or exceeding levels of discomfort and even causing potential brain tissue injury including structures in the cerebrum and cerebellum. It is significant to note that the microwave pulses may be targeted remotely, so that only the intended subject would perceive the microwave pulse-generated sound in the subject's head.

1.4 A Diplomatic Affair – the Havana Syndrome

It is interesting to note the US State Department disclosure that Havana-based US diplomats were experiencing health issues associated with hearing loud buzzing or what was described as bursts of sound in 2017 [Gearan, 2017; Harris and Goldman, 2017]. A similar announcement was made by the Government of Canada. Staff of both embassies had reported symptoms of hearing loss, ringing in the ears, headaches, nausea, and problems with balance or vertigo, which are suggestive of a connection to the inner ear apparatus within the human head.

Government officials had difficulty to pin down the source of sound. There were speculations that the diplomats may have been attacked with an advanced sound weapon. Assuming reported accounts are reliable, there may be a scientific explanation. It is plausible that the loud buzzing, burst of sound, or acoustic pressure waves could have been covertly delivered using high-power pulsed microwave radiation, rather than blasting the subjects with conventional sonic sources [Lin, 2017, 2018]. Many have come to believe that the microwave auditory effect – induced by a targeted beam of high peak-power pulsed microwave radiation – may be the most likely scientific explanation for the sonic attack [Best, 2017; Hambling, 2017; Hignett, 2017; Broad, 2018; Deng, 2018]. Of course, until the truth is revealed, this specific matter will remain somewhat of a mystery.

It is well known that robust audible sound could damage hearing and vestibular sensory systems and can alter human emotions and moods. However, it is not clear whether a weapon that covertly uses sonic energy to injure people exists today. Nonetheless, this event is calling attention to the reality that pulsed microwave radiation-induced sonic pressure waves in human heads could potentially be weaponized for health attacks. Furthermore, the required technology is mature and for the most part, commercially available or readily adaptable from existing microwave radar systems. However, existing hardware may need to be optimized to meet some specific requirements in specific operations including adaptive beam formation, steering, and focusing. Nevertheless, they can be used in nonlethal mode to transmit targeted messages, to cause task disruption and personnel disorientation, and even to apply the microwave auditory effect remotely as a lethal or nonlethal weapon. Additional discussions on this topic which is being referred to as the Havana Syndrome are included in Chap. 10.

1.5 Organizing Principles of the Book

The objective of this book is to bring together in a comprehensive book the multidisciplinary research investigation leading to a scientific understanding of the microwave auditory effect and related applications, especially the emerging microwave thermoacoustic tomography (MTT) imaging modality. The analysis and discussions in the chapters of this book pertain to relevant physical laws, exposure and dosimetry, anatomy and physiology, psychophysics and behavior, theories and models, mechanisms of interaction, computer analysis and simulation, applications in biology and medicine, and other applied aspects. Another purpose of this volume is to expand and update existing knowledge and understanding of microwave auditory effects and applications, which was the title of an earlier research monograph [Lin, 1978]. Considerable amount of scientific knowledge, data, and information have been generated since then through theoretical study, laboratory experimentation, numerical analysis, and computer modeling.

As this may be the reader's first encounter to the subject material, and since the treatment is multidisciplinary, after the Introduction, the four chapters that follow each begins with basic background information that may appear as elementary to some readers but is essential to understanding the discussions on microwave auditory effect and applications for those from a different discipline. There is a chapter on principles of microwave and RF exposure and one on brain anatomy and auditory physiology. The succeeding two chapters present the microwave property of biological materials and its influence on dosimetry and microwave absorption in biological tissues. They are intended to facilitate a fuller understanding of discussions in the ensuring five chapters about microwave auditory effect and applications.

An extensive list of references is provided in this book at the end of each chapter to furnish the knowledge base, to put the materials in proper perspective, and to overcome potential misunderstanding. The guiding principles throughout the book are that any description or conclusion must be consistent and compatible with physical laws, biological evidence, and experimental observations based on laboratory data and findings.

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Chapter 2
Principles of Microwave and RF Exposure

The physical fundamentals of microwave and RF radiation are presented in this chapter for an understanding of the essential elements of exposure of biological systems to RF and microwave radiation. These exposures are functions of the source frequency and configuration, shape and size of the exposed subjects, and orientation and location of the subject with respect to the source, among others.

The approach of this chapter is to develop but confine the coverage to the most relevant topics, rather than a comprehensive discussion of bioelectromagnetics describable by physical laws of electromagnetic theory. The reader who is interested in a broader physical and engineering account of microwave and RF radiation is referred to some readily available texts devoted entirely to the subject of electromagnetics and microwave engineering.

An understanding of the interaction of microwave and RF radiation with biological systems is facilitated through knowledge of the physical laws describing the behavior and characteristics of microwave and RF radiation in space and time. The physical principles of microwave and RF radiation are prescribed by physical laws referred to as the Maxwell's equations of electromagnetics theory. These equations represent mathematical expressions of experimentally validated observations. They are applicable for linear or nonlinear, isotropic or anisotropic, and homogeneous or heterogeneous medium. Maxwell's equations are macroscopic laws that define the relationship between space- and time-averaged electric and magnetic fields. They apply to regions or volumes whose dimensions are larger than atomic dimensions. Time intervals of observation are assumed to be long enough to allow for an averaging of atomic fluctuations.

From these four laws of electromagnetics, one may deduce all macroscopic electromagnetic characteristics and behavior including microwave and RF propagation from source to target or object, exposure of biological subjects, reflection and transmission at tissue interfaces, and dosimetry – the quantification of microwave and RF radiation's distribution and absorption in biological bodies and materials. This knowledge is important for understanding and interpretation of the effects in

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biological systems exposed to microwave and RF radiation as well as to applying them for health and safety assessment and for biomedical applications.

Microwave and RF radiation consists of oscillating electric and magnetic fields propagating through free space at the speed of light, 2.998×10^8 m/s. This speed varies depending on the material medium through which the wave travels. It is a function of the permittivity and permeability of the material media. In addition to being radiated through a transmitting antenna, microwave and RF radiation also may be conducted from the source by coaxial transmission lines or waveguides. Microwave and RF radiation may be detected and measured by diodes or similar devices and their associated instruments and systems.

2.1 The Maxwell Equations

Maxwell's four mathematical equations may be stated in either integral or differential equation form. Each formulation provides a unique description of electromagnetic radiation in space. In integral forms, they specify them along lines, through surfaces and over volumes, and lend the equations to easy physical interpretation. In contrast, the differential equations depict their behavior at points in space. These formulations are mathematically equivalent since they may be derived from each other using Stokes' and divergence theorems from vector analysis.

The integral forms of Maxwell's equations are given by

$$\oint \boldsymbol{E} \cdot \boldsymbol{dl} = -\int_s \frac{\partial \boldsymbol{B}}{\partial t} \cdot \boldsymbol{ds} \quad \left(\text{Faraday's law}\right) \tag{2.1}$$

$$\oint \boldsymbol{H} \cdot \boldsymbol{dl} = \int_s \left(\boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \right) \cdot \boldsymbol{ds} \left(\text{Ampere-Maxwell's law}\right) \tag{2.2}$$

$$\oint \boldsymbol{D} \cdot \boldsymbol{ds} = \int_v \rho dv \left(\text{Gauss electric law}\right) \tag{2.3}$$

$$\oint \boldsymbol{B} \cdot \boldsymbol{ds} = 0 \left(\text{Gauss magnetic law}\right) \tag{2.4}$$

where

E = Electric field strength in volt/meter (V/m)
H = Magnetic field strength in ampere/meter (A/m)
D = Electric flux density in coulomb/square meter (C/m^2)
B = Magnetic flux density in weber/square meter (Wb/m^2)
J = Conduction current density in ampere/square meter (A/m^2)
ρ = Charge density in coulomb/cubic meter (C/m^3)

According to Faraday's law (2.1), the total voltage induced in an arbitrary closed path is equal to the total time rate of decrease of magnetic flux through the area