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Applications of Electromagnetic Waves in Medical Imaging and Biological Systems

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Annotation: Electromagnetic waves (EMWs) play a crucial role in advancing medical imaging and therapeutic applications, offering non-invasive and accurate diagnostic solutions. However, despite their wide adoption, a knowledge gap persists in fully understanding the interaction mechanisms between EMWs and biological tissues, especially in emerging imaging modalities. This article reviews the principles and recent advancements in electromagnetic-based imaging techniques, including MRI, CT, ultrasound, microwave imaging, photoacoustic imaging, and terahertz imaging. The study also examines the therapeutic potentials of EMWs, such as in hyperthermia, magnetic field therapy, and radiation therapy. Findings highlight that EM-based technologies significantly enhance spatial resolution, real-time imaging capabilities, and diagnostic accuracy while reducing patient risk compared to ionizing radiation methods. Nevertheless, challenges related to safety standards, exposure limits, and optimization of

EMW-tissue interaction remain. The results suggest that interdisciplinary research integrating physics, biomedical engineering, and AI will be essential to unlock the full potential of EM-based medical applications.

Keywords: electromagnetic waves, medical imaging, biological systems, MRI, CT, photoacoustic imaging, terahertz imaging, therapeutic applications, safety guidelines.

1. Introduction to Electromagnetic Waves

Electromagnetic waves or optical radiation encompasses a great deal of the electromagnetic wave spectrum. The electromagnetic spectrum as known conventionally covers wave frequencies down to around 300 GHz at the very lowest (longest wavelengths) up to X-rays and beyond. That diverse span encompasses radio waves, microwave radiation, millimeter waves, visible light, and UV radiation, among others. However, electromagnetic radiation used in research on biological effects of non-ionizing radiation, there will be drawn a line in the spectrum well before the threshold where ionization of molecules and matter generally starts to occur. That means a cut-off well before the start of the spectrum for ionizing radiation such as UV, where individual photons have more energy than typical chemical bonds.

Medical imaging is the technique and process used to create images of the human body (or parts and function thereof) for clinical purposes or medical science. Traditionally it is a branch of statics, where the use of specific established technologies and techniques are relied on for optimal results. Electromagnetic imaging, using photons in the electromagnetic radiation spectrum, forms much of modern medical imaging practice. The modalities in a clinical setting are generally complex, expensive and usually require a dedicated imaging suite and the interpretation of images by a radiologist or nuclear medicine specialist. However, it is this bracket of imaging where much of the ongoing research and application development are currently focused. Smaller, simpler and cheaper alternatives are being produced for low-resource communities, developing nations and for more widespread general population use. B-mode or brightness mode (2D) ultrasound imaging is a well-established technique used for diagnostic and interventional objectives. It is widely used but can render indistinct structures as it is influenced greatly by the skill and experience of the operator, especially for inexperienced physicians. Open access non-contact medical imaging in microwave frequencies using radar systems shows promise as a means to image the interior of the body in much the same way as conventional ultrasound. Optics and photonics has, however commonly included elastic (back) scattering such as in optical coherence tomography and diffuse optical tomography. These techniques use near-infrared light for non-invasive imaging and currently offers the highest spatial resolution of all the techniques listed. Bio-photoacoustic imaging combines the high spatial qualities of optical imaging and the deep penetration of acoustic imaging. Consequently, the technique uses pulsed laser light to heat absorbent elements within tissue. Specialists working within the fields of microwave and millimetre wave technology may be interested in adopting the term ‘optical radiation’, and using it to refer to their area of work only.

Electromagnetic waves are patterns, or waves, of electromagnetic fields as they travel through space. Changes in the electromagnetic fields mutually cause each other, and those fields permeate through the environment. There is a great deal of literature about the possible effects of quite specific, simple, sources of electromagnetic fields, such as mobile phone base stations or handsets, televisions or overhead power lines, just to name a few. Modern imaging techniques have played a significant role in how the body and biology can be observed. These radars are consistent with ultrasound, an established non-ionizing imaging technique, generating high spatial resolution pictures. The early development and results of a pilot UWB RADAR imaging system are provided, offering a qualitative understanding of the feasibility of non-contact, wide bandwidth, medical imaging systems, and the possibilities they offer for 'whole-body', high resolution imaging. [1][2][3]

2. Fundamentals of Electromagnetic Theory

2.1 Maxwell's Equations James Clerk Maxwell summarized the experimental laws of electricity and magnetism with 20 equations in 1865. The 4-vector formulation of these four basic equations came much later. The general case of these four 4 coupled partial differential equations in 8 variables may look monstrously complex. For such, we have five more restricted cases: (1) stationary currents and charges, (2) no charge, (3) no current, (4) steady fields, and (5) no linear and nonlinear materials, where less number of coupled partial differential equations remain to take the form for practicing EMC/EMI/EMCAD engineers with fair simplicity.

2.2 Faraday's Law of Electromagnetic Induction Uniform magnetic field in coil results in voltage, $E = -\partial\varphi / \partial t$ as the magnetic field is turned on or off for transformer's action. In Maxwell form, (1) the curl of the induced electric field ($-\partial\Phi B/\partial t$) is equal to minus the time rate of change of the magnitude of the magnetic flux through the area is the curl of $E = -\partial B/\partial t$. Basically, the pair of curls forms Kirchhoff's voltage law.

2.3 Displacement Current This is the concept introduced by Maxwell, a quantity something like electric current required to maintain electrostatic conditions for electric field. Displacement current is due to second Maxwell's equation, the Curl[H] = dD/dt and is a type of conduction current flow. This is because time-varying electric field changes the vector of electric flux density, D. The displacement current encapsulates the principle of conservation of electric charge, like in steady electric currents simplicity of electrical power, conservation of charge states the details of current path in a circuit.

2.4 Amperes Circuital Law In Maxwell form, the Circulation of the magnetic field and the current enclosed by the path leads to a basic invitation in electromagnetic theory, that is, the introduction of a curl relation between the electric field E about a surface and the rate of change of the magnetic field B through the surface.

2.5 Picture of EM Wave Propagation Putting all the Maxwell's equations together, the self-consistency of the electromagnetic theory shows that the tight coupling of electric and magnetic fields satisfies first any two of the equations. Then, take a step farther to look closely at the structure of free space: $D = \varepsilon E$ and $B = \mu H$ and $k = \omega\varepsilon\mu = 2\pi/\lambda$ lead to the essential insight into three forms of source free Maxwell's equations, showing the space uniformly treated in this respect.

2.6 Properties of Materials Free space (another name for vacuum where light propagates) is not the same as various media. One fundamentally important property is the permittivity or the magnetic permeability. If these two are constants, Fourier solutions can be obtained. It also gives a kind of dispersion relationship and phase velocity. When ε and μ are very frequency dependent such as in dielectrics and semiconductors, Maxwell's equations may not be analytically solvable and computer aided numerical solution of differential equations can be underway. Different common materials show vastly distinct polarization mechanisms resulting in diverse frequency dispersions. Between metals and dielectrics lies the mediums with frequency dependent conductivity, important in EMC/EMI design challenge. [4][5]

3. Medical Imaging Techniques

Medical imaging techniques have been around for a few decades already. Traditional techniques, like X-rays and ultrasound, have been used since the early 1900s, whereas more recent methods have emerged over the past 30-40 years. Different modalities have different advantages and applications. For example, CT scans are considered to be good at representing high-resolution images of high-density objects, like bone and metal, yet they deliver high doses of radiation. They also require patients to lie still for long periods of time. MRI scans are said to yield high-resolution, detailed images of soft tissue, such as organs, but they take a considerable amount of time to obtain those images. They also tend to be very expensive, both to buy and to operate. The cost arises from the necessity of powerful magnets, in which helium must be constantly cooled to superconducting temperatures. MRIs are also much louder and more claustrophobic compared to other imaging methods, as they use large, noisy magnets in small, enclosed spaces. However, all those techniques are non-invasive and can produce structural images of the interior of a subject. Many medical imaging applications would benefit from the availability of a modality that can produce contrast from endogenous biological parameters that provides functional as well as structural information. Electromagnetic imaging techniques would be especially useful for this purpose, as a wide range of measurement modalities exist, that interrogate different electrical properties of a subject through the application of electromagnetic fields. Furthermore, the high speed at which electromagnetic fields can propagate make it possible to produce tomographic images that change in real-time. There are three primary parameters that the aforementioned techniques tend to measure: permittivity, conductivity and (occasionally) magnetic permeability [6].

3.1. X-ray Imaging

The first modern medical imaging technique that used electromagnetic waves was X-ray imaging. X-rays are a form of electromagnetic radiation with wavelengths that range from about 10 nm to 10 picometers. They can pass through many solid objects, including the human body. The higher the density of the material, the less the X-ray can pass through, so a photographic film or digital sensor beyond the object can form an image of shadows, like a photograph of shadows. Although this imaging technique is harmful – it can damage cells and cause cancer – here the benefits – mainly that it can be used to see what is inside opaque objects – out-weigh the harms. Because only objects of high density can be seen in an X-ray image, typically only bones are seen in an X-ray image of the human body. Three major types of X-ray imaging are widely used: simple radiography, mammography, and fluoroscopy. All of these use a focused X-ray source that stays on more or less constantly while a film, a digital detector, or a fluorescent screen captures the image. The images are typically black-and-white or shades of gray. The most recent and advanced type of X-ray computed tomography scanning system, on the other hand, uses a very large and very expensive apparatus that moves slowly around the patient to create a sequence of cross-sectional images that can be reconstructed into a 3D image viewable from any angle. CT scans can also use other types of electromagnetic waves besides X-rays, in particular, microwaves and radio waves. CT scans are used to diagnose and monitor the progression of cancer, heart disease, joint and musculoskeletal disease, cerebrovascular accidents, and other conditions. They can also image internal injuries to bones and internal organs more readily than simple X-ray imaging techniques. [1][7][8]

3.2. Magnetic Resonance Imaging (MRI)

Medical studies on all different kinds of systems and their dynamic processes constitute a profoundly important part of scientific research. Electromagnetic radiation has been commonly used as a non-invasive analytical technique in many studies involving different biological and biomedical systems. The science and techniques of magnetic resonance imaging (MRI) is one of the most powerful tools and has very appropriate applications. Also the results of researches and experiments in various activities of MRI in two fields including medical imaging and biological systems is discussed and illustrated.

Medical imaging is an important technique for detecting any abnormalities in the human body system. There are a number of techniques for the imaging purposes but the most major techniques includes MRI. MRI imaging is a technically sophisticated and expensive imaging modality that provides detailed 2-D and 3-D images of the body. It is a safe and noninvasive diagnostic technology, offering unparalleled detail of soft biological tissues- such as the brain, spinal cord, and other internal organs without the need for using damaging ionizing radiation. Therefore, it was viewed as an attractive choice to improve defect imaging in specialized industrial applications. Unfortunately this technique almost requires extreme of the experimental setup to be possible. Initially, it suffers from the extremely low imaging speed taking a number of minutes to an hour to construct a single frame. This is often not practical for industrial application where the system must be re-tasked relatively quickly. Moreover, these imaging devices are typically fixed systems, requiring the positioning of the material to be imaged in the bore of a large magnet assembly. A number of approaches have been tested to allow NMR measurements outside of the bore of the magnet, but the signal strength takes a tremendous hit, and the achievable image resolution is so poor as to render this approach unfeasible. On the other hand, a group of current carrying conductors, or coils, that can produce a predominantly homogeneous time varying magnetic field will generate a predominantly homogeneous magnetic field. This can be used to stimulate a response signal in a sample. Such a device is typically an assembly known as an NMR solenoid. It is clear that these coils can be design and deployed in a very compact fashion and a number of systems prove this. With this design, high power rf signal can be transmitted and a strong inductive signal could be received at the expense of the depth of penetration. [1][9][10]

3.3. Computed Tomography (CT)

Computed tomography (CT) is another standard clinical imaging modality. Although progress has been made in enhancing the quality of Magnetic Resonance and Ultrasound imaging, CT remains the ‘gold standard’ for certain procedures, in particular, analysis of bone pathology. However, the resolution of an emitted spectrally dense X-Ray signal from the inside of a body is primarily influenced by attenuation, and contrast suffers from the absorption coefficient not being a ‘normal’ parameter [11]. For these reasons, current Transmission Tomography Modalities require significant and continuous exposure to ionising radiation, hence real-time dynamic CT would be neither safe nor feasible. CT has become an indispensable tool to diagnose health problems throughout the human body, and it is used to study the anatomy, shape and location of structures inside the body and is able to provide an accurate and comprehensive view. CT also can overcome the overlearning problem compared to Adaptive-KNN algorithm.

Generally, advanced research focuses on developing efficient, robust, and automatic cancer detection methods in mammogram images. Due to its complex texture and weak pattern, mammogram analysis is a challenging task. Consequently, most modern image processing methods are used in conjunction with classical learning techniques to improve classification accuracy and sensitivity. In [ref: AHA + 10], the concept of Artificial Adaptive Immune Support Vector Machine (AAISVM) is developed, and the feature level fusion method is used to identify the abnormality in pathological chest X-ray images. An abnormality detection system is proposed with a texture feature descriptor using the Bilodeau Space. The feature performed best with a combined detector based on Ostus multi-thresholding, and an extensive experiment shows the robustness of the system. With more complex texture modeling and a robust learning system, a reader-aided cancer detection system can be created to alleviate unnecessary mammograms. This model reliably determines mammogram abnormalities with high sensitivity without compromising specificity or detection time, without expert skills of radiologists. The holistic experimental results demonstrate its potential for early cancer detection or prediction. [12][13]

3.4. Ultrasound Imaging

Electromagnetic Waves are everywhere hence. It is very important to control them or use them for specific purposes. This paper discusses various studies on the applications of electromagnetic waves in different areas such as medical imaging, friction analysis of an engine, mobile robotics systems, industrial monitoring systems and thermography. The extraction of the frequency-dependent electrical characteristics of biological tissues from 1 GHz to 2 GHz using ultra-wideband (UWB) electromagnetic pulses is discussed. The microwave propagation is observed focusing on the interaction of UWB pulses and human arms, and it is revealed that the UWB pulses propagate across soft and adipose tissues. Prior to the use of the UWB pulses for medical checkups or treatment, it is important to investigate the biological characteristics. It provides qualitative data about frequency-dependent electrical characteristics such as permittivity and conductivity of the biological tissues, especially in the frequency range of 1 GHz to 2 GHz. [6] Other important studies are also discussed. Ultrasonic imaging has become a useful medical imaging tool. Among them, studies on noninvasive imaging or sensing are becoming important from the medical and health-care view points. Here, the microwave sensing by using electromagnetic waves is reported, concerning the cavity and attenuation methods. The former method is to observe the cavity mode frequency in a metallic chamber filled with a phantom, which is composed of a plastic bag containing the chicken heart. The latter method is proposed and validated to achieve a noninvasive control of blood temperature. The variations in the temperature-related physiological parameters and the blood temperature can be obtained by observing the peak frequency of the phantom filling the cup-shaped insertion in the heated chicken sample. The applications of a knowledge-based educational system (KBES) designed for the modeling and the analysis of biological systems are discussed. The system is composed of two blocks: one deals with the mathematical modeling of the analyzed phenomena and it is based on the use of a commercially available FDTD-based code; the other performs the prediction based on different commercial or FDTD homemade codes. The potentiality of the KBES system is shown on text and explained by means of examples. [14] There are other recent and important works in the area of the applications of electromagnetic waves in medical imaging and biological systems.

3.5. Positron Emission Tomography (PET)

The field of nuclear is rapidly progressing in the present era. In nuclear medicine, PET has become increasingly popular because of its potential to give insight into in vivo biological processes. There are several significant advances in the detectors, electronics, and iterative reconstruction algorithms that have allowed PET to image radiotracer activity in the body with quantitative accuracy. As a result, biological scientists and physicians are being provided with detailed information about a range of biological systems that can include cerebral blood flow, glucose metabolism, receptor concentrations, cellular proliferation, and gene expression, among others [15]. This is important because these biomarkers are well-defined indicators of tissues in various states of health and disease. Further, the ability to monitor these biological systems can also be used to optimize, gauge, and stratify therapeutic interventions. Subsequently, these tools and insights into pathophysiological processes will likely revolutionize the practice of medicine.

Positron Emission Tomography is a nuclear medicine imaging modality for detecting distribution of a radiotracer in the body. Radiotracer isotope typically has a relatively short half-life, on the order of seconds to hours. Positron-emitting isotopes like 18F, 11C, 13N, and 15O are used in PET because of their decay mechanism. Radiotracers are molecules labeled with positron-emitting isotopes tagged to a biologically relevant carrier molecule. Positrons are emitted from the radiotracer and travel a short distance through tissue, losing kinetic energy primarily through coulomb interactions with orbital electrons to form positronium. As positrons continue to travel, they ultimately experience low energy annihilation with tissue electrons that releases two coincident 511-keV photons that move in opposite directions (180°). The 511-keV photons are detected by detectors in the PET camera that are in coincidence.

4. Role of Electromagnetic Waves in Medical Diagnostics

In the past years, there has been an increased exposure of the general population to electromagnetic fields (EMF) due to the intensive use of electrical appliances and the deployment in the environment of electrical systems, radio and TV transmitters or other sources.

In addition, a number of medical applications for both diagnosis and therapy rely on different parts of the non-ionizing part of the electromagnetic (EM) spectrum. Non-ionizing radiation refers to electromagnetic fields (EMF) with frequencies from 0 Hz up to 3.0 PHz, such as AM radio broadcasting at about 1 MHz, microwave ovens at the industrial frequency of about 2.45 GHz, mobile communications at e.g. 450 MHz or 1.8 GHz, the infrared radiation, the ultraviolet (UV) fluorescent lamps or lasers.

This review will deal specifically with the frequency range from 0 Hz to 10 THz (corresponding to vacuum wavelengths from kilometers to millimeters). The main focus is on emerging uses and corresponding exposure situations. Some applications in this part of the frequency spectrum are well established. An example is magnetic resonance imaging (MRI), which employs static magnetic fields, gradient magnetic fields and radiofrequency electromagnetic fields (RF). Also, laser surgery and laser therapy at visible or ultraviolet (UV) wavelengths are well known applications [16]. There are also applications serving as complements to more established diagnostic or therapeutic tools, such as electrosurgery and diathermy. More recently, other applications, like the stimulation of the vagus nerve to treat epilepsy, are increasingly accepted in a clinical setting. Finally, there are applications which are emerging or at the edge of becoming a practical tool. All these applications could involve patients exposed in a frequency range which is not well covered by the current guidelines nor by many standards. As a consequence, the exposure to the field in the frequency range of interest should not cause damaging effects either to the patient or the operator of the medical device. To assure safe exposures, exposure guidelines have been developed and are regularly revised based on the available scientific knowledge, albeit with a focus on the parts of the EM spectrum where most of the concern about exposure from common sources has arisen. [17][18][19]

4.1. Detection of Tumors

One important thing to consider is the specular reflection from a flat impedance boundary, such as the skin bounding the outer surface of the breast. Another choice of coupling medium could be a mixture of agar with sufficient water content. Refinement in obtaining patient specific relevant results require the use of patients real skin model. This is because the chest is a muscle surrounded by fat, which surrounds the skin. For the 3D microwave imaging inverse scattering results obtained, a high level of absorption is observed in the chest. This is important because any microwave energy that is absorbed causes a heat rise. In this region it is not possible to use proportional boiling water to represent the skin.

The detection, diagnosis and treatment of cancer is a significant worldwide problem. For many cancer forms, treatment is only successful if the cancer is detected and treated in its early stages. For breast cancer, the principal initial detection method is mammography. The study shows that early-stage breast cancer tumor detection is feasible with ultrawideband microwave imaging, without the need for a hip reference. The capacity to detect invasive regions of tumor uniformly surpasses the sensitivity of conventional non-ultrawideband narrow bandwidth microwave imaging systems. Finally, retrospective evaluation of the pulse profile at each antenna measurement exhibits interesting tumor-specific behavior that may guide the development of more sophisticated microwave imaging schemes. [20][21][22]

4.2. Cardiovascular Imaging

Fast diagnostic and therapeutic decisions are essential to reduce the morbidity and mortality of the patient. Knowledge of the hemodynamic changes of the patient is key in the treatment of critical cases. The successful treatment requires continuous monitoring together with a fast diagnostic tool for timely therapy. Images provided by modalities like magnetic resonance imaging (MRI) and computed tomography angiography (CTA) can be used to detect and locate hemorrhages, blockages, or aneurysms, and diagnose stroke type. However, these images take several minutes to acquire and are only available in bulky and immobile systems [23].

Temporal resolution is a significant drawback for current body imaging methods. None of the mentioned imaging modalities possess a high-speed function that images significant geographic areas of the body (such as one entire hemisphere of the brain which is vital for stroke diagnosis;). Recent advancements in conductivity and permittivity sensing and imaging made the detection capability of vessel related experiments and images on vascular matters possible in the microwave spectrum. A new method for the detection of coronary artery diseases and thrombosis formation is provided which may revolutionize both bio-sensor application areas, and understanding of various cardiovascular circulatory diseases and their relationship to suffered myocardial infarction and ischemic strokes.

There are only observations of the received signal level. Vascular abstraction relevant for body imaging such as diameter, shape, and branch points of the vascular is not covered here, and this should not be considered as vital signs of the brain. Prior works do imaging the frequency-dielectric properties of the human brain, to the extent of the cerebral cortex. It is detected that this outshines the vascular signal there from intracranial bleeding. This proximity effect means the bleeding signal shall not be available to emerging UWB helmet based health monitoring devices intending to sense heartbeat and respiration related signals.

4.3. Neuroimaging

More recently, advances in microtechnology have enabled the fabrication of ultrasound-based systems, which are capable of performing absorption and phase angle spectroscopy in living tissues. In this study, an ultra-wideband (UWB) electromagnetic pulse could be used to measure both the transmission and reflection coefficients of non-invasive tissue samples across a frequency range from 5 GHz to 11 GHz. The electromagnetic response of these samples is extracted and visualized as a complex permittivity and conductivity. Previous electromagnetic measurements have been limited to transmission measurements with single reflection measurements taken. An apparatus for multiple reflection coefficient measurements across a frequency range from 800MHz to 3GHz has been developed and verified. Iteratively retrieved complex permittivity and conductivity results of a sample showing a large dielectric contrast are presented. Similarly, an experimentally validated microwave breast model was used to illustrate the effects of transmitting in biological tissues which have low dispersion and absorption across a range of frequencies from 1GHz to 5GHz. It should be noted that most biological tissues have a dielectric constant $\varepsilon r < 50$ and simultaneously low conductivity $\sigma < 0.1$ S/m at UWB frequencies used in radar and 5G applications [6]. Bio-electromagnetic simulations above 1 GHz frequency range are computationally extensive, with permission schemes for computational phantoms using complex anatomical details, intractable with conventional numerical solvers at UWB frequencies. The open-source electromagnetic solver described herein is capable of performing incredibly detailed electromagnetic simulations directly into real-patient images without requiring simplification or abstraction. Anatomical complexities of real patient anatomy and pathology can be included in the simulation model.

5. Therapeutic Applications of Electromagnetic Waves

Therapeutic applications of the electromagnetic spectrum range from combined high intensity fields/heat used for arterial and other tumour ablation to ambulatory low-intensity fields in which bio-active windows are searched, including wound healing. Here only a small proportion of the potential biological effects for research labs are outlined: cell differentiation, bone repair using sponges that trigger bone grow substance showers, aural healing, atherosertosis and clot inhibition, and target-heat therapy. Some of these applications are macroscopic and safety related, and others are microscopic, needing addressable control and expanding bio-tech to nano-tech convergence [16]. An example of macroscopic safety is that tiny blood bourne magnetic nano-parks may cause micro-strokes with strong magnetic field gradients at vessels walls - power-lines and MR, unless placed under magnetic windows.

Doctors in the future may of course perform surgery, but in the eighteenth century surgery was not a respectable way of solving a medical problem, and more importantly there will be many more non-invasive and non-penetrating ways to diagnose and treat diseases. Waves and quantum mechanics found applications in modern physics, and postmodern medicine may take biological tissue waves and the corresponding QM approaches to model cells. Broadband sound ensures continuity to the last millennium kitchen-hearthy, and it is common tool in modern hospitals, but high-resolution medical imaging and therapies are predominantly based on high frequency waves. Some methods are advantageous for medical, but not for kitchen or industrial purposes. Millimetre wave, penetrating a water layer, used in the kitchen for drying, is very important for medical diagnostics of biological water. In vivo measurements, conducted at ambient temperature are not disturbed by an intentional water layer around ex vivo samples at mild hyperthermia temperature, i.e. medical sterilization and therapy. Optical coherent, used for music CD players, instead of as a medical monitoring and treatment tool for cardiovascular diagnostics.

5.1. Radiation Therapy

1. Medical Applications of Non-Ionizing Electromagnetic Waves A number of medical applications for both diagnosis and therapy rely on different parts of the non-ionizing part of the electromagnetic (EM) spectrum. The non-ionizing radiation (NIR) refers to the electromagnetic fields (EMFs) with frequencies from 0 Hz up to 3.0 PHz. Although medical applications are found among all these frequencies, this review deals specifically with the frequency range from 0 Hz to 10 THz. Some of the applications that have an origin in this part of the frequency spectrum are well established and are based on mechanisms of action that are well understood. They include, for example, ultrasound imaging and therapeutic applications, and magnetic resonance imaging (MRI). Several technologies for the medical use of NIR are widely known but less common. There are, however, also applications that are less well known or currently practiced only by few specialists. On the contrary, other applications are developed or used in practice, but efficacy and safety remain a concern. Examples of such applications are laser surgery and the therapeutic use of high-intensity electromagnetic fields such as diathermy and deep brain stimulation by weaker EMFs of this kind. Technologies recently used in medicine include microwave ablation, cryosurgery and transcranial magnetic stimulation (TMS). A general concern with many of these technologies is the uncertainty or lack of understanding of the mechanism of action and the potential risks. To ensure desired effects and safe medical applications, it may be necessary to better understand the interaction of complex EMFs in this frequency range with biological systems [16]. Factors contributing to such interactions include field exposure parameters, temperature increase, absorption in biological bodies, and subsequent effects of this absorption, such as alteration of cellular functions. 2. Imaging in Medical Practices Medical imaging is an essential component of both diagnosis and treatment planning, and recent patient-specific 3D imaging modalities could improve the identification of source and cycle of pain, as well as overall treatment outcomes. The use of ionizing radiation has undergone extraordinary development during the past century. Concerns about ionizing radiation exposure have motivated research towards the use of non-ionizing radiation at various frequencies. Non-ionizing radiation is much lower in energy than ionizing radiation and, as such, unable to detach the electrons from at least monoatomic molecules or atoms, to produce ions. Nonionizing radiation lies in the electromagnetic spectrum with a frequency or wavelength greater than that of the ultraviolet light, including terahertz, infrared, visible light, laser light, dim light, microwave, terahertz radiation, and radiowaves. On the other hand, the magnetic scans were classified in the non-ionizing radiation category. Consequently, imaging solutions compelled to combat the lack of ionizing radiation in this new domain. Traditional films, in both the digital and non-digital systems, however, inappropriate for the new domain, as they respond effectively to ionizing radiation in the range of several tens of kiloelectron volts. Instead, the present guideline discusses solutions adapted for the electromagnetic spectrum - e.g., optical devices such as CCD cameras, and devices suitable for the mid and far-infrared. These recommendations address the potential dangers of imaging (including imaging modalities and ionizing radiation)

and therapy of certain frequencies of non-ionizing electromagnetic radiation, as well as some safety issues in magnetic imaging resonance.

5.2. Magnetic Field Therapy

The idea of using bioelectromagnetism as a part of medical treatment has a long history. Despite this, it is only in recent years that significant theoretical as well as experimental progress has been made. Mechanisms of interaction of electromagnetic fields with animals and humans are complex. The most often mentioned mechanisms are: neural stimulation by induced electric currents, vibration of excitable membranes by electric or magnetic fields, inverse piezoelectric effect, and magnetic particles' motion along with used magnetic fields. In both medicine and biology, there are many applications of electromagnetic fields that are used. Magnetic fields find many applications, both in medical diagnostics and in the treatment. These issues are discussed here.

The magnetic field therapy is mainly used for rheumatic disorders, to decrease joint pain, muscle tension and migraine. There exist different variations in the magnetic field therapy, including the use of induced electric currents (magnetostimulation). The frequency of induced currents is in this case in the range of 5–10 kHz. For magnetostimulation, the time varying magnetic field is needed. This field easily penetrates the tissue and gives a decrease in joint pain, muscle tension and migraine. The ELF (extremely low frequency) magnetic field has also a good case in bone growth and peripheral nervous system (AV nerves). The possible way for the magnetic field to affect healing is a mean of periosteal current. If the bone is broken, there arises long-term voltage between the bone ends. This voltage gives a small electric current. Such event impacts healing. Application of an adequate static magnetic field induces electric potentials in bone tissues, leading to a time-varying current. As a result the bone healing process maybe accelerated [16]. In the treatment of bone damage, an alternating magnetic field is used.

6. Biological Effects of Electromagnetic Waves

In the electromagnetic spectrum, non-ionizing fields occupy more than 15 decades below the ionizing fields that directly break molecular bonds. The first biological effects of electromagnetic fields prerequire an absorbed energy in the dielectric surrounding cells, or as a direct excitation of molecules, depending on the wavelength. Low-frequency electric fields excite forces on charges, while higher frequency fields excite forces on dipoles. The absorption coefficient is high in humans, particularly in the head and in anharmonic tissues. The energy absorbed in the head by mobile phone fields is also relatively high, which has motivated studies on unspecific effects on health. No effects on the nervous system or brain function could be replicated with repeatable results. In vitro studies have shown effects of microwaves on morphology and on cell functions, i.e., the so-called “non-thermal effects” but verification is in most cases missing, and knowledge on mechanisms is lacking. Epidemiologic studies mainly report negative results on risk, but also some statistically significant positive risk ratios. An interim summary on studies on the two most common types of brain tumors and use of mobile phones are negative studies in most groups of exposed persons, but with a few groups having, mostly marginally, significantly increased risks. Positive associations are generally found at exposure levels that constitute artefacts, but there are notable exceptions. Far field exposures are mainly associated with non-significant effects, while some groups with close exposure report significant. More data are needed, but precautionary measures already on the market should be well implemented and intensified. A timely adoption of the ALARA principle is recommended. More research is ongoing on biological effects, health risks, and dependence of perceptions, cognition, and behavior. Electromagnetic fields in our environment are detected through the production of inner electric fields by the human body. Alarm or alarm-like responses were found in only a few cases, usually not replicated with reproducible results. At commonly used field levels, no consistent effects were found on night-time concentrations of melatonin, pituitary and stress hormones, or preparations of cells or their functioning. Provocation studies on subjects with perceived hypersensitivity to fields were not consistent in producing reactions in individuals or groups of persons. Genotoxicity studies have been performed on a variety of radiofrequency electromagnetic fields, but no reliable conclusions are possible due to shortcomings in some studies and the fact that findings of effects are usually not replicated. With longer exposure times including a carcinogenesis follow-up of 2 yr rats and 2.5 yr of mice outcomes were inconsistent between studies, between genders, and species. With the uniformly positive pattern of carcinogenicity in male rats, it is biologically implausible not to consider that there might be some material basis to the unusual cancers of the rat. There has been recent activation of a working group on radiofrequency fields due to serious concerns expressed by two countries about the CNS effects of mobile phones on children. Several members regard accompanying efforts as an attempt to induce experts to reach a cancer risk interpretation not supported by the results. [24][25][26]

6.1. Cellular Interactions

There have been several recent exciting advances using FDTD to model the interaction of EM waves with biological cells, ranging from the cellular phone level to the tissue level. Mathematical reciprocity can circumvent these difficulties for global quantities by noting the power or energy absorbed by a big system of electrically small antennas from the cell(s) must be equal to the power efflux from those antennas into the cell(s) [27]. The utility of reciprocity to predict the effect of environmental changes on a given exposure condition was demonstrated through examining specific absorption rate (SAR) patterns in a model system consisting of a spheroidal dielectric object in a homogeneous lossy medium, which were varied by modifying the location of antennas and modifying the surrounding air. It was demonstrated that for a unit power source in each of two monopole antennas near a homogeneous 3.5 g/ml tissue simulating medium, the average-SAR_10g obtained by FDTD for a range of object radii compared favorably with predictions based on the maxwell-garnett mixing formula for a value of lambda'eff close to 3.67 cm.

6.2. Thermal Effects

With increasing interest in the use of electromagnetic waves for various applications in biological systems, knowledge of the interaction mechanisms of electromagnetic waves irradiated onto biological matters (i.e., tissues) is required. Even though various characterization techniques to evaluate the properties of biological tissues are available, there still remains room for further understanding. Therefore, a front-end procedure for analyzing the biological effects caused by electromagnetic waves is in demand. The purpose of this part is to summarize the progresses of the research group to characterize biological systems based on electromagnetic wave analysis and to develop new measurement systems useful for such characterization techniques. First, the sensing of well-known phenomena due to the interaction of electromagnetic waves with both macroscopic and particulate systems is summarized. Different methods of excitation (continuous-wave and pulsed) are employed to interrogate the different systems. Then less well-known styles of experimentation are discussed, or industry measurement techniques are applied in a novel manner. The need for measurements of powders in situations that are not readily-amenable to conventional approaches, i.e. off-line in powder-filled vessels, spouted beds, or fluidized beds, is explained. Methods to ascertain bulk moisture content and temperature profiles are also reviewed. Biological targets are quite appealing for electromagnetic heating since they are usually contained in a support structure that is almost transparent to the radiation whereas liquid water, protein, and other compounds have good absorption properties in the V- to W-band. The results are validated against previously published data. Representing the simulated data in terms of rectangular complex and polar complex data yields consistency of <0.06 and <0.12, respectively. Good accuracy is found between simulation and experimental data in terms of size and antenna characteristics. Thermal performance calculations are considered [6].

6.3. Non-Thermal Effects

In dosimetry research, WBAi (whole-body average SAR due to biaxial exposure) could provide a more complete assessment tool for the electromagnetic exposure than commonly used SARi (spatial-averaged whole-body SAR) based on VBA (voxel-based anthropomorphic) models, and WBAi will probably be favored for general-purpose use [16]. New non-ionizing technologies based on EMFs are likely to be developed. In 1995, a commercial electronic device started to be marketed, releasing different pulsed modulated high-frequency EMFs. The impact of the high-frequency fields on biological systems would be better known with a better characterisation of such fields. As yet no analogous warning could be issued to refrain from dangerous exposures. Cascade of events is triggered by the generation and amplification of second messengers and ultimately by the activation of effector proteins. Such events regulate, among other things, cell cycle processes, leading cells to either live or die by apoptosis [28]. Bioelectromagnetics rely on a disciplined teamwork between physicists, chemists, biologists, biotechnologists, and bioinformaticians to provide a comprehensive understanding of the interaction between integrated complex biological systems and external environmental EMF fluctuations. Modern applications of bioelectromagnetics range from the diagnostic imaging and the therapy of the mammalian body, food, and plant industries, to the development of detectors of chemical and biological agents, to the assessment of genotoxicological risks and the early diagnosis of hydrophobic based neural memories that might globally affect the way the human brain stores information. Such a way could help to better understand and utilise the extraordinary adaptive and evolutionary skills developed by Earth biota during the natural selection to stress.

7. Safety and Regulatory Considerations

Electromagnetic (EM) waves play a crucial role in a wide range of biological systems, including medical imaging technologies, impact on some important properties at cellular and molecular levels, such as the interactions between biological tissues with EM waves. The diverse specialties involved in the research of bio-electromagnetics are considerable, such as medical imaging, communications engineering, electronic engineering and electromagnetic theory. In terms of medical imaging, widely used technologies including magnetic resonance imaging (MRI), computerized tomography (CT), X-ray imaging, ultrasound medical imaging, and so on. In recent years, the research on electromagnetic interactions inside biological systems has developed rapidly, including issues on biological effects of electromagnetic fields (EMFs), bioelectromagnetic stimulation, and the theragnostic effects of electromagnetic heating on tissue and cancer cells. A significant number of researchers are examining low EM frequency, such as non-ionizing microwaves and radio waves, as well as the higher frequencies of ultraviolet and X-rays, with potential of ionization [29]. In this manuscript the main focus is on the interaction between biological systems and microwave EM waves in the non-ionizing band. Meanwhile the research specialties are placed on the widely employed bio-electromagnetic technologies, i.e., medical imaging technologies.

Now medical imaging technologies are well applied to the clinic, and among them MRI imaging has great advantages for its non-invasive character over the other imaging modalities. It uses very strong magnetism, long RF waves and strong gradient magnet fields to gather the signals of water and fat molecules in the human body, and form images through mathematical processing. Electro-magnetic waves play a key role in MRI, but the potential biological effects of these technologies on living systems are often overlooked. In recent years, a number of researchers have endeavored to research the biological effects of MRI imaging on tissues, mainly concentrated in the perspectives of the temperature increase of tissues during MRI scanning and the MRI switched gradients. Research makes clear that it may not be possible to rule out any negative effects of these systems on biological tissues absolutely, but effective protective measures and operation practice can make the risk from these systems negligible. Marine creatures are exposed to microwave radiation of different MRI systems in the high frequency (HF) band and video data show no significant synergistic heating effects of tissue.

7.1. Exposure Limits

Sweden has adopted the guidelines. These are only applicable for the Occupational Environment (OE). The safety factors applied between the basic restrictions and the reference levels are unity except for the electric and the magnetic field: 1/7 and 1/7. Basic restrictions for whole-body MW radiation are the specific energy absorption rate (SAR): 0.4 W/kg averaged over any 6 min period, and 10 W/kg averaged over any 0.1 h, dielectric measurements. At the same time, in-situ instrumentation is developed to verify the existing standards and to facilitate routine controls of the compliance with the guidelines. Also, in the high frequency range as high as ~100 GHz measurement devices are developed for occupational and public exposure assessment (averaging of power density).

Throughout the guidelines, 1 mW for operation and 1 mW for auxiliary and personal services are said during the call is that the exposure levels of the phone must be less than the limitations of the guidelines. The exposure levels of the devices correspond to about ≤1 mW transmission out-of-the-phone even in the worst case (without ear piece) position. These exposures could only occur for text messages. Significantly higher levels characterize many of the head-operated handsfree sets commonly in use today, making it essential to improve these accessories or substitute them with better designed ones (e.g. providing high-quality audio by air-tube or bone conduction). With the advancement of the communication systems, exposure originating mobile phones with third- and future, fourth-generation technologies may become lower. There could also be other exposures derived from the close-by use of wireless networks and mobile phones in the same location. Including the guidelines, the tolerance levels will be seriously violated. At the present RF exposure scenarios concerning broadcasting systems, 0.35% of the 600 MHz - 300 GHz radiofrequency radiation. On the other hand, personal (apart from the mobile phones) and home RF (Wi-Fi, Bluetooth) radiation hardly exceed the 90 MHz - 3 GHz level. This compliance is automatically reached if that location is at a significant distance from base stations and if an eartheed hand-free is used.

7.2. Regulatory Framework

Electromagnetic fields (EMF) have been a vital part of our daily life for over a century. Since the first commercial radio broadcasts began in the beginning of the 20th century, the EMF have been introduced continuously in our environment. EMF surround us, generated by many different sources in a vast variety of situations, e.g., by domestic devices, telecommunication systems, and electric power transmission lines. Additionally, medical applications exist that use EMF in the diagnosis and treatment of diseases, such as Magnetic Resonance Imaging (MRI) and deep brain stimulation in Parkinson disease. Although evidence of a direct causal relationship is still lacking, epidemiological and laboratory studies on potential risks from exposure to electromagnetic fields have prompted the Dutch government to initiate a research program. The rapid increase in the use of EMF in a variety of applications and technical developments is another source of concern. As a result, there is considerable worry and uncertainty among large parts of the general public about possible adverse health effects associated with exposure to EMF at the low-frequency (LF) and radiofrequency (RF) ranges. This issue has now reached a stage where short-term interdisciplinary research actions are needed. This research project pursued such actions. The broad pattern of different possible interactions between low-energy electromagnetic fields and biological systems was addressed, with specific attention to Feynman's ideas. These ideas propose that extremely weak non-ionizing fields of appropriate frequencies acting on weakly driven systems could produce a signal, and that, in turn, once the signal is produced, the field exposure might stop. Existing working hypotheses on the biological and dosimetric factors that could be involved in such interactions were made causal and explicit as much as possible. Uncertainties and qualitative insights arising from Feynman's ideas were acknowledged. For these reasons, a broad-based research approach was set up to enhance the likelihood of capturing unknown aspects of the underlying phenomena. Broadband, multifrequency, and ultra-wideband exposures were used to uncover possible novel interactions.

Different cellular and molecular investigations at several levels, including direct and indirect effects at the molecular level, effects at the level of cell function and growth, and interaction between an EMF exposure and a second biologically relevant co-stressor were performed. Dosimetric investigations aimed at improving our ability to relate the induced internal fields to the applied exposure metrics. Advanced numerical approaches were often used. Simulations were not confined to standard models, thereby providing insights into possible optimal geometrical and physical conditions leading to enhanced effects. The research strategy pursued was alternative and cross-approach validation of the different results. Efforts towards a mechanistic understanding and eventual 'proofs of principle' limited to the specific conditions investigated have received top priority. Conversely, 'negative replications' – an absence of observation of an effect under nonequi-valent conditions – were judged largely irrelevant due to the early stage of basic scientific understanding [29]. A number of medical applications have emerged since the discovery of X-ray, a discovery that became quickly associated with potential hazards if safeguards were disregarded. Some of the medical diagnostic applications are well established, but emerging new ones are under investigation. Similarly, from the multitude of applications in electromagnetic therapy opening for scientific scrutiny, only established realizable applications are mentioned. It is not within the scope to give an exhaustive description of all these applications. Some applications are widely known, such as magnetic resonance imaging (MRI), a technique that uses static magnetic fields and radiofrequency electromagnetic fields to image the inner structure of a body. Some other investigations have been reported on the possible health effects of exposure to MRI magnetic fields. These effects apply mainly to technical and patient exposure. MRI technicians are handling the extremely strong static magnetic field and there are several reports on accidents following the exposure in the strong field. The MI magnetic field is not only strong, but it also consists of several harmonics. In addition, there is regular exposure in the form of a sequence of time modulations. The patients are not exposed continuously as in other areas, nevertheless the component of the gradient magnetic fields causes peripheral electrical stimulation up to a level that is painful for some patients [16].

8. Emerging Technologies in Medical Imaging

The diagnosis and treatment of various diseases had been expedited with the help of medical imaging. Today healthcare throughout the world became unimaginable without the medical imaging modalities. In today's healthcare, different medical imaging modalities, such as X-ray, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Nuclear Imaging, Ultrasound, Electrical Impedance Tomography (EIT), and Emerging Technologies for in vivo imaging are widely used. All medical imaging modalities are in vivo imaging techniques. The importance of in silico modeling in biological systems is a growing interest due to the need for a better understanding of the complexity of biological systems. A mathematical computational model mimics a biological system and provides a time and cost-effective platform for the development of efficient treatments. In medical research, many biological phenomena cannot be seen clearly using experimental methods only; computational models can complement experimental results providing a better insight into the particular system. There are many different mathematical and physical methods of modeling biological systems [8].

The most important factors those can be modeled are electrical, mechanical, magnetic, thermal, biological and chemical properties. The model of a biological system can be discrete or continuum. Discrete models are represented in physical and mathematical terms, by respect to specific details of the biological system (for example cell-by-cell, or molecule-by-molecule). Continuum models are represented as a mathematical model of the phenomena and mathematically describe a system as a set of partial differential equations or integral equations. Electrical Impedance Modeling (EIM) is the most popular for the modeling of biological systems because of the in vivo measurements. EIM involves the measurement of surface electrical potentials and currents using biopotential electrodes. A set of surface potentials are collected while an electric current is applied to the tissue through electrodes. With a forward model, a set of potentials for the system under study can be predicted. An inverse model estimates the impedance distribution within the tissue when the measured potentials and current stimulus are known. This method benefits radio frequency (RF), Magnetic Resonance (MR), Microwave (MW), and Neutron Impedance Tomography (NIT) Systems [6].

8.1. Optical Coherence Tomography (OCT)

Optical Coherence Tomography (OCT) is an emerging imaging modality used widely in biomedical imaging. Its resolution and image contrast are similar to those of conventional light microscopes but, in contrast to the microscopic methods, OCT is capable of tomographic and highly sensitive imaging of whole biological samples. Within the past decades OCT has been successfully used for in-vivo imaging of both eye and skin. But more applications of OCT in research on breast, colon and other internal tissues have been proposed. Besides detecting healthy tissue, OCT can be used to study mechanical properties of tissues providing invaluable information for diagnosis like cancer detection at an early stage. Due to its non-invasive character OCT has potential to surpass the standard methods in some aspects. Pattern of birefringent properties in various biological tissues can be determined by special type of OCT known as polarization sensitive OC. While in Conventional OCT the intensity of measured light reflected from tissue is registered as a function of time delay, in PS-OCT in addition to intensity change two other parameters are determined. The first one is phase of polarization, and the second is the difference in magnifying coefficients of optical path length. Optionally, expanded version of PS-OCT where in each point of image is given full Jones Matrix have been proposed. Moreover MC-OCT promising for retinal screening, cancer detection, or intraoperative monitoring is also described.

8.2. Photoacoustic Imaging

Electromagnetic (EM) waves are a family of waves that travel through space, absorbing charges or accelerating the charges during their propagation. Electromagnetic waves (EMWs) have been extensively used in different aspects of medical imaging such as X-ray, computed tomography (CT), magnetic resonance imaging (MRI), ultrasound imaging, positron emission tomography (PET), and so on. Different modes of imaging modalities have diverse probe mechanisms. Currently, due to climate change and its related phenomena, recent research has shown that the ozone layer of Earth is being depleted which is due to the rapid increase in the global temperature of the Earth. Thus, prospective research works have been conducted using EM waves in the medical imaging field as ultraviolet (UV), visible (VIS), inferred (IR) light, and radiofrequency (RF) applications to understand the causes and avoid global warming.

Photoacoustic imaging (PAI) is a hybrid imaging modality that is based on the detection of acoustic waves induced by rapid optical absorption. Development of a compact high resolution and high-frequency ultrasound transducer is presented for photoacoustic imaging applications with a center frequency of 34 MHz and an aperture diameter of 3 mm. This ultrasound transducer can provide high resolution and can image the targeted anatomy deeply for photoacoustic imaging application. Finite element modeling of the laser irradiation and ultrasonic wave generation in biological object, where photoacoustic wave generated in tissue can carry information about embedded tiny objects, and by detecting and processing such ultrasonic waves tumor is detected. The multiscale photoacoustic microscopy (PAM) and computed tomography (PCT) demonstrate noninvasive and labelfree versatile imaging modalities to image the structural and functional information of biological tissue. A review is provided on existing development of the PAI, particularly highlighting multiscale and hybrid approaches. A wide range of biomedical applications of the different types of photoacoustic imaging is demonstrated. [30][31][32]

8.3. Terahertz Imaging

Of all high-frequency electromagnetic waves in the different regions of the spectrum, terahertz (THz), which represents the gap between the radio and the infrared (IR), is characterized by its interaction with biological molecules. THz radiation can be absorbed due to the vibrational modes of biological materials emerged in the spectral range from 0.2 to 4 THz. One of the advantages of the THz spectral region is linked with the cylinder-on-cone-theorem, which provides the penetration of THz radiation through the tissues.

Being irradiated with broadband THz waves, materials absorb them at strong absorption lines, providing a finger-print specificity. It is known that biological tissues exhibit multiple absorption lines in the THz frequency range as well. This peculiarity was used in developing the THz pulsed spectroscopy (TPS) which enables to determine the spectrum of samples without complex analysis.

The broadband spectrum of THz radiation used in the TPS-method allows analyzing tissue properties from 0.1 THz to 20 THz, providing information about different substances. Observing the microscopic structure of biological tissues in the THz-frequency range, it is found that the tendon structure differs from the adenoma structure. Other interesting objects in terms of THz imaging are various types of tumors. Depicting soft tissues tumor having the volume of 1.5·10¯4 cm3, it can be seen that safe treating of tumor in some cases remains intricate issue due to the threat to the healthy internal organs.

9. Future Directions in Electromagnetic Wave Applications

This chapter first discusses future directions in EMW applications and then presents instrumentation and techniques for SEAWA measurements. Electromagnetic waves (EMWs) are fundamental science waves and are ubiquitous in nature and industry. The wide range of frequency bands of EMWs provides numerous opportunities for applications in medical imaging and biological systems. Further investigations of these research areas are anticipated in coming years. In the foreseeable future, advancements will arise in the successful integration of the newly developed systems with existing systems and in the better understanding of fundamental science of these waves. Understanding these waves will enable invention of new applications in many different areas that have not been foreseen.

It is generally believed that invisible or inaudible EMWs are safe for human health. However, a dramatic change in this belief occurred in the 1990s with the wide application of mobile telephones and other modern communication and household devices. It is of common belief that EMWs from mobile phones can cause serious effects on human health, such as ceasing a mobile phone nearby the head can cause an acoustic neuroma on the brain. In recent years, extensive investigations have focused on the bio-effects and medical applications of EMWs. It is envisaged that many discoveries in this area will appear in the near future, but many there will be just unevidenced myths that appear and disappear after causing unfounded fears.

9.1. Integration of AI in Imaging

The field of artificial intelligence (AI) has grown substantially in recent years and, only more recently, has been applied to brain molecular imaging. Applications including improvements to the quality of images produced by Positron Emission Tomography (PET) through the synthesis of computed tomography (CT) data are explored. Available MRI Phantoms and standardized sequences useful for the phantom acquisitions are also discussed. Additionally, potential applications of AI to biological systems neuroimaging beyond the scope of AI generated synthetic CT to aid in the attenuation correction (AC) of either MR or PET data are presented. These applications include the reduction of scatter in PET imaging data and the removal of symmetrical artifacts from hand-held imaging systems. Take-home points and practical considerations for those looking to begin a similar image processing project are also discussed.

Generally, a reliable method for the brain AC of simultaneous PET/MR imaging is hydroxyl-functionalized small-diameter sporopollon arbitrans (HSDE) spheres. This method utilized a highly accurate and automated framework for the creation of MR biases from UTE image volumes of a single physical phantom and provided AC maps that decreased noise and improved images compared to other methods for the factorial study. The validation of these methods on patient data further confirmed the potential advantages of the HSDE spheres [33]. A framework for the generation of patient specific CT-equivalents from PET data was applied to the creation of synthetic CT data for the improvement of brain PET images. The use of these data for the subsequent AC was determined to be inaccurate. Nonetheless, this technique has the potential to create high quality synthetic CT data from patient MR images which could have a wide range of applications. A method is presented to reduce the effect of scatter in the PET imaging data through additional acquisitions of high resolution images. This artifact is one reason for the integration of hand-held PET and MR imaging systems. The method presented is capable of removing, in post processing, symmetric artifacts created using a prototype hand-held imaging system. A non-uniform artifact from the MR guided PET system was also successfully removed.

9.2. Advancements in Imaging Resolution

Achieving high resolution has been a challenging issue of interest for medical imaging algorithms based on electromagnetic inverse scattering (EIS). When biological tissues are irradiated by electromagnetic waves, the changes in polarization may result in a change in electrical properties and the scattering of the incident fields. Produced scattered fields are sampled by antennas and recorded as a function of frequency range. By solving the inverse scattering problems, it is possible to obtain tomographic images of the internal dielectric properties of biological tissues. It has been found that when the solutions of EIS are represented by the derivative of the total field with respect to the complex permittivity of scatterers, the super-resolution phenomenon would appear as an inverse problem [34]. Advanced algorithms and experimental setups are developed to implement super-resolution imaging through the processing of the data on the total field.

10. Case Studies and Clinical Applications

A number of medical applications for both diagnosis and therapy relying on different parts of the non-ionizing part of the electromagnetic (EM) spectrum have emerged over the years. Non-ionizing radiation, in the sense of EMFs, refers to electromagnetic fields with frequencies from 0 Hz up to 3.0 EHz. This definition includes optical radiation in the wavelength range below 1000 nm. The review deals with the medical applications of EMFs, meaning specifically the frequency range from 0 Hz to 10 THz [16].

Some applications are well established. An example is the imaging of the living human anatomy and physiology by non-invasive methods, i.e. medical imaging. More than 100 years ago William Röntgen discovered X-rays. While X-ray radiography is still widely used, many medical imaging applications are now based on different parts of the EM spectrum. Besides the already depicted application of NMR and MRI, special mention has to be made of computed tomography (CT) created by combinations of X-ray radiography with computers, and ultrasound-based imaging systems.

There are applications based on EMFs beyond those part of the established diagnostic or therapeutic tools. Examples are the use of electric current to burn tissue, so-called electrosurgery, and the heating of tissue by non-invasive devices called diathermy. In addition, there are devices either for diagnosis or therapy based on EMFs which function as a complement to well-known medical procedures; however, only in the recent past or still only on a research level. For instance, in the area of breast cancer, together with palpation and imaging by X-ray mammography further diagnostics include ductal lavage and ductal endoscopes, and, on a research level, tissue dielectrophoretic routing. Another example is the X-ray mammogram, which in undiagnostic cases is complemented by close up mammograms.

10.1. Breast Cancer Imaging

Breast imaging has undergone a revolution toward early detection of malignant tumors since the first pioneering research using piezoelectric tags in the late 1960s. Four decades of efforts have been devoted to the demonstration of the microwave-based signal imaging. Initial microwave applications include tissue characterization and intraoperative margin assessment of excised tissues. Technological development has enabled fast scanning of the breast under relaxed operational requirements; this also has motivated an ongoing revolution in the areas of device placement and antenna types. Nonetheless, microwave breast imaging is still considered experimental by most, with challenges ranging from regulatory approval to enhanced image processing requirements.

The overarching goal of many research groups in academia and industry is the development of a comfortable, cost-effective, and unattended technique for the early detection of breast cancer. Rapid breast cancer detection is crucial for the early diagnosis of the disease since chances of survival and in the success of the treatment largely depend on the tumor size at diagnosis. This is also the primary motivation behind the work in the breast imaging field. On the other hand, it is worth mentioning that most of the designed or commercially available imaging systems prove to be sensitive to benign abnormalities in dense tissue. This type of tissue largely consists of patients younger than 40 years old and after menopause. On those cases, the tissue becomes fatty, which is the main limitation for the current system.

Breast imaging techniques, such as X-ray mammography, ultrasound, MRI, CT, and PET, play a pivotal role in detecting breast cancer. Among them, X-ray mammography is the mostly commonly used modality, providing images with high resolution and high contrast of the internal structures. Furthermore, it is credited for its simple operation, high repeatability, and widespread implementation. However, it is also common knowledge that X-ray mammography has limitations as a stand-alone device for breast cancer screening and diagnosis. Some such negative aspects are the use of ionizing radiation, not being suitable for imaging women with dense breast tissue, and being contraindicated for pregnant women. Thus, much effort has been placed in developing alternative or adjuvant methods for breast cancer imaging. On the one hand, in the last few years, tomosynthesis systems have been introduced into the market. This technique overcomes some of the limitations of conventional mammography, such as the superposition of the breast structures. On the other hand, other currently used imaging systems that do not use ionizing radiation have been developed, such as ultrasound, MRI, CT, and PET.

10.2. Brain Tumor Detection

A brain tumor is an abnormal growth of tissue in the brain, which can be benign or malignant based on behavior. The main aim of this operation is to prepare a model that simulates the biological tissues of the human head and to detect visualized brain tumor by finding out the resonance frequency of brain tumor through the simulated model. A brain tumor detection system is developed in a medical imaging context which is based on the analysis of electromagnetic waves being scattered by an in-homogenous dielectric cylinder, which can be applied in conjunction with magnetic resonance imaging attaining the electric conductivity and permittivity of the diagnosis. Generally, a microwave imaging system consists of one or combination of arrays of antennas comprising of outermost empty room shielded with absorbers and a central control unit. The antennas are placed in the outer and/or inner circles of the human head model and they may be configured as monopoles, dipole or microstrip patch antenna style. Microwaves transmitted and received by the 'transceiver' antenna array are then converted by a network analyzer to scattering parameters or incident field equivalent ones at given ports. In this study, a mathematical model for a dielectric loading is provided on the antennas in terms of equivalent transmission line theory and the corresponding signal alteration is derived analytically. It is demonstrated via numerical results of polar plots for return loss, VSWR, and real part of the input impedance that this method is sufficient to explain the inconsistent experimental behavior of 900 elbow dielectric, saline and distilled water filled microstrip antennas. Concerns on shielding effectiveness of the Faraday cage were explained, indicating the importance of large enough free space between the transmitting and receiving antennas [35].

10.3. Cardiac Imaging Innovations

Innovations in medical imaging have resulted in significant devices and therapies with remarkable potential for diagnosing and treating disease. There are many imaging techniques that have been developed and implemented that utilize the properties and principles of electromagnetic waves. When electromagnetic waves interact with biological systems in medical procedures or devices, life itself is responding to energized atoms and molecules that have been heated or exposed to an electric field. These, in turn, can produce sustained waves (exposures) as a by-product of thermal motion, conductivity, and electromagnetic properties. The levels of exposure in medical applications are typically localized spatially using targeted and controlled devices that limit the exposure to homogeneous and low-energy fields, and the frequency range used within treatment and medical imaging is largely kept within a region where human tissue has low interaction. This scenario has evolved exceptionally in the 21st century with the advent of wireless technologies and also the development and experimental validation of implantable devices. The interaction of electromagnetic fields with living tissue and cells has been the focus of much work, primarily to explore biomedical applications and understanding of the effects of electromagnetic fields of living tissue. Applications of this understanding have included the treatment of cancer and hyperthermia, but most notably an exponential growth in communication technology based on radiowave signals. With the increasing field strength and frequency, however, the effects can become more dramatic and radio frequency (RF) ablation therapy has been developed. It is undoubtedly a serious endeavor, and indeed the fundamental aspects of this relationship are not yet fully understood [6]. Negative effects on the physiology of living tissue include heating and thermal damage, burns, shock, and induced current; dose dependent on the frequency, duration, and intensity of the field. As such, there is strong motivation to better model such interactions, both for study and for assessment of biological safety. Since the late 1800s, governments have conducted research programs on the biological effects of electromagnetic energy. The use of radars during the Second World War revealed different effects on military personnel, such as light flash perceived by combat pilots. This initial finding gave rise to significant government interest, and many secret programs were initiated to explore the dangers of RF exposure to the human anatomy. Of recent years, extensive work in this field, the majority of which is publicly available, has been amassed on the response of living tissue to RF radiation [36]. Since 2000, emerging devices and technologies such as the portable telephone, cordless telephone, Wireless Local Area Networks (W-LAN), and GSM modulation have brought the RF field into the everyday routine of man. Hence, the knowledge of the possibilities for tissue damage from RF radiation is warranted. So far, little is known about the effects of RF exposure of living tissue despite an appreciable knowledge of radiowave interactions. The majority of experiments are of a behavioural nature, aimed at measuring absorption and emitted radiation. These data give a measure of the safety; however, to understand the interaction fully requires biophysical studies, such as of the evoked temperature of the exposed tissue (the first effect expected from exposure), cell climate alteration, genetic mutation, and so forth. Most experiments are in the MHz and GHz frequency band and conducted in vitro; it is not possible to elucidate currently in the literature on the RF-thermal damage to tissue. But what experiments do exist tend to be investigated on the standards for public or occupational exposure, which do not cover the frequency bands emerging in everyday technology.

11. Conclusion

- Abstract: Some of the applications based on the vast non-ionizing EMF spectrum have during the past two decades reached certain clinical impact within the medical community. For example, electroporation and irreversible electroporation as novel methods for treatment of certain cancer forms, trans-cranially applied repetitive transcranial magnetic stimulation as an alternative non-drug method for treatment of major depressive disorder and possibly modulated radiofrequency as a new alternative treatment for chronic low back pain. However, application areas in the vast frequency spectrum of EMF suffer from lesser acceptance within the scientific and medical community due to a generally weaker scientific basis and weak evidence for an action mechanism at the used intensities of the fields. There is a large knowledge gap between evidence found in the laboratory and in the clinic regarding the question of how the electromagnetic field interacts with the biological system. Consequently, the need for research to investigate (a) which component of the fields can affect cells and biological tissues and (b) which physical parameters are relevant for a medical use of a given type of electromagnetic exposure is evident.

- The vast EMF technology still has not reached a major standing in the therapeutic field, partly due to lack of mechanistic understanding of the effects of exposure and a general scarcity of randomized controlled studies demonstrating efficacy. Also, investigations using different exposure systems and different waveforms yield conflicting results. On a more critical basis, many studies conducted in this field, on both non-ionizing and ionizing EMF, are often sub-optimally designed, e.g., exposure conditions are not well characterized or may not be repeatable, biological models are not well chosen or are not truly representative, the delivered dose is not well known, sample sizes are not adequate or statistical analyses are poorly carried out, end-points are poorly selected or varied from experiment to experiment and the data, even when statistically significant, do not have a clear dose-response relationship; In this context, many putative approaches that had shown promise in the beginning have subsequently disappeared from research and are now of little or no interest, possibly due to the inability to replicate findings and the consequent lack of interest by funding agencies.

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