Antennas and Other Electromagnetic Applicators in Biology and Medicine

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I. INTRODUCTION

Studies of electromagnetic (EM) field interactions with biological systems date back at least to the 1700's when Galvani and Volta, among others, experimented with electrical effects in frog's legs, and Mesmer used magnets to treat patients. Since that time, both the electrical processes inherent in biological systems and various medical and biological applications of EM fields have been studied extensively.

Medical and biological EM applications may be classified into two broad groups: 1) therapeutic, and 2) informational (including diagnostics and measurement of material EM properties). Examples of therapeutic applications include diathermy, hyperthermia for cancer therapy, rewarming of hypothermic patients, enhancement of bone and wound healing, nerve stimulation and neural prosthesis, microwave angioplasty, treatment of benign prostatic hyperplasia, and cardiac ablation. Some examples of informational applications are imaging (including electrical impedance, microwave, and nuclear magnetic resonance imaging), measurement of lung water content, tumor detection, and personnel dosimetry. Studies of how EM fields interact with biological systems (EM bioeffects) are other examples of informational applications. Most of these medical and biological applications involve EM coupling into and/or out of the body. This coupling usually requires some device, such as an antenna, to transmit a signal into a body or pick up a signal from a body. At lower frequencies, the device is often called an applicator instead of an antenna, since it is usually short compared to a wavelength and does not function like a radiating antenna. At higher frequencies, the device is usually some form of traditional radiating antenna. In many biological and medical applications, the antenna operating conditions are different from the more traditional free-space, far-field conditions. Often the nearfield and mutual interactions dominate, and the antenna environment is usually lossy.

II. THERAPEUTIC APPLICATIONS

A. Hyperthermia for Cancer Therapy

Hyperthermia (increasing the body temperature to 410° C or higher) was used to treat cancer patients as early as 1893 by increasing patient temperature through administering bacterial toxins, and EM diathermy was used to produce hyperthermia as early as the 1920's [2]**.** The objective in hyperthermia therapy is to heat tumors uniformly to the desired temperature and maintain that temperature for a given time despite the body's attempt to maintain normal body temperature by its thermoregulatory systems. Heating internal tumors is difficult. Consideration of the plane-wave penetration depth, defined as the depth at which the plane-wave power density is 112 that at the surface, gives a good idea of what the limitations are. In muscle tissue the plane-wave depth of penetration is less than 1 cm at 2450 MHz, about 1 cm at 915 MHz, and about 5 cm at 27 MHz. Since finite applicators typically produce less penetration than plane waves, heating a deep lying tumor at these frequencies would overheat the surface, and operation at lower frequencies therefore seems desirable. At low frequencies, though, the wavelength is so long that the energy cannot be localized to a small region, and only large regional heating can be obtained. Worse than that, at low frequencies, the applicator will be electrically small if its physical size is manageable, and near fields will dominate. Since near fields decay rapidly with distance away from the applicator, dominant nearfields often overheat the surface. Consequently, practical heating of internal body tumors without overheating the surface is very difficult at any frequency.

1) Noninvasive Applicators: Noninvasive (not penetrating the body) applicators may be classified as belonging to three main groups: 1) E-type (low-frequency) applicators, which produce mainly an E field that heats the tissue, 2) H-type (low-frequency) applicators, which produce mainly a magnetic field, which in turn induces the E field that heats the tissue, and 3) radiative applicators.

a) E-type applicators: Capacitor-plate applicators are typical E-type applicators. These applicators are usually operated at either 13.56 MHz or 27.12 MHz, two of the frequencies assigned to industrial, scientific, and medical use (ISM frequencies). Capacitive applicators heat deep tissue well, but they usually produce large components of E field normal to the fat muscle interface, which overheat the fat because boundary conditions require the normal E fields at the interface to be discontinuous by the ratio of the permittivities, and since fat has a lower permittivity than muscle, the E field in the fat is higher [3] & [4]. With multiplate capacitor configurations [5], internal heating patterns can be adjusted by changing the relative voltages applied to the various plates. Ring capacitors can produce deep internal heating without overheating the surface if a proper gap is maintained between the rings and the body surface. The helical-coil applicator is like an H-type applicator in some respects, but its heating characteristics seem to be more like an E-type applicator, since the strong *E* field produced between the turns of the coil is mainly responsible for tissue heating. Large pitch angles (coils more parallel to the axis) produce better results [7]. A surface semi cylindrical helical coil heats well internally, but tends to overheat the surface [8].

b) H-type applicators: Perhaps the simplest H-type applicator is a single coaxial current loop. A device called the magnetrode consists of a single sheet coaxial current loop [9]. Since the coaxial current loop produces eddy current type *E* fields that circulate around the axis of the loop, heating in the center of the body is minimal. Generally speaking, H-type applicators seem not to couple as strongly to the body as E-type applicators, and relatively high currents are usually needed to get adequate heating. H-type applicators have the advantage that they produce an E field mostly tangential to the fat, which therefore does not overheat the fat. Since most of them are designed to operate at ISM frequencies of 13.56, 27.12, or 40 MHz, the depth of penetration is typically a few centimeters.

c) Radiative applicators: Various kinds of open-ended waveguide applicators, some loaded with dielectrics to provide better impedance matching and coupling to the body, have been studied over the years. These single waveguide applicators generally produce penetration less than the theoretical plane-wave penetration. Phased arrays at lower frequencies can provide better penetration, but not a small spot size because the wavelength is too long. An annular phased array (APA) consisting of two side-by-side arrays of eight dielectrically loaded apertures operating at frequencies from 55 to 110 MHz is used extensively to provide a deep regional heating pattern that can be adjusted to some extent by phasing the radiators. Operation in this frequency range provides deep penetration, but not a small focused spot.

2) *Invasive Applicators:* Invasive applicators can produce more uniform and controllable heating patterns than noninvasive applicators, but they require some kind of implantation in the tissue, this is not feasible for all tumors. Electrical invasive applicators are of three basic types: 1) arrays of needles that produce RF localized current fields (LCF), 2) radiating microwave antennas, and 3) inductively heated ferromagnetic seeds. In the RF LCF systems, RF currents produced by voltage sources connected between needle pairs, or between one set of needles and another set, produce ohmic heating. The heating pattern is affected by tissue inhomogeneities, since the current will tend to follow the paths of least resistance. Parallelism of the needles also affects uniformity of the pattern. Since current density concentrates near needle surfaces, the heating is strongest there, decreasing as the current spreads out between the needles. Heating patterns are adjusted by switching sources repeatedly between alternate pairs of needles and by dielectric coatings on a portion of each needle. Implanted radiating microwave antennas, either singly, or in arrays, both phased and nonphased, have been used extensively for heating certain kinds of tumors. Where it is feasible to implant antennas, well controlled heating patterns can be achieved. Implanted microwave antennas heat both through ohmic and dielectric losses. A typical implanted antenna consists of coaxial cable with the center conductor extended. Variations include steps in the diameter of the extended center conductor, various dielectric coatings on the center conductor, and helical coils wound around the center conductor. In the third method, ferromagnetic segments (or seeds) are implanted and then heated by an externally applied low-frequency (less than 500 kHz) magnetic field. The overall heating pattern is a function of the size, shape, and ferromagnetic properties of the seeds. Advantages are that no connections between the source and the seeds is required, and the size, shape, and properties of the seed can be chosen to optimize the heating pattern, but a strong magnetic field is required to produce the heating.

B. Other Therapeutic Applications

Antennas and other EM applicators similar to those used for hyperthermia, particularly capacitive and inductive applicators, have been used for diathermy. EM applicators can produce deeper heating than methods that simply heat the body surface and rely on thermal conduction to carry the heat to the deeper tissues. Similar applicators have also been used to rewarm hypothermic patients. If peripheral tissues are warmed while the heart is still cold, as happens with conventional rewarming, the warmed peripheral tissues demand increased circulation that overloads the still cold heart. A better method is to rewarm the heart first by EM techniques, which increases cardiac output and circulates warmed blood to the peripheral tissues without overloading the heart.

III INFORMATIONAL APPLICATIONS

Although magnetic resonance imaging (MRI) is a field of research by itself, the design of the coils to produce the RF magnetic fields is a crucial element of an MRI system. The quality of the image depends on the uniformity of the magnetic fields inside the body to be imaged. At frequencies in the lower MHz range, where the size of the coil is small compared to a wavelength, a saddle-shaped coil has been traditionally used with great success. As the MRI systems are designed to operate at higher magnetic field strengths (and therefore at higher frequencies) to improve the intrinsic sensitivity, the inductance of the traditional saddle coil becomes too high to resonate. Consequently, other structures, such as the slotted resonator, have been developed to operate at frequencies higher than 100 MHz. Various waveguide and horn apertures have been used in microwave imaging systems. Microwave imaging seems desirable because the contrast in permittivities of different body tissues is high, leading one to expect good contrast in microwave images. The same fundamental limitations that plague the development of hyperthermia applicators also limit microwave imaging, however. To get good resolution requires using frequencies for which the wavelength is short, but at these high frequencies, the attenuation is so high in the body that images are difficult to obtain. Lower-frequency electrical impedance methods have been used to obtain diagnostic information such as total body water, change in water volume, and cardiac function.

Microwave radiometry is an interesting application of antennas because it is based on measuring EM fields emitted by the body itself, in contrast to other methods which require applying EM fields to the body. Waveguide and horn apertures are typically used in microwave radiometers that have been used both for breast tumor detection and for measuring changes in lung water content. The breast tumor detection is based on local temperature variations produced by the tumors, and the measurement of lung water changes on the change in emissivity with water content. Another informational application of antennas is measuring the permittivity of biological objects, which is important both for design of EM systems that interact with biological systems, and possibly for diagnostic purposes. In particular, in-vivo measurement of permittivities can be important, because the permittivity of excised tissue may be different from that of intact tissue in the living animal.

IV CONCLUSION

Antennas and other EM applicators have been used in many different ways in medicine and biology. Most of these applications involve coupling of the EM fields into and/or out of the body. A common characteristic of many of these applications is the difficulty of coupling energy into the deep tissues without damaging the surface of the body. Recent rapid developments in numerical electromagnetic techniques are expected to have great impact on the medical and biological applications of antennas and other EM applicators.

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