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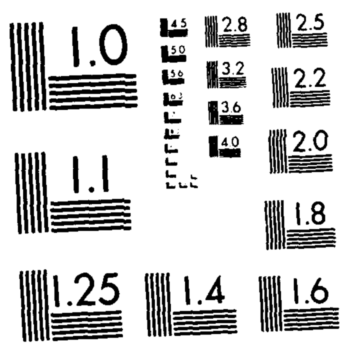
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TRANSIENT INTERACTION OF ELECTROMAGNETIC PULSES IN DIELECTRICS AND MICROWAVE BIOPHYSICS

FINAL REPORT

THEODORE C. GUO
WENDY W. GUO

MAY 12, 1988

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This research includes the following three subjects:

1. Pressure Waves Generated by Microwave Pulses: A thorough formulation on microwave thermoelastic and microwave electrostrictive effects is developed. It is shown that pressure waves may be generated via two physical mechanisms, one by thermoelastic process and another by electrostrictive force. On the thermoelastic process, pressure waves are generated by microwave pulses if there are thermal, mechanical, or electrical discontinuities in dielectrics. Therefore, pressure wave may be generated in a dielectric even when the microwave absorption is homogeneous, such as a small dielectric body. The theoretical results, confirmed by experimental measurements, show that an absorption of microwave energy by water at the rate of 6.5 kW/gram in a water-air interface produces a pressure wave with

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peak amplitude as high as 10% of the atmospheric pressure. This result does not include the electrostrictive effect, which may further enhance the pressure waves if microwave pulses have short rise time. For water or biological materials with high water content, a rise time of 1 nanosecond is the marginal modulation rate, beyond which the electrostrictive effect contributes more to the pressure waves than the thermoelastic effect.

2. Transient Dielectric Response: A non-steady state model of dielectric relaxation is developed to analyze dielectric response to short microwave pulses in the transient regime. The model is equivalent to Debye's model with a modification for time-dependency of the damping coefficient in the transient regime to account for irreversible processes and non-steady state nature before the dielectric and the external field reach a steady-state interaction. It was found that, due to this time-dependency, dielectric susceptibility is not diagonal in the frequency domain, and therefore linear superposition principle is not valid in the transient regime. An experimental set-up is proposed to measure the off-diagonal matric elements of dielectric susceptibility in frequency domain.

3. Microwave Dosimetry and Microwave Imaging: Two non-invasive microwave dosimetry techniques are developed, which are also applied to develop three-dimensional microwave imaging algorithms of arbitrary inhomogeneous dielectric bodies. One technique is based on an inverse scattering theorem which provides a qualitative imaging with little computation time, and another technique is based on digitizing the scattering integral equation to form a scattering matrix and then inverting the matrix. The scattering matrix algorithm provides quantitative three-dimensional images of dielectric permittivity with resolution limited only by signal-to noise ratio and not by wavelength. A method of computing scattering vector field from an arbitrary inhomogeneous three-dimensional object was also developed.

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FINAL REPORT

on

TRANSIENT INTERACTION OF ELECTROMAGNETIC PULSES IN DIELECTRICS AND MICROWAVE BIOPHYSICS

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1. BACKGROUND

Due to recent progress in developing equipments that can generate short microwave and millimeter wave pulses, there has been an increasing proliferation of microwave pulse transmitters, some with short pulse width (0.1 microsecond) and extremely high intensity (100-1000 megawatts). Microwave pulse transmitters are used extensively by the military for communication and remote control; using microwave pulses as directive energy weaponry and as means of transporting energy has also been contemplated. Electromagnetic pulses (EMP) are also emitted in nuclear blasts and from EMP simulators. All this production of microwave pulses affects the operation of military personnel in non-combat environment as well as in battle fields. Therefore minimizing microwave damage is central to successful operations of all military units. Understanding basic interactions between microwave pulses and dielectric materials will contribute greatly to the protection of human subjects from microwave damage and to the development of preventive measure.

Until recently most analyses on microwave effects have been based on continuous wave approach. Recognizing the importance of basic understanding of the interactions between short radiation pulses and dielectric materials, and its potential application to radiation hazards and radiation treatment to biological materials, the Walter Reed Army Institute of Research (WRAIR) started a program at the Catholic University of America (CUA), beginning 6/1/85, to study the transient interaction of electromagnetic pulses in dielectrics and microwave biophysics. The program was administrated by the Office of Naval Research (ONR). Originally the program was intended for three years to end on 5/30/88. However, due to budget constraint, the third year funds was not provided and the program prematurely ended on 9/30/87. This document reports the program progress as of the end of funding and constitutes a final report of the program. The main body of the report provides à progress summary with technical details given in the appendices which are publication reprints.

2. PROGRAM OBJECTIVES

The long-term objectives of this program are as follows:

2.1. To understand the basic physics of interaction between microwave radiation pulses and dielectric materials, including biological systems.

2.2. To define and derive characteristic physical quantities relating to the absorption and energy conversion of short radiation pulses in dielectric materials, especially water dominated media, such as biological subjects, and to define biological hazard of microwave pulses.

2.3. To understand the basic interactions of microwave radiation pulses with biological subjects, and to understand the mechanisms of secondary interactions resulting from microwave pulses, to define and to quantify physical and biological parameters of these interactions with respect to dielectric properties and pulse parameters, such as carrier frequency, pulse width, and peak power.

2.4. To develop dosimetric techniques and hazard specification that are applicable for transient, near-field, and high-field regimes, and to develop applications of microwaves, including imagery and target organ analysis.

3. SCOPE OF WORK

The program consists of the following three subjects:

3.1. Transient Dielectric Relaxation and Absorption

This task is to study the interaction of microwave radiation pulses with dielectrics and biological systems, and the material response to ultra-short pulses in the transient regime.

3.2. Microwave to Acoustic Energy Conversion Induced by Microwave Pulses

This task is to study mechanisms through which pressure waves may be generated by microwave pulses, and to derive a relationship between microwave pulses and the generated pressure waves.

3.3. Microwave Scattering, Inverse Scattering, Dosimetry, and Imagery

This task is to develop non-invasive techniques for dosimetry of dielectric bodies under microwave exposure, and to develop algorithm for three-dimensional medical imaging using low-level microwaves.

4. PROJECT PROGRESS

During the first year of this project, research was performed on developing a non-invasive microwave dosimetry technique, and on continuing previous theoretical studies on transient dielectric interaction and microwave to acoustic energy conversion. As progress was being made in WRAIR on the installation of a high-power pulsed microwave generator, our effort in the second year was focused on developing theoretical basis to support forthcoming experiments in WRAIR on biological effects of transient and high power microwave damage. On the transient effects, we have developed a theoretical basis for experimental observation of temporal non-linearity in the transient regime, which may be measurable and applicable to the experimental setup being planned at WRAIR. On microwave acoustics, we incorporate electrostrictive effect in the pervious formulation, and established criteria to predict the dominant mechanism, thermoacoustic or electrostrictive, for generating pressure waves by microwave pulses.[1,2] On dosimetry, we have a major breakthrough on developing an algorithm for evaluating the vector fields both inside and outside a three-dimensional body of arbitrary geometry and dielectric profile.[3] We have also developed a formula for computing the vector fields inside the dielectric body from measurement of scattered fields in a limited region outside the body. Our success in developing the non-invasive dosimetry algorithm also led us to discover a non-diffractional imagery technique, which may provide images with resolution limited only by signal-to-noise ratio, and not by wavelength of the probing microwave or by geometrical configuration of the receiving antenna.[4]

The effort of this program during the two funded years have resulted in publication of six papers.[1,2,3,4,5,6] The following gives a technical summary of the progress and status in each task of this program. Details of research results are given in the appendices, which are reprints of our publications.

4.1. Transient Dielectric Response

Theory of Transient Response

Our effort on this subject has been focused on developing theoretical basis to support forthcoming experiments in WRAIR on nonlinear biological effects of transient and high power microwave damage. The objective was to devise a theoretical scheme for experiments that are able to isolate the effects of short and high-intensity microwave pulses from low-intensity continuous waves (CW) on biological materials. One may directly analyze the materials and compare the damage between pulse-wave exposure and CW exposure. However, from the observation of the damage alone, it is not possible to conclude if the observed pulse or high-intensity effects are direct primary electromagnetic effects or indirect non-electromagnetic secondary effects that are induced by the microwave pulses. Therefore, instead of directly analyzing damage to biological materials, we studied the approach of analyzing the pulse propagation and the field strength of the microwave pulse.

Our previous theoretical studies have shown that, due to a non-steady state and irreversible process in the transient regime, dielectric relaxation cannot be parameterized by time-independent parameters, such as the damping coefficient in the transient regime. However, for experimental and practical purpose, macroscopic parameterization is desirable. Therefore we propose the following time-dependent model in the transient regime for the dielectric polarization current, J(t), which is the time-derivative of the dielectric polarization P(t):[7,8,9,10]

$$\tau(t)\cdot\frac{dJ}{dt} + J(t) = g\cdot\frac{dE}{dt} \tag{1}$$

$$\tau(t) = H(t)\tau_o[1 - \exp(-t/\tau_1)] \tag{2}$$

The model was conceived from the reasoning that the damping coefficient vanished initially and, as molecules approached an equilibrium or a steady state, it gradually increased to a final value, viz., Debye's steady-state value. The time it takes to reach the steady-state value is characterized by τ_1; the function H(t) is the Heavyside function which is zero for $t<0$, 1/2 for $t=0$, and 1 for $t>0$. With this model, it was found that the dielectric is nonlinear in the transient regime in a way that any frequency component of the the dielectric response may depend on the action of different frequencies. Thus, given an electric field as an action, then the dielectric polarization in the frequency regime, P(ω), depends on E(ω) in the following way:

$$P(\omega) = \int_{-\infty}^{\infty} \chi(\omega,\omega')E(\omega')\cdot d\omega' \tag{3}$$

where $\chi(\omega,\omega')$ is the dielectric susceptibility. In mathematical terms, dielectric susceptibility is not diagonal in the frequency regime. This means that, in the time regime, response at a certain time, t′, caused by an action at an earlier time t, does not depend on the difference t-t′ only. Therefore, linear superposition of action-response relationship is no longer valid. This is expected because, in the transient regime, the dielectric is in a non-steady state and undergoes irreversible processes. We also derived the function $\chi(\omega,\omega')$ from eqs. 1 and 2, and obtained:[7,8]

$$\chi(\omega,\omega') = \frac{g}{2\pi i}\cdot\frac{\tau_l}{\tau_o}\cdot\frac{\omega'}{\omega+i0}\cdot\frac{\Gamma(-i\omega\tau_l+\tau_l/\tau_o)\cdot\Gamma(-i\omega'\tau_l+1)}{\Gamma(-i\omega\tau_l+1)\cdot\Gamma(-i\omega'\tau_l+\tau_l/\tau_o)}\cdot\sum_{n=0}^{\infty}\frac{1}{(\omega'-\omega-in/\tau_l)(-i\omega'\tau_l+n+\tau_l/\tau_o)}$$

$$= \frac{g}{2\pi i}\cdot\frac{\tau_l}{\tau_o}\cdot\frac{\omega'}{(\omega+i0)(\omega'-\omega-i0)}\cdot\frac{\Gamma(-i\omega\tau_l+\tau_l/\tau_o)\cdot\Gamma(-i\omega'\tau_l+1)}{\Gamma(-i\omega\tau_l+1)\cdot\Gamma(-i\omega'\tau_l+\tau_l/\tau_o+1)}$$

$$\times\, {}_3F_2(i(\omega'-\omega)\tau_l,\ -i\omega'+\tau_l/\tau_o,\ 1;\ i(\omega'-\omega)\tau_l+1, -i\omega'\tau_l+\tau_l/\tau_o+1;\ 1)$$

where Γ is the gamma function and ${}_mF_n$ is the generalized hypergeometric function[11].

There are several experimental indications that electromagnetic pulses with pulse width of the order of nanoseconds or shorter may produce transient effects in biological materials. One of these experimental indications concerns the life-times of excited vibrational modes of DNA chains. Based on the line-widths of vibrational excitations by microwaves observed recently, the life-times are of the order of 120 nanoseconds.[12,13] The time it takes to reach an equilibrium state or steady state must be longer than these life-times. Another experimental evidence of transient phenomenon is the recent observation of time-dependency of dielectric susceptibility of an inorganic solid under high field.[14] The observation was derived from applying electric fields in the range of megavolts per centimeter to thin-film of amorphous aluminum oxide, Al_2O_3. It was found that the dielectric susceptibility depends on time for as long as hundred seconds. While the value of τ_o, which is the steady-state Debye's relaxation time, is known for most dielectrics, the exact values of τ_l have never been measured. The above experimental observations indicate that non-steady state transient regime exists in dielectrics and it may last longer than the microwave pulse width. Availability of the values of τ_l will provide much knowledge on dielectric response to high-intensity short microwave pulses. Therefore, our research was focused on devising some theoretical base for an experimental measurement of τ_l for some materials, especially for solution of biological materials in liquid water. For dielectrics composed of large molecules, it is expected that τ_l will be quite long comparing to pulse width of existing microwave pulse systems. From the observation of the excited vibrational modes of DNA chains,[12,13] it indicates that τ_l must be of the order of 120 nanoseconds or longer. This suggests that transient non-steady state effect may play an important role in response of DNA solutions to nanosecond microwave pulses.

Experimental Proposal

The above result suggests that any transient effect or high field effect in dielectrics is expected to produce non-linear harmonic and anharmonic generation in the electromagnetic spectrum. Conventional non-linear analyses employ network analyzers to study the output spectrum from dielectric specimens which are exposed to a monochromatic wave; non-linearity is inferred if harmonic generations are observed in the output spectrum. This method cannot be applied to pulsed fields since the input contains a wide spectrum of frequencies. Therefore different method must be undertaken to analyze transient effects and high field pulse effects. To this end, we have found a macroscopic effect of the transient state model that is applicable to pulse inputs; the effect may also be measurable and applicable to an experimental setup that has been planned at WRAIR. To briefly summarize, our approach is to analyze the scattering matrix of a dielectric specimen under an incident pulsewave. The scattering matrix is constructed from the measurements of input and output waves and analyzed in the frequency domain. Transient effects or high-field pulse effects are inferred if the scattering matrix have off-diagonal elements. This scattering matrix approach appears to be, in a very broad sense, similar to the inverse scattering approach that we have developed in microwave dosimetry and imagery. Indeed, all physical techniques which infer the characteristics of unknown objects by analyzing their action-response data are, in a broad sense, inverse scattering and imagery. The difference is in the physical characteristics that are being "imaged". In the scattering matrix approach described here, it is the temporal and spectral dielectric response that is "imaged", whereas in conventional imaging, the spatial distribution of some physical characteristics is imaged.

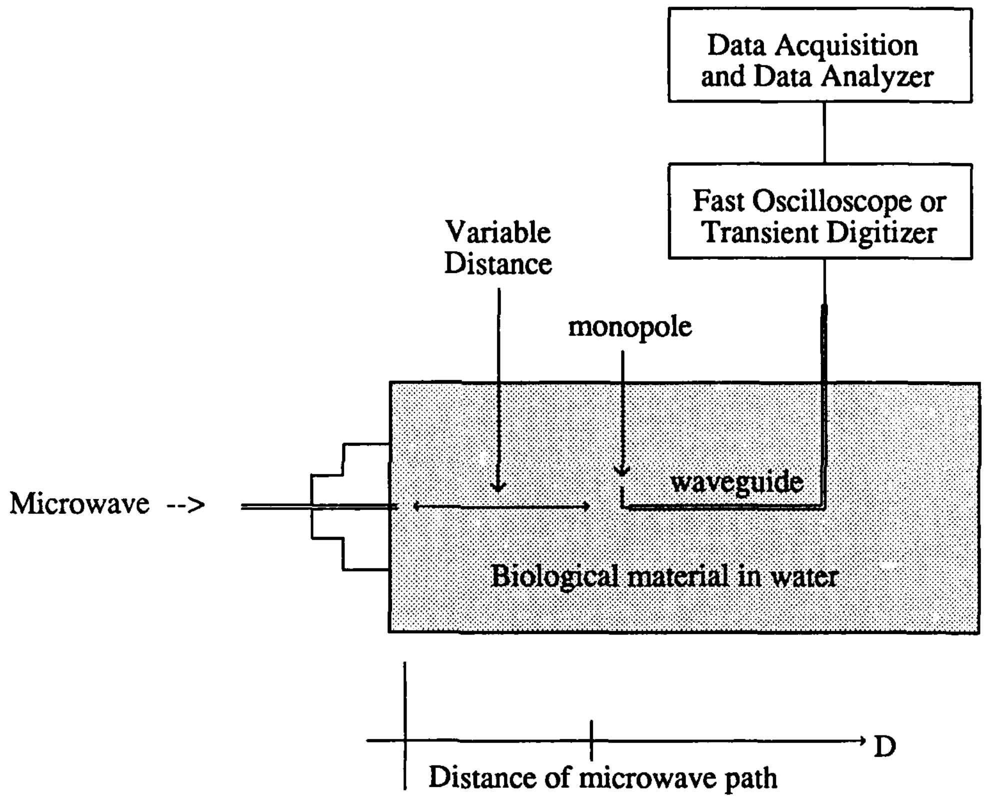

Figure 1. Sketch of experimental setup to measure the field strength along the path of a microwave pulse in a solution of a biological material in water.

To describe the scattering matrix approach in more detail, let us consider a one-dimensional propagation in an experimental setup as illustrated in Figure 1. Take two points along the propagation path of a microwave pulse, say x_1 and x_2. The material between these two points may be regarded as the specimen; the electric field of the microwave pulse at x_1 may be considered as an input field to this specimen, and that at x_2 may be considered as the output field from the specimen. Both the input field, denoted by $f^{(i)}$, and output field, denoted by $f^{(o)}$, are functions of time. By making time-resolved measurements of these two functions at a certain sampling rate, one obtains two column vectors in the time domain; these two vectors may be Fourier-transformed to the frequency space. We shall construct a scattering matrix from the measurements of a set of input fields and the corresponding set of output fields. If there are total of N samples in the time-resolved measurements, then these two vectors are of N-dimensional. In order to construct the scattering matrix, one must then prepare N input fields and N output fields. So, measurements of the fields of N pulses must be made. Let $\{f_n^{(i)}\}$ and $\{f_n^{(o)}\}$, where n = 1, 2, ..., N, be the sets of output vectors and input vectors, respectively. From these two sets of fields, we may then construct the input matrix and output matrix as follows: Lining up the N input vectors, $f_n^{(i)}$, one by one as columns of a matrix, one obtains a square matrix $F^{(i)}$, which is the input matrix; similarly, lining up the N output vectors, $f_n^{(o)}$, one by one as columns of a matrix, one obtains the output matrix, $F^{(o)}$. It can then be proven that the scattering matrix is the product of these two matrices:

$$S = F^{(o)} \cdot [F^{(i)}]^{-1}. \tag{4}$$

The scattering matrix obtained this way has the property that

$$S f_n^{(i)} = f_n^{(o)} \quad (n = 1, ..., N). \tag{5}$$

It is remarked that the N microwave pulses must be linearly independent, viz., the input matrix, $F^{(i)}$, must be non-singular. In other words, the determinant of $F^{(i)}$ must not vanish. Instead of making measurements on N input pulses, one may alternatively use one single pulse, and make time resolved measurements at N+1 successive points of equal spacing along the path of the pulse. Thus, the pulse measured at, say x_i, is the output pulse of the previous layer of material and the input pulse of the next layer of material. Since the dielectric is assumed to be homogeneous, the layers of material between all successive pairs of points are identical. So, the pulses at x_1, x_2, ..., x_N are N input pulses to the specimen, and the pulses at x_2, x_3, ..., x_{N+1} are corresponding output pulses. Owing to dielectric dispersion and, perhaps, also transient or other non-linear effects, these N input pulses will be linearly independent, and may then be used to construct the input matrix.

Based on the transient state model that was discussed earlier (cf. eqs. 1-4), we have studied the properties of the scattering matrix S constructed from the field measurement data as described in the last paragraph. We found a distinct property which may be used to isolate transient effect from continuous wave (CW) effect. If there is any transient response in the biological material, or any dielectric material, between the two points x_1 and x_2, then the matrix S will not be diagonal in the frequency domain. Conversely, if there is no transient effect, then the scattering matrix must be diagonal in the frequency domain. Thus, this property may be used to isolate transient response from CW effect. This approach is applicable to the measurement setup planned at WRAIR. While we believe that the basic principle of this approach is sound, there is still a technical problem that needs further investigation. The problem concerns the finite sampling rate and finite time duration of measurement. Ideally, theory requires that infinitely many pulses be measured at both x_1 and x_2, and that measurements be made continuously in time. Finite sampling of measurement on finite number of pulses will then cause some "spreading" of the diagonal elements of the matrix S into off-diagonal part, thereby produce some mixing of the CW effect with transient effect. The effect of this spreading may be treated as a noise in the measurement data. The magnitude of this noise level remains to be investigated.

The effect of off-diagonal matrix elements in transient response is equivalent to harmonic generation in non-linear circuit theory. Therefore, the principle of the above approach also applies to high-field effect, however, there is a problem that needs separate consideration. Any high-field effect must give rise to a E^2 dependency in the output fields, therefore, some normalization method may also be needed on the output fields, as well as the input fields. The advantage of this method over conventional method of analyzing harmonic generation is that it is not limited to monochromatic input source; pulse input of arbitrary waveform may be employed.

4.2. Stress Waves and Pressure Waves Induced by Microwave Pulses

Acoustic waves generated by pulsed microwaves have been cited as a mechanism for microwave hearing.[15,16,17] More recently it has been demonstrated that acoustic waves are transduced in dielectric objects simulating the ocular lens when exposed to pulsed microwaves.[18] The effect has also been cited as the operant mechanism for cellular damage in studies of the murine ocular lens in vitro.[19] Three theories on the microwave auditory mechanism have been reviewed and compared by Lin,[20] viz., the radiation pressure theory, the electrostrictive theory, and the thermoacoustic theory. Among them it was found that only the thermoacoustic mechanism could produce elastic waves of magnitude large enough to explain the experimental observations. Comparing to the magnitude of acoustic pressure generated in typical biological tissues, the electrostrictive effect was found to be about two orders of magnitude smaller, while the radiation pressure three orders of magnitude smaller.[21]

Previous theories on microwave electrostrictive process and microwave thermoacoustic process are, however, based on a linear wave equation with a generating function derived from the microwave pulses. Pressure waves are thereby generated in a way similar to a forced harmonic oscillator. In the case of the thermoacoustic process, the generating function is derived from an inhomogeneous heating by the microwaves, whereas in the case of the electrostrictive process, it is derived from stress due to dielectric polarization.[22,23] This approach fails to consider the proper balance of the distribution of the absorbed microwave energy among the internal thermal energies and the bulk kinetic energy, and the effect of thermal or dielectric discontinuities at medium interface. Also neglected is the coupling between the thermoacoustic process and electrostrictive process, which may result from dependency of dielectric permittivity on various thermodynamical coefficients, such as mass density, temperature, and pressure; the transient effect of ultra-short electromagnetic pulses may further enhance the electrostrictive effect. We approached these problems by making a thorough formulation of the coupling of microwave pulses to pressure waves, with particular emphasis on material discontinuity and electromagnetic transient effect. Elastic wave equations were then derived for both thermoacoustic and electrostrictive effects, and some models of air-water system were used to make numerical computation and estimate the generated pressure waves in water. Contrary to previous theory that thermoacoustic pressure waves were generated mainly by inhomogeneous distribution of microwaves in dielectrics,[20] it was found that pressure waves are generated whenever there is a discontinuity in thermal or dielectric parameters in the medium. As to the ratio of electrostrictive effect to thermoacoustic effect, it depends on the rise time of the microwave pulse, being greater than one for rise time shorter than a nanosecond, and smaller than one for rise time longer than a nanosecond. This result is in contrary to previous estimate based on a simpler theory, which gave a ratio of the order of 10^{-2}, and independent of the rise time of microwave pulses.

The following paragraphs provide a summary of our results in thermoacoustic and electrostrictive effects. Details of the formulation are given in Appendices A, B, and F and other references cited therein.

Thermoacoustic Effect

Our approach to derive the coupling from microwave pulses to acoustic waves started from the basic laws of thermodynamics: the conservation of mass, the conservation of momentum, the conservation of energy, and the thermodynamic equation of state;the thermodynamic equation of state was represented by the following expression of internal energy in terms of some thermodynamical coefficients:

$$d_t U_I = [-C_p/(\rho\beta_p) + (1/\rho^2)p_{ij}\partial_j v_i/\nabla\cdot v]d_t\rho + (C_v/\beta_p)(\kappa_T)_{ij}d_t p_{ij} \tag{7}$$

which we derived from the first and second laws of thermodynamics.[24] In the above equation, ρ is the mass density, $\mathbf{v}$ is the bulk velocity, p_{ij} is the stress tensor, C_v and C_p are the specific heats (per unit mass) at constant volume and constant pressure, respectively, β_p is the isobaric thermal expansion coefficient, and $(\kappa_T)_{ij}$ is the isothermal compressibility tensor. By mutual substitution among equations representing these laws, one may obtain the wave equations for any of the thermodynamic quantities. The boundary conditions may be obtained by first transforming these equations to the Lagrangian specification (in which the boundary surface is stationary) and then integrating each term across a thin layer of the boundary interface.[6,24] If the strain tensor is isotropic, one obtains the following wave equation for the stress tensor, p_{ij}:

$$\partial_i[(\rho_o/\rho)^{1/3}(C_v/C_p)(\kappa_T)_{ij}\partial_t p_{ij}] - \partial_i[(\rho_o/\rho)^{1/3}(1/\rho)\partial_j p_{ij}]$$
$$= \partial_t[(\rho_o/\rho)^{1/3}(\beta_p/C_p)P] \qquad (8)$$

where C_v and C_p are the specific heats (per mass) at constant volume and constant pressure, respectively, β_p the isobaric thermal expansion coefficient, κ_T the isothermal compressibility, ρ the mass density, P the microwave specific absorption rate (SAR), and the subscript $_o$ signifies that the quantity is evaluated at its ambient equilibrium value.

To illustrate the implications of the wave equations and their respective boundary conditions, we consider a dielectric sphere of radius a surrounded by air at 1 atmospheric pressure. A square pulse of microwave of duration τ and amplitude P_o is incident upon the sphere. The sphere is assumed to be small so that the microwave absorption exhibits no spatial variation. In the linear approximation, the solutions of pressure waves in the frequency domain are then:

$$p_1(r,\omega) \;=\; -i\left(\frac{c^2\rho\beta_p}{C_p}\right)_1 \frac{P(\omega)}{\omega - i0}\cdot\left[\frac{j_o(k_1 r)}{j_o(k_1 a) - \tan\varphi\cdot\frac{h_o(k_2 a)}{h_o'(k_2 a)}\cdot j_o'(k_1 a)} - 1\right] \qquad (9)$$

and

$$p_2(r,\omega) \;=\; -i\left(\frac{c^2\rho\beta_p}{C_p}\right)_1 \frac{P(\omega)}{\omega - i0}\frac{h_o(k_2 r)}{h_o(k_2 a)}\cdot\left[\frac{j_o(k_1 a)}{j_o(k_1 a) - \tan\varphi\cdot\frac{h_o(k_2 a)}{h_o'(k_2 a)}\cdot j_o'(k_1 a)} - 1\right] \qquad (10)$$

where $j_n(x)$ and $h_n(x)$ are, respectively, the spherical Bessel and Hankel functions of the first kind of order n, the subscripts 1 and 2 label the dielectric and the air media, respectively, $c_{1,2} = [C_p/\rho C_v\kappa_T]^{1/2}$, $\tan\varphi = (\rho c)_2/(\rho c)_1$, and $P(\omega)$ is the Fourier transform of the square pulse SAR, which is given by:

$$P(\omega) \;=\; -(2\pi)^{1/2}\, P_o\, \frac{1 - e^{i\omega\tau}}{2\pi i\cdot(\omega - i0)} \qquad (11)$$

Similar results may also be obtained for the bulk velocity at either side of the interface. The total acoustic energy coupled into the air may be obtained by calculating the work done by the dielectric on the air at the interface. To the first order, the result is:

$$E_{air} \;=\; 4\pi a^2 p_o \int_{-\infty}^{\infty} v_1(a,t)dt \;=\; 4\pi a^2 p_o (2\pi)^{1/2}\cdot v_1(a,\omega{=}0)$$

$$= (2\pi)^{1/2}\,\frac{4\pi a^3}{3}\, p_o\left[\frac{\beta_p}{C_p}\right]_1 \cdot P(\omega{=}0) \qquad (12)$$

Since $E_{abs} = (2\pi)^{1/2}(4\pi a^3/3)\rho_l P(\omega=0)$ is the total microwave energy absorbed through the entire pulse, coupling efficiency of the absorbed microwave energy to the acoustic energy in the air is then:

$$\eta_{air} = \frac{E_{air}}{E_{abs}} = p_o[\frac{\beta_p}{\rho C_p}]_l \quad (13)$$

Take the dielectric to be water at 30 °C, so $\beta_p = 2.8\text{x}10^{-4}$ °C^{-1} and $C_p = 4.186\text{x}10^7$ erg/gm-°C. With the equilibrium pressure of the air, p_o, being 1 atm = $1.01\text{x}10^6$ dynes/cm^2, the coupling efficiency is then $\eta_{air} = 6.7\text{X}10^{-6}$ for a sphere of 1 cm diameter.

The minimum pressure amplitude generated in the water may be estimated by the fundamental harmonic in eq. 9. Taking an optimal pulse width of $\tau = \pi/\omega_o$, it gives a pressure amplitude of $(2a/\pi)(c\beta_p/C_p)_l P_o$. Using the values of β_p and C_p for 30 °C as cited above, a peak SAR of P_o = 15 kW/gm results in a pressure wave of amplitude equal to 0.1 bar in the water,[25] which is 10% of the initial equilibrium pressure. This fraction of variation in pressure will also result in at least equal fraction of error in the linear approximation. Similar calculation was also made for a one-dimensional air-water system.[24] It was found that, accounting for only the n = ±1 term, a peak SAR of 6.5 kW/gm results in a pressure wave of amplitude equal to 0.1 bar in the water;[26] if up to the first 11 terms are included, a peak SAR of 4.5 kW/gm suffices to generate pressure waves of such amplitude.

Electrostrictive Effect

We approached the problem of electrostrictive effect by including, in the equations of conservation of momentum and conservation of energy, the following electrostrictive tensor:[27]

$$\sigma_{ij} = \frac{E^2}{8\pi}[\varepsilon - \rho(\frac{\partial\varepsilon}{\partial\rho})_T]\delta_{ij} - \frac{\varepsilon}{4\pi}\cdot E_i E_j \quad (14)$$

The total stress on the dielectric is the sum of material stress and electrostrictive stress:

$$s_{ij} = p_{ij} + \sigma_{ij} \quad (15)$$

However, it is the material stress p_{ij} which is responsible for the material strain, and therefore accountable in the thermal internal energy. Indeed, in the presence of an electromagnetic field, the material stress automatically adjusts itself in reaction to the electrostrictive stress. Therefore, in deriving the equation of state which is represented by an expression of internal energy in terms of some thermodynamical coefficients (cf. eq. 7), only the material stress is included. Upon some isotropic assumption, we then derive the following wave equation for the total stress tensor:[1,2]

$$\partial_i\left(\frac{1}{\rho}\partial_j s_{ij}\right) - \partial_t\left(\frac{C_p}{\beta_p}+\frac{\sigma}{\rho}\right)^{-1}\cdot\left(\frac{C_v}{\beta p}(\kappa_T)_{ij}\,\partial_t s_{ij}\right)$$
$$= \left(\frac{C_p}{\beta_p}+\frac{\sigma}{\rho}\right)_o^{-1}\cdot\left[\rho_o\partial_t P + \left(\frac{\rho C_v}{\beta_p}(\kappa_T)_{ii}\right)_o\partial_t^2\sigma - \partial_t^2\left(\frac{\varepsilon|E|^2}{8\pi}\right)\right] \quad (16)$$

where the subscript o signifies that the quantity is evaluated at its ambient equilibrium value, and σ is the isotropic electrostrictive pressure:

$$\sigma = -\left(\frac{|E|^2}{16\pi} \left[\frac{\varepsilon}{3} - \rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T \right] \right) \tag{17}$$

For an isotropic dielectric, $s_{ij} = -s\delta_{ij}$ and $(\kappa_T)_{ij} = \kappa_T/3$, so $\Sigma(\kappa_T)_{ii}$ (sum over i) is κ_T, the above wave equation is then further reduced to

$$\nabla^2 s - \left(\frac{C_p}{\beta_p} + \frac{\sigma}{\rho} \right)_o^{-1} \cdot \left(\frac{\rho C_v \kappa_T}{\beta_p} \right)_o \partial_t^2 s$$
$$= -\left(\frac{C_p}{\beta_p} + \frac{\sigma}{\rho} \right)_o^{-1} \cdot \left[\rho_o \partial_t P + \left(\frac{\rho C_v \kappa_T}{\beta_p} \right)_o \partial_t^2 \sigma - \partial_t^2 \left(\frac{\varepsilon |E|^2}{8\pi} \right) \right] \tag{18}$$

Equation 18 is a typical linear wave equation with the velocity $\tilde{c}$:

$$\tilde{u} = \left(1 + \frac{\sigma\beta_p}{\rho C_p} \right)_o^{1/2} \cdot \left(\frac{C_p}{\rho C_v \kappa_T} \right)_o^{1/2} = \left(1 + \frac{\sigma\beta_p}{\rho C_p} \right)_o^{1/2} \cdot u \tag{19}$$

where u denotes the acoustic velocity in the dielectrics in the absence of the electromagnetic waves. The electromagnetic waves change the acoustic velocity through the electrostrictive pressure σ. To estimate the magnitude of this correction, we consider water at room temperature as the dielectric, for which $\beta_p = 2.8\times10^{-4}$ °C^{-1}, $C_p = 4.186\times10^7$ erg/gm-°C, $\rho = 1$ gm/cm^3, and $\varepsilon = 80$. We also assume that the dielectric permittivity is linearly proportional to the mass density, so $(\partial\varepsilon/\partial\rho)_T = \varepsilon/\rho$, then eq. 17 gives $\sigma = (\varepsilon|E|^2)/(24\pi)$. Assume a plane electromagnetic wave of intensity I = 1 kW/cm^2 (which is equivalent to an electric field of amplitude 2.9×10^4 volts/m), then its field magnitude is $|E|^2 = 8\pi I/(c\sqrt{\varepsilon}) = 0.94$ erg/cm^3, where c is the speed of light in vacuum. Then $\sigma = 1$ dyne/cm^2, and the fractional change to the acoustic speed is $(\sigma\beta_p)/(\rho C_p) = 6.7\times10^{-12}$, which is insignificant. While the fractional change of acoustic speed is negligibly small for most dielectrics under currently available microwave sources, it may be appreciable for some dielectrics under lower frequency electromagnetic fields.

As illustrated at the end of the last paragraph, for most dielectrics and for microwave intensity up to gigawatts/cm^2, the term σ/ρ on both sides of eq. 18 may be neglected. Eq. 18 may then be rewritten as

$$\nabla^2 s - \frac{1}{u^2} \partial_t^2 s = -\frac{\beta_p}{C_p} \partial_t \left[\rho_o P + \left(\frac{\rho C_v \kappa_T}{\beta_p} \right)_o \partial_t \sigma - \partial_t \left(\frac{\varepsilon |E|^2}{8\pi} \right) \right] \tag{20}$$

where $u = [\rho C_v \kappa_T / C_p]^{1/2}$ is the speed of sound in the dielectric in the absence of the electrostrictive force. The three terms inside the brackets on the right hand side are the generating forces of pressure waves. The first term represents the thermoelastic effect, the second term is the electrostrictive force, and the third term comes from the electromagnetic energy of dielectric polarization. The above equation will be our basis for comparing the relative strength of the three forces on microwave to pressure wave coupling. From the expression of these three forces in the above equation, one sees that time variation, namely, transient effect, of the microwave pulses has an important effect on the electrostrictive force and on the polarization energy. Here we may make a preliminary estimation of the relative sizes of these three coupling forces. First we express them in terms of $|E|^2$. Let α be the attenuation coefficient of microwave intensity as defined by the equation $I(x) = I_o e^{-\alpha x}$. Then the first term is $\rho_o P = \alpha I = (\alpha c\sqrt{\varepsilon}/8\pi)|E|^2$. If the dielectric permittivity is linear in ρ, then $(\partial\varepsilon/\partial\rho)_T = \varepsilon/\rho$, so eq. 17 gives $\sigma = (\varepsilon|E|^2)/(24\pi)$ and the electrostrictive term gives $[(\rho\varepsilon C_v\kappa_T)/(24\pi\beta_p)]\partial_t|E|^2$. Denote by t_r the rise time of a microwave pulse, then $\partial_t|E|^2 \sim |E|^2/t_r$. Thus, the relative magnitudes of the electrostrictive and polarization terms with respect to the thermoelastic term are, respectively,

$$\frac{\text{Electrostrictive effect}}{\text{Thermoelastic effect}} = \frac{\rho C_v \kappa_T \sqrt{\varepsilon}}{3c\alpha\beta_p}\,\frac{1}{t_r}$$

$$\frac{\text{Polarization effect}}{\text{Thermoelastic effect}} = \frac{\sqrt{\varepsilon}}{c\alpha}\,\frac{1}{t_r} \qquad (21)$$

One sees that the second and the third driving forces may be larger than the thermoelastic term if the microwave is rapidly modulated, contrary to the estimate by previous theory that the electrostrictive effect is two orders of magnitude smaller[20]. For water at 30 °C, ρ = 1 gm/cm^3, $C_p = 1.013 \cdot C_v = 4.186\times10^7$ erg/gm°C, $\kappa_T = 4.46\times10^{-11}$ cm^2/dyne, $\beta_p = 2.8\times10^{-4}$ °C^{-1}, and, at 3 GHz, $\alpha = 0.88$ cm^{-1} and $\varepsilon = 80$. The above ratios are then, respectively:

$$\frac{\text{Electrostrictive effect}}{\text{Thermoelastic effect}} = \frac{0.75 \text{ nanosec}}{t_r}$$

$$\frac{\text{Polarization effect}}{\text{Thermoelastic effect}} = \frac{0.34 \text{ nanosec}}{t_r} \qquad (22)$$

One may conclude that, for water, a rise time of 1 nanosecond is the marginal modulation rate, beyond which the electrostrictive term and the polarization term contribute more to the pressure waves than the thermoelastic term.

Comparison with Experimental Measurements

Pressure measurements were made at WRAIR in air-water system similar to the models in our theoretical computation. Pressure waves were measured in both air and saline liquid for two types of vessels placed in an WR 975 exposure system. The first vessel was ca. one inch on each side with a 1/8 inch wall thickness. The second vessel was circular in cross section, one inch in outer diameter, 1/8 inch wall thickness, and made of acrylic plastic. Both were filled with phosphate buffed saline. These vessels were placed into the WR 975 via the same waveguide below cut-off window as the actual lenticular exposure chamber. The two vessels extended beyond the waveguide to provide a liquid column for coupling of the acoustic wave into regions where the hydrophone would not be subject to direct influence of the electromagnetic field. Each vessel was separately matched to the microwave source with the triple stub tuner. Typical return losses were ca. -15 to -20 dB for either vessel. All liquid based pressure measurements are expressed in dB relative to 0 dB = 1 micro Pascal, and all air based pressure measurements are made in dB relative to 0 dB = 20 micro Pascal. Both air and water pressure measurements were tested for direct electromagnetic field effects. The results of the measurements appeared to be in agreement with our theoretical calculation.[6]

4.3. Microwave Scattering, Inverse Scattering, and Dosimetry

An important practical aspect of microwave biological damage concerns the dosimetry of microwaves in biological bodies. Biological bodies are complicate dielectric structures and multiple scattering and reflection from dielectric interfaces often make it impossible to predict microwave dose distribution in the bodies. Experimental measurements using insertion technique are used, but the instruments often produce unpredictable disturbances on the electromagnetic field and thus render the measurements inaccurate. Therefore non-invasive measurement techniques are much desired. Our effort in this subject has been to develop an inverse scattering approach to accomplish microwave dosimetry by measuring scattered fields.

There are two aspects in this subject. One is the determination of scattered fields from the dielectric profile of a dielectric object, and another concerns the determination of the electric fields inside the target from measurement of the scattered fields in a limited region outside the target. Both aspects have been under intensive investigation by many researchers. On the determination of scattered fields from dielectric profiles of scattering objects, previous approaches by other investigators included: 1) Born approximation, of which the accuracy was limited,[28] 2) the moment method by Richmond, which applied to only two-dimensional objects, viz., objects with cylindrical symmetry,[29,30] and 3) linear parameter technique with moment method, which approximated the field inside the scatterer by a linear combination of some basis functions and then numerically solved the linear coefficients. Therefore our main effort on this aspect has been to extend Richmond's moment method to three-dimensional object with arbitrary geometry and dielectric profile. Our effort has been quite successful. We have developed the following algorithm to compute the scattered field of arbitrary three-dimensional dielectric objects from their dielectric profile. As to the second problem, viz., determination of electric fields inside a target from measurement of scattered fields in a limited region outside the target, it is the problem of inverse scattering, and is also related to microwave imaging; once the field inside the target is known, one may then obtain a dielectric image in terms of the profile of dielectric permittivity of the target. On this subject, we also developed two inverse scattering approaches. The first approach utilizes a method of "soft focusing" of scattering data to reconstruct qualitative dielectric images with negligible computing time. The second approach utilizes a method of converting the integral wave equation to matrix equation and reconstructs images by matrix inversion. This method provides images with resolution limited only by signal-to-noise ratio and computer power, and not by wavelength. Both algorithms achieve three-dimensional imaging by measuring scattered waves in the near zone where the wave structure is correlated to the "depth" of the target.

Microwave Scattering

The objective of this problem was to develop a method to compute scattered microwave fields from an arbitrary three-dimensional inhomogeneous object. Our approach is to convert the integral equation into a matrix equation by digitizing the target space and the measurement space. First, denote by V_o the region occupied by the dielectric object, and by V_α a region outside of V_o in which scattered fields are measured. We divide both V_o and V_α into a number of small cells, say, N cells, and denote by $\mathbf{x}_i$ and $\mathbf{y}_i$, respectively, the centers of the ith cell in V_α and V_o. Let $f_o^{(i)}$ be a N-dimensional vector representing the incident field in the N cells inside the dielectric body V_o, and let $f_\alpha^{(s)}$ be a N-dimensional vector representing the scattered fields in the N cells inside the measurement region V_α. Then we have developed the following formula to compute $f_\alpha^{(s)}$ from the incident field $f_o^{(i)}$:

$$|f_\alpha^{(s)}\rangle = G_\alpha(S^{-1} - G_o)^{-1}|f_o^{(i)}\rangle \qquad (23)$$

where S, G_o, and G_α are, respectively, dielectric profile of the scattering body, Green's matrix inside V_o, and correlated Green's matrix between V_α and V_o; $f_o^{(i)}$ is the incident field inside the target, which is known and readily obtainable in analytic form. Note that, since we are dealing with vector fields, each element of the N-dimensional vectors is itself a 3-dimensional vector, and each element of the N x N matrices is a 3 x 3 matrix. Explicitly, the matrix S is given by:

$$S_{ij} = \frac{-1}{\varepsilon_m} [\varepsilon(\mathbf{y}_i) - \varepsilon_m]\, \delta_{ij} \qquad (\mathbf{y}_i \subset V_o) \tag{24}$$

As to G_o and G_α, we have been successful in developing analytical formulas for these matrices, and thereby avoided making any Born approximation or linear parameterization. Denoting by k_m the wave number in the background medium, a the radius of a sphere of volume equal to that of the cells, $\mathbf{y}_i$ and $\mathbf{y}_j$, respectively, the centers of the ith and jth cells inside V_o, and $\mathbf{x}_i$ the center of the ith cell in V_α, the results are, for the matrix G_o:

$$i = j: \quad (G_o)_{ij} = \overleftrightarrow{\mathbf{I}} \left(1 + \frac{2}{3} a^2 \frac{d}{da} \left[\frac{\exp(ik_m a)}{a} \right] \right) \qquad (\mathbf{y}_i, \mathbf{y}_j \subset V_o)$$

$$i \neq j: \quad (G_o)_{ij} = a \frac{\exp(ik_m|\mathbf{y}_i - \mathbf{y}_j|)}{|\mathbf{y}_i - \mathbf{y}_j|} \cdot [\cos(k_m a) - \frac{1}{k_m a} \sin(k_m a)] \qquad (\mathbf{y}_i, \mathbf{y}_j \subset V_o)$$

$$\times \left(\overleftrightarrow{\mathbf{I}}(1 - \frac{1}{ik_m|\mathbf{y}_i - \mathbf{y}_j|} + \frac{1}{(ik_m|\mathbf{y}_i - \mathbf{y}_j|)^2}) - \frac{(\mathbf{y}_i - \mathbf{y}_j)(\mathbf{y}_i - \mathbf{y}_j)}{|\mathbf{y}_i - \mathbf{y}_j| \cdot |\mathbf{y}_i - \mathbf{y}_j|}(1 - \frac{3}{ik_m|\mathbf{y}_i - \mathbf{y}_j|} + \frac{3}{(ik_m|\mathbf{y}_i - \mathbf{y}_j|)^2}) \right) \tag{25}$$

and, for the correlated matrix G_α between V_α and V_o:

$$(G_\alpha)_{ij} = a \frac{\exp(ik_m|\mathbf{x}_i - \mathbf{y}_j|)}{|\mathbf{x}_i - \mathbf{y}_j|} \cdot [\cos(k_m a) - \frac{1}{k_m a} \sin(k_m a)] \qquad (\mathbf{x}_i \subset V_\alpha,\ \mathbf{y}_j \subset V_o)$$

$$\times \left(\overleftrightarrow{\mathbf{I}}(1 - \frac{1}{ik_m|\mathbf{x}_i - \mathbf{y}_j|} + \frac{1}{(ik_m|\mathbf{x}_i - \mathbf{y}_j|)^2}) - \frac{(\mathbf{x}_i - \mathbf{y}_j)(\mathbf{x}_i - \mathbf{y}_j)}{|\mathbf{x}_i - \mathbf{y}_j| \cdot |\mathbf{x}_i - \mathbf{y}_j|}(1 - \frac{3}{ik_m|\mathbf{x}_i - \mathbf{y}_j|} + \frac{3}{(ik_m|\mathbf{x}_i - \mathbf{y}_j|)^2}) \right) \tag{26}$$

Details of description of these quantities and derivation of the formulas are given in Appendix C.

Microwave Dosimetry and Quantitative Microwave Imaging by Matrix Inversion

The Green's matrix approach described above also allowed us to solve the second aspect of dosimetry problem, viz., the determination of the electric field inside the target from measurement of the scattered field in a limited region outside the target. We have derived the following equations relating the scattered fields in V_o and in V_α to the total fields inside the dielectric body, V_o:

$$|f_o^{(s)}\rangle = G_o S |f_o\rangle \tag{27}$$

$$|f_\alpha^{(s)}\rangle = G_\alpha S |f_o\rangle \tag{28}$$

where f_o is a N-dimensional vector representing the total fields in the N cells of the dielectric body. Applying the inverse of G_α to both sides of the second equation and substituting the result to the first equation, and then adding the incident fields $f_o^{(i)}$ to both sides, one gets:

$$|f_o\rangle = |f_o^{(i)}\rangle + G_o G_\alpha^{-1} |f_\alpha^{(s)}\rangle \tag{29}$$

which gives the total field inside the dielectric body in terms of the measured scattered field in any region, say V_α, outside the body. With this formula, we have accomplished the principal goal of non-invasive dosimetry.

The above approach may also be extended to microwave imaging. Once the field is known inside the target V_o, one may then derive the dielectric profile inside the target. To this end, we first derived the following relationship:

$$S[|f_o^{(i)}\rangle + G_o G_\alpha^{-1} |f_\alpha^{(s)}\rangle] = G_\alpha^{-1} |f_\alpha^{(s)}\rangle \tag{30}$$

from which we obtained the dielectric profile inside the target in terms of the scattered field outside the target:

$$S_{ii} = \frac{-1}{\varepsilon_m}[\varepsilon(y_i) - \varepsilon_m] = \frac{\sum_j (G_\alpha^{-1})_{ij} f_\alpha^{(s)}(\mathbf{x}_j)}{f_o^{(i)}(\mathbf{y}_i) + \sum_{j,k} (G_o)_{ij}(G_\alpha^{-1})_{jk} f_\alpha^{(s)}(\mathbf{x}_k)} \tag{31}$$

The above equation gives the dielectric permittivity of the i^{th} cell, S_{ii}, in the target in terms of the scattering fields $f_\alpha^{(s)}(\mathbf{x}_j)$ in any scattering space, V_α, outside the scatterer, and the incident fields $f_o^{(i)}$ inside the scatterer. The incident fields inside the scatterer, $f_o^{(i)}(\mathbf{x}_j)$, are known analytically.

There is still one problem that needs further study. It concerns the data stability of the inverse of the matrix G_α. Our dosimetry algorithm, as described by the above equation, requires computation of the inverse of G_α. If this matrix is almost singular, then computation of its inverse may be unstable with respect to noises and errors in the data of its matrix elements. Therefore, further effort on non-invasive dosimetry must be focused on developing techniques to stabilize the inverse of G_α.

Microwave Dosimetry and Qualitative Microwave Imaging by "Soft Focusing"

The objective of inverse scattering is to reconstruct the target from the scattered field. From Maxwell's electromagnetic theory, if one knows the scattered field everywhere in space, the source of the field, which is the induced charge-current distribution in the target, can be derived completely. However, in practice, one can only measure the scattered field exterior to the target and only at a limited number of points in space which are often confined in a small region. The question is then how much information on the scattering target one can infer based on a limited knowledge of the scattered field. Here we remark that the term "scattering field" differs from the conventional definition in the sense that it refers to a field anywhere outside of the target; it does not need to be far away from the target. Indeed, the fields for image reconstruction must be close to the target in order to contain information on the depth of the target.

Our approach to inverse scattering with a limited number of data is to use a soft focusing technique to focus the scattering data back to the target. Mathematically, soft focusing is similar to regular focusing of radiation, which we call "hard focusing". In hard focusing, the substance is some sort of radiation, the tool is a lens, and the focal point is where the radiation energy converges. In parallel, the substance of soft focusing is a set of information data, the focusing tool is some algorithm, and the focal point is where the information consolidates. The soft focusing technique is based on an inverse scattering theorem that we have formulated:[5,31]

$$\frac{c}{\varepsilon_m}\iiint_{V_o}\left[-(\nabla\cdot\mathbf{A}_w)\left(\nabla\cdot\frac{\chi-\chi_m}{\chi}\mathbf{P}\right)+k_m^2\mathbf{A}_w\cdot\frac{\chi-\chi_m}{\chi}\mathbf{P}\right]d\mathbf{x} = \sum_n \mathbf{J}_n\cdot\mathbf{E}_{scatt}(\mathbf{x}_n) \tag{32}$$

where the quantities are defined as below:

c	Speed of light in vacuum.
V_o	Space occupied by the target.
ε_m, χ_m	Dielectric susceptibility and dielectric permittivity, respectively, of water, which is the background medium.
$\chi = \chi(\mathbf{x})$	Dielectric susceptibility of the target.
$k_m = \sqrt{\varepsilon_m}\omega/c$	Wave number of the probing microwave in the background medium.
$\omega/2\pi$	Microwave frequency.
$\mathbf{P} = \mathbf{P}(\mathbf{x})$	Induced dielectric polarization in the target.
$\mathbf{x}_n$	Coordinate of the n^{th} element of the receiving array.
$\mathbf{E}_{scatt}(\mathbf{x}_n)$	Electric field of the scattered wave measured by the n^{th} element of the receiving array.
$\mathbf{J}_n$	Weighing factor to be applied to the n^{th} element of the array.
$\mathbf{A}_w = \mathbf{A}_w(\mathbf{x})$	Vector field that would be produced by a set of current elements equivalent to the set of weighing factors $\{\mathbf{J}_n\}$.

The theorem described above may be considered as a generalization of Lorentz reciprocity theorem.[32,33,34] So, multiplying the measured scattered field at each of the array element with a weighing factor, then the sum of the products is c/ε_m times the sum of the integrals of $\nabla\cdot[(1-\chi_m/\chi)\mathbf{P}]$ and $[(1-\chi_m/\chi)\mathbf{P}]$ weighted by, respectively, $-\nabla\cdot\mathbf{A}_w$ and $k_m^2\mathbf{A}_w\cdot$. The weighing field $\mathbf{A}_w$ is equal to the vector field that would be produced by a set of current distribution equal to the weighing factors, $\{\mathbf{J}_n\}$, so it is given by:

$$\mathbf{A}_w(\mathbf{x}) = \sum_n \frac{\exp(ik_m|\mathbf{x}-\mathbf{x}_n|)}{|\mathbf{x}-\mathbf{x}_n|}\mathbf{J}_n \tag{33}$$

The integral on the left hand side of eq. 32 is to integrate over only the target, therefore it will not be affected by the values of $\mathbf{A}_w$ outside the target. This gives us a free hand to select the weighing factors $\{\mathbf{J}_n\}$. To retrieve dielectric property of the target at a focal point, say $\mathbf{x}_f$, one then finds a set of weighing factors $\{\mathbf{J}_n\}$ such that the corresponding vector field $\mathbf{A}_w$ has a sharp peak at $\mathbf{x}_f$, and negligibly small elsewhere inside the target. We have found that this is possible by selecting the magnitude of the vector $\mathbf{J}_n$ to be the phase-amplitude conjugation corresponding to the path from the element $\mathbf{x}_n$ to the desired focal point, $\mathbf{x}_f$:

$$|\mathbf{J}_n(\mathbf{x}_f)| = c|\mathbf{x}_n - \mathbf{x}_f|\cdot\exp(-ik_m|\mathbf{x}_n - \mathbf{x}_f|) \tag{34}$$

As to the direction of $\mathbf{J}_n$, if only one direction of the scattered field is measured by the array elements, then $\mathbf{J}_n$ may be chosen to be in that direction only, so that the sum on the right hand side of eq. 32 can be calculated from the measured field.

To summarize our approach of soft focusing, one first acquires the scattered fields at each of the array elements at $\{\mathbf{x}_n\}$, a qualitative dielectric property of the target at any point, say $\mathbf{x}_f$, is given by:

$$\text{Qualitative dielectric property at } \mathbf{x}_f = \sum_n \mathbf{J}_n \cdot \mathbf{E}_{scatt}(\mathbf{x}_n) \tag{35}$$

where the magnitude of $\mathbf{J}_n$ is given by eq. 34, and its direction is taken to be that of the field being measured. If only one direction, say, y-direction, of $\mathbf{E}_{scatt}$ is measured, then take $\mathbf{J}_n$ to be only in y-direction, so that only the measured part of the field enters the above equation. The set of factors $\{\mathbf{J}_n\}$ works like a synthetic soft lens for focusing the scattering data, and the weighing field, $\mathbf{A}_w(\mathbf{x})$, gives the equivalent field pattern of the soft lens. Therefore, the quality of the soft lens may be evaluated by analyzing the field pattern of $\mathbf{A}_w(\mathbf{x})$. Note that, given any lens $\{\mathbf{J}_n\}$, the corresponding field $\mathbf{A}_w(\mathbf{x})$ will have all sorts of peaks outside some finite region. These peaks will contribute to the integral on the left hand side of eq. 32 unless they are outside the target. Therefore, some *a priori* knowledge on the geometrical extent of the target is a necessary condition of the applicability of the above "soft focusing" method.

We have made numerical computation and modeling to analyze the sensitivity of the above "soft focusing" technique. The computation is based on a water-immersed medical imaging system that we studied for the Walter Reed Army Institute of Research (WRAIR). The receiving antenna has hexagonal lattice structure with 127 waveguide-fed antenna elements, each of size 4 mm × 7 mm (see Figures 1a-1c of Appendix E or reference 5). The system operates at 3 GHz in water. These results show a 3 dB focusing resolution of about 5 mm in the transverse direction, and 11 mm in the longitudinal direction (see Figures 2-5 and Table 1 of Appendix E or reference 5).

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