PAPER Special Issue on Biological Effects of Electromagnetic Fields

A Noninvasive Method for Dielectric Property Measurement of Biological Tissues

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SUMMARY A noninvasive method for measuring complex permittivity of biological tissues is proposed. The noninvasive method is based on an inverse scattering technique which employs an iterative procedure. The iterative procedure consists of solving an electric field integral equation using the method of moments and minimizing the square difference between calculated and measured scattered fields. Implementation of the noninvasive method requires the knowledge of the target shape, the incident and measured scattered fields. Based on the noninvasive method, a measuring system of complex permittivity is developed and its reliability is verified.

key words: *noninvasive measurement, complex permittivity, biological tissue, inverse scattering*

1. Introduction

Electromagnetic (EM) absorption of human body is dependent on dielectric properties of biological tissues. Many investigations of the dielectric properties of biological tissues have been conducted [1], [2]. In these investigations, measurement techniques include impedance bridges, resonant circuits, transmission line/waveguides and resonant cavities [3], and measurement results serve to validate electric impedance models of tissue structure, but are not capable of yielding information on the actual living tisssue dielectric properties. In addition, the influence of surrounding tissue organization could not be ascertained from these measurements. The recent development of an in-vivo probe technique, steming from the application of an antenna modeling theorem to the characterization of unknown dielectric media, provides the opportunity for obtaining dielectric properties over a range of physiological conditions [4]. But the technique is not a totally noninvasive method.

A leading technological candidate for the noninvasive measurement of dielectric properties is the EM inverse scattering technique. One approach has been proposed to solve the exact equation of the EM inverse scattering problem by using a numerical method [5]. The method of moments is used to generate a matrix equation relating the scattered field at discrete points located in the vicinity of a biological target with the complex permittivity. Then the complex permittivity is determined by a matrix inversion and simple matrix operations. However, numerical tests have shown that the amount of errors allowed in measurement of the scattered field should be several orders of magnitude below the resulting uncertainties in the measured dielectric properties. A feasible measuring system has not been presented.

The present study has been made in an effort to establish a feasible noninvasive method for dielectric property measurement of arbitrarily shaped biological tissues. The noninvasive method is based on the Born-type iterative procedure which has been reported in one-dimensional and two-dimensional cases [6]–[8]. In this paper, the forward scattered problem of three-dimensional dielectric objects is first formulated, and then the iterative procedure for noninvasive measurement is described. Based on the noninvasive method, an automatic measuring system is developed and preliminarily experimental results are shown.

2. Forward Scattering Formulation

When an arbitrarily shaped biological target with conductivity $\sigma(r)$ and relative permitivity $\epsilon_r(r)$ is illuminated by an EM wave, an EM field is induced inside the target and an EM wave is scattered externally by the target. The total electric field $E(r)$ for all points in space can be considered to be a sum of $E^i(r)$, the incident field, and $E^s(r)$, the scattered field from the target. i.e.,

$$E(r) = E^i(r) + E^s(r) \tag{1}$$

From the volume equivalence theorem, the target can be replaced with the ambient medium with conductivity σ_{am}, relative permittivity ϵ_{ram} and an equivalent source with electric current density $\tau(r)E(r)$ where $\tau(r) = [\sigma(r) - \sigma_{am}] + j\omega\epsilon_0[\epsilon_r(r) - \epsilon_{ram}]$ is the complex permittivity. The scattered field $E^s(r)$ can be expressed in terms of the equivalent electric current density using the tensor Green's function $G(r, r')$. Substituting it into Eq. (1) yields the following electric field integral equation [9]

$$[1 + \frac{\tau(r)}{3j\omega\epsilon^*_{am}}]E(r) - PV\int_V \tau(r')E(r')G(r, r')dV' = E^i(r) \tag{2}$$

where r indicates a point inside the target, PV denotes the principal value and $\epsilon^*_{am}(r) = \epsilon_0\epsilon_{ram}(r) +$

Manuscript received November 4, 1993.

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$j\sigma_{am}(r)/\omega$.

The method of moments with pulse expansion and point matching procedure may be used for Eq. (2) to obtain the following matrix equation

$$([A]\cdot[T]-[I])\cdot[E]=-[E^i] \tag{3}$$

where $[A]$ is a $3N\times 3N$ matrix (N: the number of blocks into which the target is divided) which depends on frequency, dielectric properties of the ambient medium, block sizes and relative positions of the blocks, $[I]$ is an identity matrix and

$$[T] = diag[\tau(r_1),\cdots,\tau(r_N),\tau(r_1),\cdots,\tau(r_N),\tau(r_1),\cdots,\tau(r_N)]$$

$$[E] = [E_x(r_1),\cdots,E_x(r_N),E_y(r_1),\cdots,E_y(r_N),E_z(r_1),\cdots,E_z(r_N)]^T$$

$$[E^i] = [E^i_x(r_1),\cdots,E^i_x(r_N),E^i_y(r_1),\cdots,E^i_y(r_N),E^i_z(r_1),\cdots,E^i_z(r_N)]^T$$

where $r_i(i=1,2,\cdots,N)$ indicates the position of i-th block and T denotes the transpose.

On the other hand, the scattered field outside the target is related to the total field $E(r)$ inside the target through the following equation [9]

$$E^s(r)=\int_V \tau(r')E(r')G(r,r')dV' \tag{4}$$

We assume that the biological target is composed of L different tissues. It is a realistic assumption, based on an anatomic knowledge or X-ray image, that the shape and size of each type of tissues of the target are known. So each of the tissues can be divided into many small blocks, respectively. Then

$$N_1+N_2+\cdots+N_L=N \tag{5}$$

where N_l means that the l-th tissue is divided into N_l blocks. For the dominate direction of the scattered field, assuming it to be z direction, we have

$$[B_z]\cdot[E^t]\cdot[\tau]=[E^s_z] \tag{6}$$

where $[B_z]$ is an $M\times 3N$ matrix (M: the number of measurement points of the scattered field) which depends on frequency, dielectric properties of the ambient medium, block sizes and the relative positions of the blocks and the locations where the scattered fields are measured, and

$$[E^s_z]=[E^s_z(r_1),\ E^s_z(r_2),\cdots,\ E^s_z(r_N)]^T$$

$[E^t]=$

$$\begin{bmatrix}
E_x(r_1) & 0 & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
E_x(r_{N_1}) & 0 & \cdots\cdots & 0\\
0 & E_x(r_{N_1+1}) & \cdots\cdots & 0\\
\cdots & \cdots & \cdots & \cdots\\
0 & E_x(r_{N_1+N_2}) & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & 0 & \cdots\cdots & E_x(r_{N_1+\cdots+N_{L-1}+1})\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & 0 & \cdots\cdots & E_x(r_N)\\
E_y(r_1) & 0 & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
E_y(r_{N_1}) & 0 & \cdots\cdots & 0\\
0 & E_y(r_{N_1+1}) & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & E_y(r_{N_1+N_2}) & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & 0 & \cdots\cdots & E_y(r_{N_1+\cdots+N_{L-1}+1})\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & 0 & \cdots\cdots & E_y(r_N)\\
E_z(r_1) & 0 & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
E_z(r_{N_1}) & 0 & \cdots\cdots & 0\\
0 & E_z(r_{N_1+1}) & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & E_z(r_{N_1+N_2}) & \cdots\cdots & 0\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & 0 & \cdots\cdots & E_z(r_{N_1+\cdots+N_{L-1}+1})\\
\cdots & \cdots & \cdots\cdots & \cdots\\
0 & 0 & \cdots\cdots & E_z(r_N)
\end{bmatrix} \tag{7}$$

$$[\tau]=[\tau(r_1),\ \tau(r_2),\cdots,\ \tau(r_L)]^T$$

The same matrix equation as Eq. (6) can also be obtained in x and y directions. In our study, only the scattered field in the dominate direction is utilized because measurements of the scattered fields in all three directions are time-consuming and accurate measurements of the weaker scattered fields in non-dominate directions are not easy.

3. Noninvasive Method

We now consider the determination of complex permittivity from known incident and scattered fields. As shown in the previous section, for given $[E^i]$ and $[T]$, the total field $[E]$ inside the target can be solved numerically from Eq. (3). On the other hand, when the total field $[E]$ is known, the complex permittivity $[\tau]$ can be determined from Eq. (6). However, we only known the incident field $[E^i]$ and the scattered field $[E^s_z]$ measured at some measurement points (It should be pointed out that $[T]$ is equivalent to $[\tau]$). A feasible choice is to use an iterative procedure that solves alternately these two equations to obtain successive approximations for the

unknown field $[E]$ inside the target and the unknown complex permittivity $[\tau]$.

We start our iterative procedure by assuming that the target has the same complex permittivity as the ambient medium. In the initial step, the total field $[E]$ inside the target is obtained by solving Eq. (3). The obtained $[E]$ in such a way is substituted into Eq. (6) to determine the complex permittivity $[\tau]$. Because the measured scattered field includes measurement errors, we employ a minimization technique instead of directly solving Eq. (6) to determine $[\tau]$. The fundamental equation of the minimization is

$$\| [E^s_{zm}] - [B_z] \cdot [E^t] \cdot [\tau] \|^2 \rightarrow min \tag{8}$$

with the condition

$$\| [\tau] \|^2 \rightarrow min$$

where $\| \cdot \|$ stands for the norm of vector and $[E^s_{zm}]$ indicates the measured $[E^s_z]$. The minimization is carried out by using a pseudoinversion algorithm based on singular value decomposition of matrix $[B_z] \cdot [E^t]$[10]. The solution of Eq. (8) yields the first approximation of $[\tau]$. Since $[T]$ can be obtained from $[\tau]$, this allows the computation of the second approximation of the total field $[E]$ with Eq. (3). Subsequent substitutation again leads to an equation of minimization, whose solution yields $[\tau]$ in the second step. This process is repeated until a stable solution is reached. In such a way, the noninvasive measurement of complex permittivity is realized.

4. Measuring System

Based on the above noninvasive method, a measuring system of the complex permittivity has been developed. Figure 1 shows the structure of the measuring system. A dipole antenna is installed in a wooden probe to collect scattered field data. The probe is driven by stepper motors to scan a measurement plane. The stepper motors are controlled by a personal computer. The sensor's outputs (both amplitude and phase difference related to a reference signal) are measured by using a vector voltmeter. The scattered field data are obtained from the difference between the sensor's outputs in the presence and in the absence of the target. The measured data are A-D converted and then transformed to a workstation. In the workstation, the complex permittivity is determined by using the proposed iterative procedure.

The main performances of the measuring system are shown in Table 1 [11].

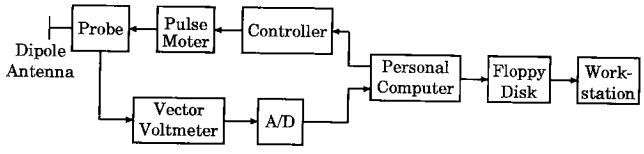

Fig. 1 Structure of measuring system.

Table 1 Performances of measuring system.

Scanning region	three-dimensional space
Scanning position error	within 2 mm
Scanning speed	within 1 second for 1 point
SNR	above 25 dB

5. Experimental Verification

To assess the capability of the noninvasive method, several experiments have been performed by means of our measuring system in an anechoic chamber.

5.1 Homogeneous Target

Figure 2 shows the geometrical arrangement of the experiment. A saline water model was used to simulate a high water content tissue such as muscle. The saline water model had a size of $10 \times 8 \times 16$ cm^3 and was divided into $5 \times 4 \times 8$ blocks. A half-wave dipole antenna was used to induce an EM wave at 1GHz to irradiate the saline water model. The vertical component of the scattered field was measured at a 1 m $\times$ 1 m vertical plane with a scanning position interval of wavelength/4 (13×13 measurement points). The complex permittivity of the saline water model, with varied salinity, were determined by using the proposed method. Figures 3 and 4 show measurement results. Also shown are the conductivity and relative permittivity calculated from an experimental equation given in Ref. [12]. All of them are in fair agreement.

5.2 Inhomogeneous Target

The geometrical arrangement of the experiment was the same as shown in Fig. 2, except that the target was a two layer model and the vertical component of the scattered field was measured not only at the plane as shown in Fig. 2 but also at the left and right vertical planes of the target. The outer layer of the model was saline water

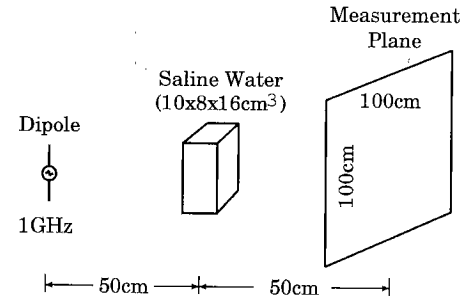

Fig. 2 Geometrical arrangement of experiment.

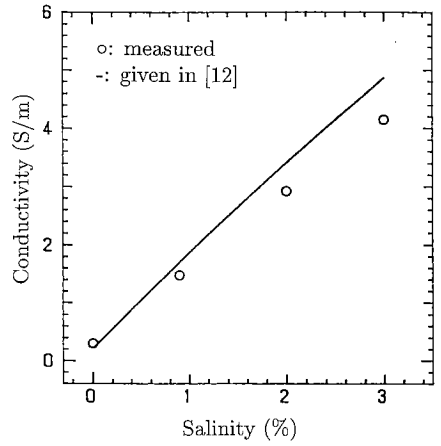

Fig. 3 Measured conductivity of saline water.

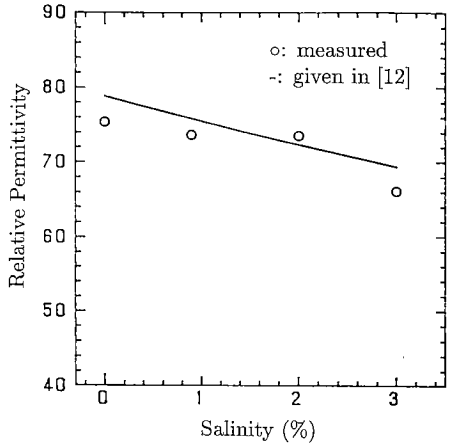

Fig. 4 Measured relative permittivity of saline water.

Table 2 Measurement result of two layer model.

	Inner layer	Outer layer
Known σ	0.0	1.6
Measured σ	0.08	1.76
Known ϵ_r	5.9	76.0
Measured ϵ_r	4.72	70.35

with $\epsilon_r = 76$ and $\sigma = 1.6$. The inner layer of the model was salt with $\epsilon_r = 5.9$ and $\sigma = 0$. The outer and inner layers were divided into 112 and 48 blocks, respectively. Table 2 gives the measurement results of the complex permittivity. It can be seen that both conductivity and relative permittivity have been measured with a similar value to known one. It should also be seen that the measured complex permittivity for the inner tissue has a larger error than that for the outer tissue, due to EM wave attenuation through the outer high water content tissue. Therefore, the need of measurements of the scattered field around the target or multiple irradiations must be emphasized.

6. Conclusion

A noninvasive method has been proposed and a measuring system has been developed for dielectric property measurement of dielectric objects including biological tissues. The noninvasive method is based on an inverse scattering technique which employs an iterative procedure. The noninvasive method is feasible to not only living tissues but also such a tissue surrounded by other tissues. Preliminarily experimental results have shown that the complex permittivity can be measured with a fair amount of accuracy. Most measurement results have been obtained within $N/4$ iteration steps (N : the number of blocks).

Further study is required for actual biological tissues.

Acknowledgment

The authors would like to express their deep thanks to Mr. T. Sato, Miyagi National College of Technology, for his contribution to the development of the measuring system, and Prof. H. Echigo, Tohoku Gakuin University, for his constructive comments.

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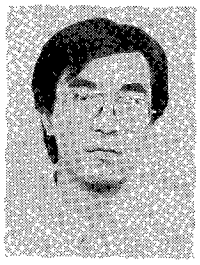

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