Breast Tumor Characterization Via Complex Natural Resonances

Y. Huo, R. Bansal, and Q. Zhu

Electrical and Computer Engineering Dept., Univ. of Connecticut, Storrs, CT 06268

Abstract — **The research described in this paper is aimed at modeling tumors in breast tissue as buried dielectric targets so that their complex natural resonances (CNR) can be identified and correlated with clinically useful properties. FDTD simulation and Prony's method are used to demonstrate the approach numerically. The technique is proposed as a modality complementary to ultrasound tumor detection.**

I. INTRODUCTION

Breast cancer is the leading cause of cancer deaths in women in the United States. At present, **x-ray mammography** is the primary screening tool used for detecting nonpalpable breast cancers. However, approximately 20% of breast cancer cases are missed by mammography [1]. Mammography is also limited in its inability to distinguish between benign and malignant lesions because they may impart similar attenuation to the x-rays passing through them. For example, benign cysts and certain tumors cannot be differentiated. Standard **ultrasound** is excellent in differentiating benign cysts from solid lesions and is routinely used in conjunction with x-ray mammography. Current ultrasound scanners can detect and resolve breast lesions a few mm in size. Ultrasound *specificity* in breast cancer detection, however, is low as a result of the overlapping acoustic characteristics of benign and malignant lesions. **Magnetic Resonant Imaging** (MRI) offers exciting potential for increased tissue characterization compared to other imaging modalities. It has the advantage of high soft tissue contrast that can demonstrate small breast lesions and lesion architecture. MRI, although ideal for showing soft tissue contrast and lesion morphologic characteristics, lacks differentiation between benign and malignant breast lesions because MRI generates tissue contrast based on physical parameters (e.g., spin-lattice and spin-spin relaxation times) which are *not* tumor specific. In addition, MRI is a rather expensive ($2-4 M) technology and as such is considered too costly for mass-screening purposes.

Recently, microwave imaging has been explored as a new modality for breast cancer diagnosis since microwaves interact with biological tissues primarily according to the tissue water content, a fundamentally different mechanism from other modalities such as X-rays and ultrasound [1, 2]. Reported data show that malignant tumors have significantly larger microwave scattering cross sections than normal fatty breast tissues because of the large water content (muscle-like properties) and the high vascular content of malignant tumors. At the same time, the realization of a clinically viable microwave imaging systems faces tremendous technical challenges since high-resolution imaging (comparable to ultrasound or mammography) requires a sophisticated scanned antenna array. On the signal-processing side, it should be noted that the classical projection-type tomography algorithms are not applicable at microwave frequencies.

Experimental and theoretical studies [3, 4] on buried military targets (a mathematically similar problem) suggest that if a target (tumor) is excited by a short electromagnetic pulse, the backscattered signal includes identifiable contributions from the complex natural resonances (CNR) of the target. These complex resonant frequencies are relatively independent of the ambient medium (heterogeneous breast tissue) and the antenna location but depend strongly on the shape and electrical properties (permittivity, conductivity) of the target (tumor). Therefore, one of the goals will be to model tumors in breast tissue as buried dielectric targets so that their complex resonances can be identified and correlated with clinically useful properties. The proposed method [5] for *characterizing* breast tumors using CNRs will be complementary to ultrasound detection. The method may use only one antenna (for transmission and reception) or two antennas (one for transmission and one for reception).

II. METHODOLOGY

In this feasibility study, we use the Finite Difference Time Domain (FDTD) method for numerical simulation. We developed a customized FDTD program using C language. The simulation setup is shown in Fig.1. For the purposes of this feasibility study, it is assumed that a medium with the same electrical properties as the breast tissue is placed adjacent to the breast for matching. The whole simulation region is filled with a medium with $\varepsilon_r = 9$ and $\sigma = 0.4$ S/m to approximate the normal breast tissue. Algorithms in [6] are used to directly match the

0-7803-7695-1/03/$17.00 © 2003 IEEE

conductive medium to the Absorbing Boundary Condition (ABC). The Uniaxial Perfectly Matched Layer (UPML) is used as the ABC [6] with a 20-cell boundary layer. The cell size Δ is chosen as 0.5 mm, and the time step Δt is 2.75 ps. The antenna is a resistively loaded dipole [2] satisfying $\sigma = \sigma_0(1 - y/h)$, where σ_0 = 60 S/m and h = 1 cm is the length of one arm. The resistively loaded antenna is excited by a modulated Gaussian pulse $V(t) = V_0 \sin[2\pi f(t - t_0)]e^{-[(t-t_0)/\tau]^2}$, where V_0 = 1 V/m, τ = 110 ps, $t_0 = 3\tau$, and f = 5 GHz. The corresponding current (at the center of the antenna derived from the simulation) and its spectrum are shown in Fig.2 (a) and (b) respectively. The simulation is done first without any tumor (incident field), and then with the tumor. The difference in the induced antenna current is a good approximation to the pure tumor response.

We use an ellipsoid shape to approximate the tumor. The ellipsoid surface satisfies the following equation

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1. \qquad (1)$$

We concentrate on a shape a = b = 5 mm, and c = 2.5 mm. The electrical properties of the tumor are varied and we investigate the possibility of the above-mentioned characterization. We assume the variation of conductivity σ is between 0.4 and 4 S/m, and ε_r varies between 20 and 45.

The Singularity Expansion Method (SEM) is a technique to approximate the response of scatterers to an EM pulse by considering the properties of the response in the s-plane. It was initially developed by Baum [7], and has been investigated by many authors since then [8-10]. It is shown that the **late time response** can be approximated by

$$f(s) = \sum_m A_m (s - s_m)^{-1} \qquad (2)$$

in the s-plane. The inverse Laplace transformation gives

$$f(t) = \sum_m A_m e^{s_m t}. \qquad (3)$$

In equations (2) and (3), $s_m = \alpha_m + j\omega_m$ corresponds to one of the poles of the scatterer. The complex natural resonant frequencies are equivalent to the poles, and are defined as $\tilde{f}_m = s_m/(j2\pi)$. If (2) is used to approximate the response of the scatterer, **Prony's method** [11] can be used to extract the poles s_m, and the residues A_m directly from the time domain signal.

Numerical solutions for the complex resonant frequencies of conducting targets are available in the literature [4]. We used that data to test our method. The extracted poles approximately correspond to the lowest order CNRs given in [4].

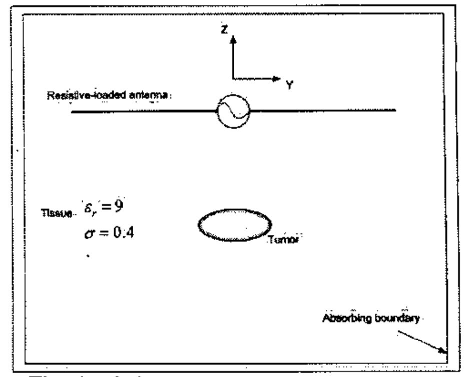
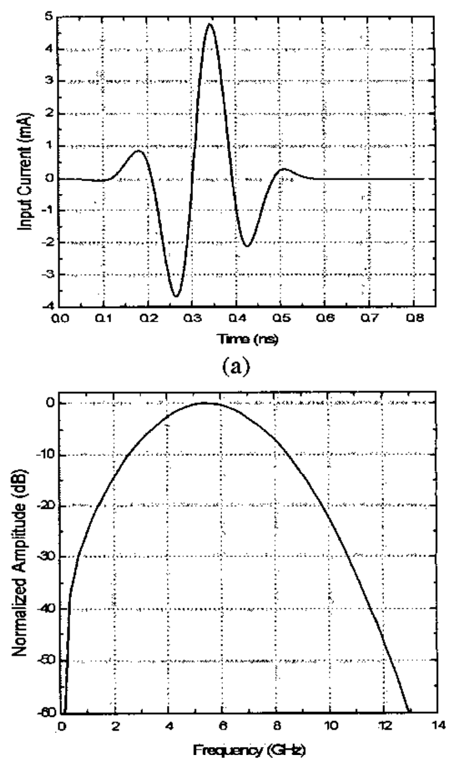


Fig.1 The simulation setup.



(a)

(b)

Fig.2 (a) The input pulse on the center of the antenna. (b) The spectrum of the input pulse.

III. SIMULATION RESULTS

Some simulation results are given in this section. In the following results, the time step of 2.75 ps is used. The transient response is shown in Fig.3 for a tumor with a = b

= 5 mm, and c = 2.5 mm, $\varepsilon_r = 50$ and $\sigma = 0.4$, 2, 4 and 6 S/m, respectively. The **specular return** represents the direct reflection from the tumor surface and carries little information about the electrical parameters inside the tumor.

Part of the **late-time response** is sampled and the sampling window is shown in Fig.4 for the tumor with $\varepsilon_r = 50$ and $\sigma = 0.4$ S/m.

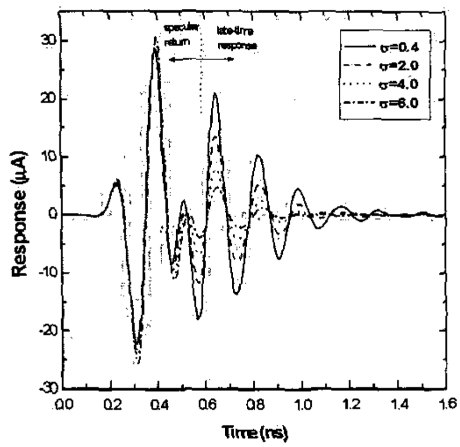


Fig.3 Response of the ellipsoid with $\varepsilon_r = 50$ and $\sigma = 0.4$, 2, 4 and 6 S/m, respectively.

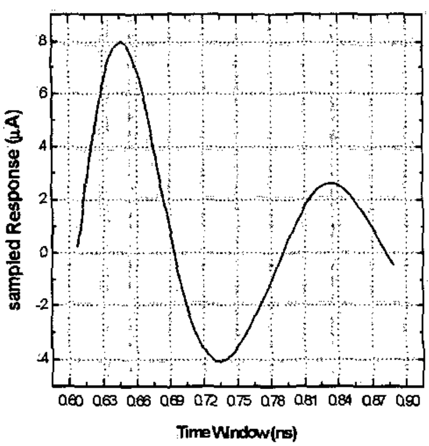


Fig.4 Sampling window.

Via Prony's method, two dominant poles are extracted as shown in Table I.

The permittivity of the tumor is changed to $\varepsilon_r = 40$ and $\varepsilon_r = 45$. The extracted poles are shown in Table I as tumors #2 and #3 respectively. The poles are shown in Fig.5 and compared with those of the $\varepsilon_r = 50$ tumor. The loss tends to increase with decrease of ε_r. This is because when the dielectric constant is high, the wave is more confined to the interior, and therefore the decay is slower.

Then we keep $\varepsilon_r = 50$ and change the conductivity of the tumor to $\sigma = 0.4$, 2, and 6 S/m. The extracted poles are shown in Table I as tumors #4-6 respectively. The poles are also shown in Fig.6 and compared with those of tumor #1. It can be seen that the trend is that the loss of the poles increases with an increase in the conductivity.

From the simulation results, it is seen that the pole locations of a tumor are sensitive to the tumor dielectric properties, which may correlate with tumors at different stages or of different types.

IV. CONCLUSION

A method is proposed for using an EM pulse and complex natural resonance extraction to characterize electrical properties of breast tumors. The preliminary FDTD simulation shows that the tumor electrical properties are differentiable according to the complex frequencies (poles) of the tumor. This approach can work as a modality complementary to the ultrasound detection technique.

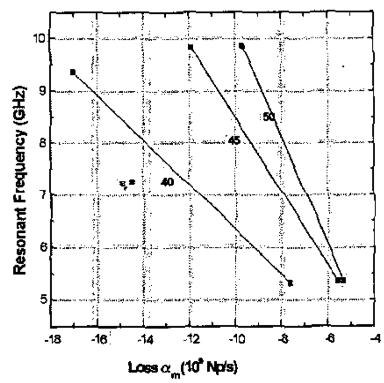


Fig. 5 Extracted poles for ellipsoidal tumors with σ=4 S/m and varying ε_r.

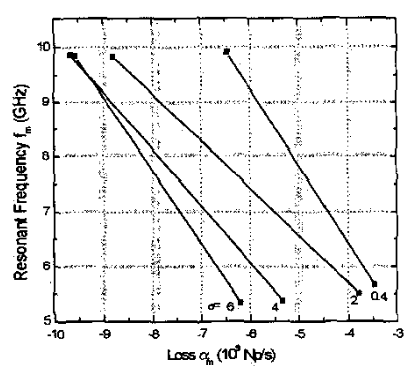


Fig. 6 Extracted poles for ellipsoidal tumors with ε_r=50 and varying σ.

TABLE I. Extracted poles for different tumors. All tumors have a = b = 5mm and c = 2.5 mm. The unit for α_m is 10^9 Np/s and GHz for $\omega_m/2\pi$.

Tumor#	σ	ε_r	Pole#	α_m	$\omega_m/2\pi$	A_m
1	4	50	1	-9.67	9.86	0.72
			2	-5.33	5.37	4.41
2	4	45	1	-11.90	9.83	0.76
			2	-5.59	5.37	4.10
3	4	55	1	-9.56	9.77	0.99
			2	-3.86	5.30	4.18
4	0.4	50	1	-6.47	9.91	1.39
			2	-3.46	5.66	10.93
5	2	50	1	-8.80	9.84	1.16
			2	-3.77	5.50	6.84
6	6	50	1	-9.68	9.86	0.41
			2	-6.19	5.33	2.71

REFERENCES

[1] S. Hagness, A. Taflove and J. Bridges, "Two-Dimensional FDTD Analysis of a Pulsed Microwave Confocal System for Breast Cancer Detection: Fixed-Focus and Antenna-Array Sensors," *IEEE Trans. Biomed. Engr.*, Vol. 45, No.12, Dec. 1998, pp. 1470-1479.

[2] S. Hagness, A. Taflove and J. Bridges, "Three-Dimensional FDTD Analysis of a Pulsed Microwave Confocal System for Breast Cancer Detection: Design of an Antenna-Array Element," *IEEE Trans. Antennas and Propagat.*, Vol. 47, No.5, May 1999, pp. 783-791.

[3] L. Peters, J.J. Daniels, and J.D. Young, "Ground Penetration Radar as a Subsurface Environmental Sensing Tool," *IEEE Proc.*, Vol.82, No.12, Dec. 1994, pp1802-1821.

[4] C.-C Chen and L. Peters, "Buried Unexploded Ordance Identification via Complex Natural Resonances," *IEEE Trans. Antennas and Propagat.*, Vol. 45, No.11, Nov. 1997, pp. 1645-1654.

[5] S. Dewald and R. Bansal, "Complex Resonance Frequencies of Biological Targets for Microwave Imaging Applications," *Electron. Lett.*, Vol.38, No.25, 5th Dec. 2002, pp.1633-1634.

[6] A. Taflove and S. C. Hagness, *Computational Electromagnetics: the finite difference time-domain method.* Artech House, 2000.

[7] C.E. Baum, "On the singularity expansion method for the solution of electromagnetic interation problem," Interaction Note 88, Air Force Weapons Lab., 1971.

[8] L. Marin, "Natural Mode Representation of Transient Scattered Field," *IEEE Trans. Antennas and Propagat.*, Vol. 21, No.6, June 1973, pp. 809-818.

[9] F.M. Tesche, "On the Analysis of Scattering and Antenna Problems Using the Singularity Expansion Technique," *IEEE Trans. Antennas and Propagat.*, Vol. 21, No.1, Jan. 1973, pp. 53-62.

[10] M.A. Morgan, "Singularity Expansion Representations of Fields and Currents in Transient Scattering," *IEEE Trans. Antennas and Propagat.*, Vol. 32, No.5, May 1984, pp. 466-473.

[11] L.M. van Blaricum and R. Mittra, "A Technique for Extraction the Poles and Residues of a System Directly from Its Transient Response," *IEEE Trans. Antennas and Propagat.*, Vol. 23, No.6, Nov. 1975, pp. 777-781.