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A Heterogeneous Breast Phantom for Microwave Breast Imaging

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Abstract—**Recently there has been significant attention given to imaging biological tissues using microwave radiation. In order to verify microwave imaging algorithms, realistic body models are needed to measure and simulate the penetration of microwave energy into the tissue and to reconstruct the image. We have created a phantom which has dielectric properties that are close to the properties of the real breast tissue. The phantom includes materials that accurately simulate the dielectric properties of skin, fat, gland and tumor tissues while providing good contrast of conductivity. The phantom is fabricated from materials that are widely available and is easy to make. In addition the elasticity of the materials enables the phantom to be shaped into two dimensional (2D) or three dimensional (3D) forms.**

I. INTRODUCTION

Microwave Imaging (MI) has shown potential for biomedical and in particular, breast imaging application [1][2][3]. MI works by illuminating the object with microwave energy from single or multiple source points. The image can be reconstucted using a radar method [3] or by tomography [1] which solves an inverse scattering problem to map the dielectric properties of the object. Since the scattered field depends on the dielectric properties of the object, it contains information about the object type and shape.

In spite of research that shows the ability of this technology, there is a lack of realistic breast phantoms for testing and benchmarking different algorithms. An ideal phantom should be non toxic, cheap, easily available, easy to make and show minimum change in dielectric properties in time. It should include heterogeneities that are similar to a real breast. One of the challenges is to find materials that can mimic different tissue properties over a wide range of frequencies and show similar dispersive behavior.

The dielectric properties of biological tissues have been investigated by a number of researchers. For example [4] provides the permittivity and conductivity of different human body tissues over a wide frequency range. Recently a large scale study was performed to measure the dielectric properties of breast tissue including normal, malignant and benign tumors [5][6]. In this study tissue composition was quantified in terms of percentages of adipose, fibroconnective and glandular tissues. They showed that the dielectric properties of breast tissue are primarily determined by the adipose content of each tissue sample. Secondary factors such as patient age, tissue temperature and time between excision and measurement had only negligible effects on the observed dielectric properties. It was concluded that the difference between normal adipose tissue and cancer tissue is large, with up to a 10:1 contrast, while the contrast between malignant and normal fibroconnective / glandular breast tissues is considerably lower, no more than approximately 10%.

Phantoms for brain, muscle, bones and adipose and glandular breast tissues have been proposed [7] - [11] for ultrasound to microwave frequencies. However, most breast phantoms developed for microwave imaging do not include the heterogeneity of the breast. In addition, they are mostly liquid and cannot be formed into different shapes.

In this study, we have developed procedures for making a heterogeneous breast phantom. We used materials that are widely available and non toxic. The steps are simple and phantom has elasticity similar to solids or gelatin.

II. METHODS AND PROCEDURES

A procedure given in [9] can be used to fabricate a breast phantom which is valid for wide frequency range. Oil and water are the main ingredients of this phantom. As suggested in [10], by increasing surfactant, emulsification improves and utilized phantom is more uniform. Another procedure reported in [11] can provide a phantom for heterogeneous ultrasound and Magnetic Resonance (MR) application.

For this study, based on [9] - [11] we have developed a new procedure that provides more elasticity to build a heterogeneous phantom. The method is simple and fast. The resulting material has dielectric properties similar to real breast tissues.

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The starting point for the proposed phantom was based on the procedures given in [9] and [11]. The phantom in [11] was proposed for MRI and ultrasound. We measured the dielectric properties at microwave frequency and found that it has a permittivity similar to fibroglandular tissue. The suggested phantom in [9] was modified to provide better elasticity and matching with the tissue properties. In summary, we replaced gelatin by agar and changed some of the preparation steps.

The following are the steps for the fibroglandular tissue [11]:

1. In a 1 liter (L) beaker at room temperature, add 42 grams (g) of propylene glycol and 675.5 mL of 18 megohm-cm double de-ionized water.
2. Slowly add, while stirring, 107.8 g of gelatin.
3. Cover the beaker with polyethylene food wrap and insert small hole in the top. Hold in place with a rubber band.
4. Place the beaker in a larger, metal or Pyrex container of hot water which in turn is placed on a heat source.
5. Heat the water until the gelatin mixture reaches 90°C and becomes transparent. Remove bubbles at the meniscus. This is the molten gelatin.
6. Remove the molten gelatin from the hot water bath and immerse partially in cold water bath.
7. As molten gelatin is cooling, heat 700 mL of safflower oil to 50°C in a 2 L beaker.
8. Add 700 mL of the 50°C molten gelatin to the 50°C safflower oil and mix vigorously with a table spoon that is bent at a right angle to minimize disturbances on the surface.
9. Add 7.7 mL of Ultra Ivory liquid surfactant (anionic and nonionic surfactants with no phosphate) and continue stirring until the emulsion is nearly white and a separation of oil does not occur when stirring is stopped.
10. Cool in cold water bath to 40°C and slowly add, while stirring, 5.292 g of formalin (37% formaldehyde solution).
11. Cool the emulsion to ~34 °C and pour into molds for further cooling and congealing. Congealing temperature is approximately 26 °C.
12. Cross-linking between formaldehyde and gelatin takes about 8 hours.

For skin, tumor and fat the procedure is as follows:

1. Mix oil and surfactant by the amount mentioned in table I.
2. Mix formaldehyde and p-toluic acid in a separate beaker and shake it to get a uniform light blue solution.
3. Heat up the water and add oil-surfactant while stirring the solution.
4. Add formaldehyde-p-toluic acid to the solution and stir continuously.
5. Add agar pinch by pinch (1tbsp per time). Mix to make a uniform solution.
6. Add Alizarin to change the color for different parts of phantom.
7. Cover the main container of phantom material with non-stick cooking and baking paper. Make the partitions using different pipe sizes.
8. Pour the cooked materials into the container and put them in the fridge.

III. MEASUREMENT METHOD

The complex permittivity of materials can be represented by

$$\varepsilon = \varepsilon_0 \left(\varepsilon' - j\varepsilon'' \right) = \varepsilon_0 \left(\varepsilon' - \frac{j\sigma}{\omega \varepsilon_0} \right) = \varepsilon_0 \varepsilon' \left(1 - \tan \delta \right) \qquad (1)$$

where $\varepsilon_0 = 8.854 \times 10^{-12}$ (F/m) is the free space permittivity, σ is the conductivity (S/m), $\tan\delta = \varepsilon''/\varepsilon'$ is the loss tangent, and ε' is the relative permittivity of material. The dispersive characteristics in biological tissues, allows us to mathematically model their behavior by Debye or Cole-Cole equations [12]. Parameters of these models are available from the tissue measurements [4].

There are different methods to measure the dielectric properties. Free space techniques are usually used in millimeter wave range, *e.g.* in [13], while resonant cavity methods are useful for solids [12]. We used an open-ended transmission line method using an Agilent 85070E high temperature probe, shown in Fig. 1.

TABLE I. MATERIAL WEIGHT PERCENTAGE FOR SKIN, FAT, TUMOR AND GLAND

	Skin	Fat	Tumor	Gland
Water	66.588	14.412	74.627	45.654
Oil	17.152	62.959	7.679	43.526
Surfactant	1.094	11.808	0.711	0.338
Formaldehyde	0.280	0.061	0.313	0.358
p-toluic acid	0.070	0.016	0.078	0
Agar	11.915	9.990	13.357	0
1-propanol	2.801	0.755	3.140	0
Alizarin	0.100	0	0.100	0
Propylene glycol	0	0	0	2.839
Gelatin	0	0	0	7.286

Fig. 1. Agilent 85070E dielectric measurement probe.

IV. RESULTS

As reported in [6], there is a large variation in breast tissue dielectric properties. To compare our phantom with real tissue, we used Debye model given by

$$\varepsilon = \varepsilon_0 \left(\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau_0} - j\frac{\sigma_s}{\omega\varepsilon_0} \right) \qquad (2)$$

where ε_∞, ε_s, σ_s, and τ_0 are respectively, the relative permittivity at infinite and zero frequencies, the conductivity at zero frequency and the relaxation time constant. The parameters used in this paper are given in Table II. As shown in [6], the tumor permittivity is about 10% higher than glandular tissue.

The dielectric properties of each tissue mimicking phantom were measured individually. A sample of each tissue was made in the form of a disk with minimum diameter of 10cm and a thickness of 4cm. One of the samples (skin) during measurement is shown in Fig. 2.

TABLE II. DEBYE PARAMETERS [14]

	ε_∞	ε_s	σ_s (S/m)	τ_0 (ps)
Skin	15.93	39.76	0.83	13.00
Gland	13.81	49.36	0.738	13.00
Transitional	12.99	37.19	0.397	13.00
Fat upper	3.987	7.535	0.080	13.00
Fat lower	2.848	3.952	0.005	13.00

Fig. 2 and Fig. 3 show the skin and glandular phantoms, respectively. Fig. 4 shows the breast phantom in a cylindrical shape. To create the heterogenous background, the fibroglandular phantom was shaped in different molds and was inserted inside the fat phantom. The measured dielectric properties of assembled phantom vs. the Debye estimate of dielectric properties of real breast tissue are depicted in Fig. 5 and Fig. 6. In these figures, the upper region belongs to very dense fibroglandular tissue and malignant tumors. The low water content tissue phantoms, followed by the transitional region containing 31-84% fat are in the lower regions. The lowest region is for adipose or fatty tissues.

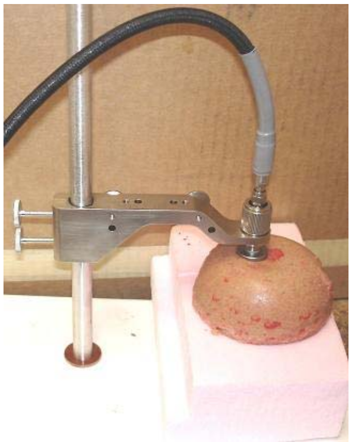

Fig. 2. Skin phantom under measurement.

As is shown in Fig. 5 and Fig. 6, the permittivity of the phantom follows the permittivity of the real breast tissues. While there is a good contrast between the conductivities of the various phantom materials, the measured conductivity has a different frequency response and is significantly higher than real breast tissues.

Fig. 3. Glandular section (gland) of phantom.

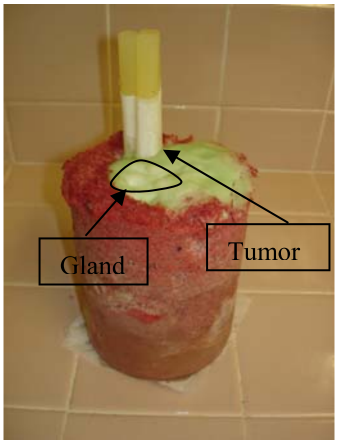

Fig. 4. Breast phantom including skin, fat, gland and tumor.

V. CONCLUSION

A heterogeneous phantom is fabricated that includes skin, fat, fibroglandular and malignant tumor tissues. The relative permittivity of proposed phantom follows the real breast tissue closely. In terms of conductivity, there is a good contrast but the conductivity falls outside the range of real breast tissues.

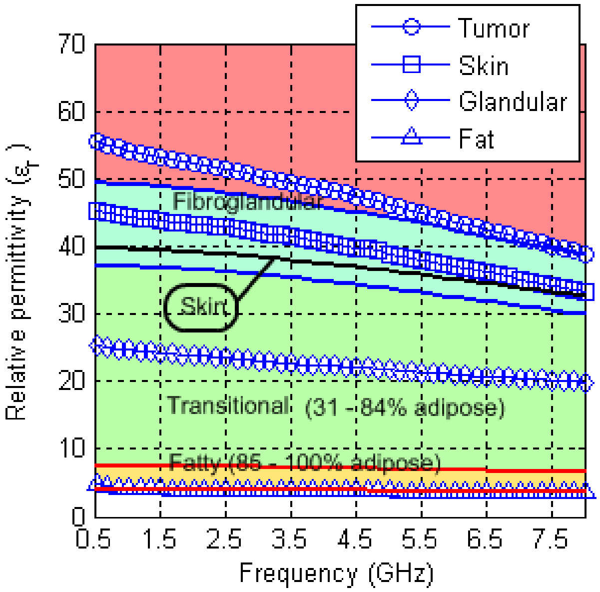

Fig. 5. Relative permittivity of phantom materials compared with the distribution of real tissue permittivity.

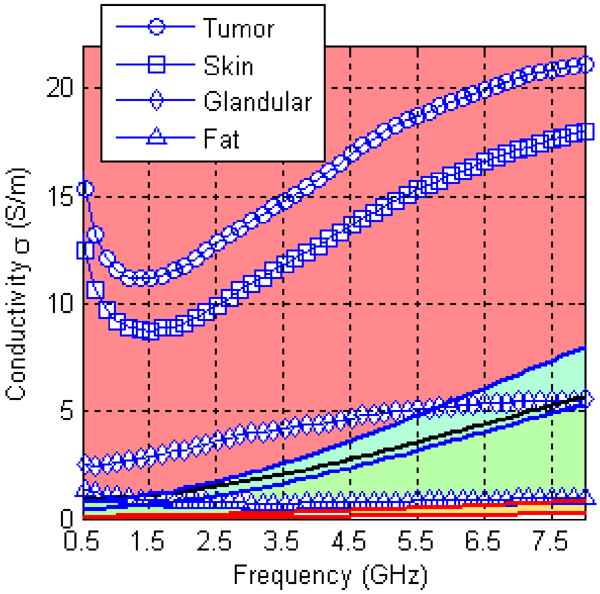

Fig. 6. Conductivity of phantom materials compared with the distribution of real tissue conductivity.

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