Experimental investigation of the mammary gland tumour phantom for multifrequency microwave radio-thermometers


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Abstract—Microwave radiometry is a spectral measurement technique for resolving the electromagnetic radiation of matter when its temperature is above absolute zero. The radio-thermometer utilises this technique and consequently can provide temperature distributions in subcutaneous biological tissues. A new phantom was proposed that imitates a mammary gland tumour, and the brightness temperature was observed using radio-thermometers operated at different frequencies, 1.75 GHz and 3 GHz. The proposed phantom, simulating heat diffusion propagated by tissues around real tumours, revealed that the thermal characteristics of the tumour imitator were well matched to the heat transfer properties of a real tumour and a proportional linear relationship between the location of the tumour imitator and the brightness temperature in a homogenous medium was established. From experiments using the proposed mammary gland tumour phantom and a clinical trial on patients with breast cancer, it could be concluded that a radio-thermometer with a short wavelength (λ = 10 cm, i.e., f = 3 GHz) is useful to resolve a thermal anomaly at a shallow depth in an homogenous medium such as a breast.

Keywords—Microwave radio-thermometer, Thermal anomaly, Mammary gland tumour phantom


1 Introduction

The theory of ‘black-body radiation’ implies that all matter at a temperature above absolute zero emits electromagnetic radiation owing to the motion of the charged particles of the atoms and molecules. The level of emission is a function of both frequency and temperature. Microwave radiometry is a spectral measurement device for measuring the electromagnetic radiation dissipated in the microwave frequency region.

The microwave radio-thermometer is a short-range application of the electromagnetic noise field generated by a thermal volume, similar to the heat transfer mechanism existing in biological tissues. Compared with a long-range application, which is concerned with either remote sensing of radio stars or emissivity measurements of materials, a short-range application should consider diffraction arising from the edge of an antenna as its major concern. Although the radio-thermometer and infrared thermography are based on the same physical principles, the depths of penetration in biological tissues are quite different: several centimetres with microwave and less than a millimetre for infrared.

During the last decade, many research groups have demonstrated the possible clinical use of the radio-thermometer for early breast cancer diagnosis (Carr, 1989; Land, 1983; Enel et al., 1984; Leroy et al., 1987; Mizushina et al., 1993; 1995; Plancot et al., 1987). They introduced their prototypic radio-thermometers based on the ‘Dicke’ radio-thermometer (Dicke, 1946). Simultaneously, their own biological phantom models were proposed to evaluate their prototypes. Their phantoms were actually simple tumour imitators merely placed into a medium such as water. The temperature of the tumour imitator was kept at a temperature that differed from that of its surrounding medium by a certain number of degrees. Most of the phantoms
were supposed to allow the experimental determination of the following spatial resolutions of the radio-thermometer:

(a) minimum detectable spatial size of a tumour imitator $\Delta r$, $\Delta y$
(b) maximum detectable depth of a tumour imitator $L_{\text{max}}$
(c) minimum detectable temperature difference $\Delta T$ between a tumour imitator and its surrounding medium.

However, these phantoms did not provide the above-mentioned spatial resolution measures for real biological tissues. For example, PLANCOt et al. (1987) suggested one type of biological phantom model. This model comprised a main container filled with water at temperature $T_0$. A long cylindrical object of smaller diameter $D$ (second container) was placed vertically in the main container. It was filled with water at temperature $T_0 + \Delta T$. The bottom of the second container was kept apart from the bottom of the main one by an adjustable distance $Z$. The antenna-applicators of two radiothermometers with central receiving frequencies of 1.5 and 3 GHz were placed in contact with the bottom of the main container through a radio-transparent window.

The ratio $\Delta T_R / \Delta T$ ($\Delta T_R$-radio-thermometer readings) with respect to $Z$ for the various $D$ values and the visibility with respect to $D$ for the various $Z$ values were sought. The temperature resolution of the radio-thermometer was about 0.1°C. However, owing to the discrepancy of this phantom, the heat transfer mechanism between the contents of the main container and the second one was actually different to the heat transfer mechanism between a real mammary gland tumour and its surrounding tissues. Besides, this phantom model lacked constructional properties and other important aspects, that would allow the evaluation of how and what error water temperature values $T_0$ and $T_0 + \Delta T$ related to the main and second containers. Without this, it is difficult to have confidence in the claimed data and application for real biological tissues with a carcinogenic tumour. Hence, this phantom model cannot be used as a mammary gland tumour.

 Mizuahina et al. (1993; 1995) described a medical radiothermometer system to retrieve a depth temperature profile from inside biological tissue by measuring the brightness temperature using a multifrequency radio-thermometer. This phantom model comprised a water bath equivalent to a real muscle. The water temperature was maintained at about 45°C. The bottom of the phantom was uniformly heated by the bath water to 45°C, and the top of the phantom was cooled by circulation of distilled water at 22°C. The distilled water was pumped through a plastic box with a water layer depth of 10 mm. Thermocouples for direct temperature measurements were placed in a plastic box at various heights. A contact-type waveguide antenna attached to the radio-thermometer achieved contact through a plastic box of 10 mm thickness. However, such a phantom did not allow the formation of local thermal anomaly. Besides, the imitation of mammary gland tissue (especially of its upper layers) by a muscular equivalent tissue medium was not justified.

In this paper, to overcome this lack of generality in the above-mentioned phantom designs, we have proposed a mammary gland tumour phantom that imitates more closely a real mammary gland tumour. Using the proposed phantom, we also investigated the operating frequency-dependency of a radiothermometer in terms of a volume that is coupled with a radio-thermometer antenna.

### 2 Principles of mammary gland tumour

#### 2.1 Absorptive and radiative properties of biologic tissues

Unlike the black body, real media are characterised by at least two additional parameters when we investigate their thermal radiation in the microwave range. These are a penetration depth $d_v$ at frequency $v$ and a reflection coefficient from interfacing boundaries $R_v$. Physically, $R_v$ means the depth of a layer that effectively forms radiation. The penetration depth forms nearly 63% of the total radiation. To determine $d_v$, it is necessary to apply the following condition:

$$\int_0^d \gamma_i(z')dz' = 1$$  \hspace{1cm} (1)

where $\gamma_i$ is the absorption coefficient. This means that the radiation intensity of the medium formed at $d_v$ depth when it reaches a surface is attenuated by approximately 2.73 times. If the desired medium is homogeneous in terms of $\gamma_i$, i.e. $\gamma_i(z') = \text{const} = \gamma_i$ then (1) becomes

$$d_v = \frac{1}{\gamma_i}$$  \hspace{1cm} (2)

The absorption coefficient and penetration-depth level can be calculated by considering the complex relative permittivity of the medium $\varepsilon = \varepsilon' + i\varepsilon''$, where $\varepsilon'$ is a measure of the amount of polarisation produced by the electric field, and $\varepsilon''$ is the loss factor associated with it. This loss factor is equivalent to displacement conductivity $\sigma$ in the case of biological material (Troistkii et al., 1981)

$$\gamma_i = \frac{2\pi v\sqrt{2}}{c} \left(\sqrt{(\varepsilon')^2 + (\varepsilon'')^2} - \varepsilon'\right)^{1/2} = \frac{1}{d_v}$$  \hspace{1cm} (3)

The value of $\varepsilon$ depends on frequency $v$ to a large extent. If $\varepsilon' < \varepsilon''$, $\gamma_i$ becomes

$$\gamma_i = \frac{2\pi v\varepsilon''}{c\sqrt{\varepsilon''}} = \frac{1}{d_v}$$  \hspace{1cm} (4)

Biological tissues are classified by highly absorptive tissues (muscle, blood, liver, skin, brain and skin) and slightly absorptive ones (fat, bone and lung), according to their electromagnetic absorption characteristics. In particular, mammary gland tissues relate to fatty tissues. However, it is necessary to note that the values of $\gamma_i$ and $d_v$ differ for various samples of even the same kind of tissues. Penetration depth $d_v$ for distilled water and other human body tissues at wavelength $\lambda = 10, 17, \text{and} 25 \text{ cm}$, based on (4), is calculated in Table 1 (Campbell and Land, 1992; Chaudhary et al., 1984). Especially, the deviation of $d_v$ in muscular tissues is up to 15% of its nominal value. For fatty tissues, this index does not exceed 10%. For an example, physiological salt solution (9 g of NaCl salt per 11 of distilled water) can be used as a physical model equivalent to muscular tissue if we consider $\gamma_i$ and $d_v$ values. Distilled water exposed to frequencies of less than 3 GHz is quite a good equivalent medium of fatty tissues in terms of attenuation (Troistkii et al., 1981).

The main advantage of using distilled water for simulating biological tissue in a phantom is its high heat capacity and low viscosity characteristic. The first factor provides sufficient heat transfer during the circulation of hot water through a thermal anomaly inside a phantom. The second factor helps to mix the distilled water effectively to provide a homogeneous temperature for the surrounding tissues and also to use thermal anomaly.

<table>
<thead>
<tr>
<th>Wavelength in air $\lambda$, cm</th>
<th>Penetration depth $d_v$, cm</th>
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<tbody>
<tr>
<td>10</td>
<td>4.9</td>
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<tr>
<td>17</td>
<td>6.5</td>
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<td>25</td>
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