Early breast cancer detection method based on a simulation study of single-channel passive microwave radiometry imaging

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Abstract. The aim of the present study is to provide a methodology for detecting temperature alterations in human breast, based on single channel microwave radiometer imaging. Radiometer measurements were simulated by modelling the human breast, the temperature distribution, and the antenna characteristics. Moreover, a simulated lesion of variable size and position in the breast was employed to provide for slight temperature changes in the breast. To detect the presence of a lesion, the temperature distribution in the breast was reconstructed. This was accomplished by assuming that temperature distribution is the mixture of distributions with unknown parameters, which were determined by means of the least squares and the singular value decomposition methods. The proposed method was validated in a variety of scenarios by altering the lesion size and location and radiometer position. The method proved capable in identifying temperature alterations caused by lesions, at different locations in the breast.

1. Introduction

Microwave Radiometry (MWR) has been explored as complementary to mammography and clinical examination in breast cancer detection [1]. It has been shown that MWR imaging can be used to detect differences in temperature distribution in the human breast when a lesion is present [2]. This is because breast tumours have electrical properties at microwave frequencies that are significantly different from those of healthy breast tissues [3], especially at early lesion development [4]. Two methods for MWR imaging have been studied; the so-called active and the passive methods. Active methods involve transmission of microwave signals to the breast area and measurement of corresponding reflections. Passive methods incorporate radiometers to detect lesions based on temperature differences from normal tissues [5].

MWR involves measurement of the power in the microwave region of the natural thermal radiation from body tissues to obtain the so-called brightness temperature of the tissue under observation. The relationship between real temperature value $T(x,y,z)$ at a location $[x,y,z]$ and brightness temperature value $T_{b_j}$ is given by [6]:

$$T_{b_j} = \iiint_{FOV} W_j(x,y,z) \cdot T(x,y,z) \cdot dx dy dz$$  \hspace{1cm} (1)
where $FOV$ is the antenna’s field of view, $W_j(x,y,z)$ is a weighting coefficient function, which depends on the antenna properties and tissue characteristics, and $j$ indicates the number of different tuned frequencies. The calculation of $T(x,y,z)$ cannot be made explicitly, thus, other numerical techniques must be applied. In the present study, a methodology is proposed for estimating $T(x,y,z)$, where the temperature distribution can be approximated by a mixture model of distributions with unknown parameters. The proposed method assumes a passive single-channel microwave radiometer, it simulates sets of radiometer measurements and attempts to find an estimate of the original temperature distribution, in order to detect and visualize alterations, if any, in internal breast temperature.

2. Material and Methods

2.1. Simulation of single-channel radiometer measurements

Initially, the human female breast was simulated as an hemisphere of radius $R$ and with three basic homogeneous layers, the thoracic muscle, the connective tissue and the skin layer [7]. Next, a single channel microwave radiometer was considered, with an antenna tuned at frequencies

$$f_j = 1 + j * 0.5\text{GHz}$$

with $j = 0, 1, 2, 3, 4$ which accounted for electrical field measurements at different depths (11.60, 0.80, 0.62, 0.48, 0.38 cm) in the human body. The weighting coefficient function $W_j(x,y,z)$ was estimated based on a recent work of Nikolopoulos et al [8]. Also, a spherical lesion of varying diameter and location was considered for inducing temperature variations. The internal temperature $T$ at point $(x,y,z)$ was modelled by means of a Butterworth function. The average temperature was approximated to 37°C inside the human body, about 36°C at skin depth, and that the lesion induced 0.7°C divergence.

Subsequently, the brightness temperature $T_{b_j}$, was calculated as the weighted average of the real temperature values in the radiometer’s FOV by employing equation (1). Figure 1 shows the simulated human breast, along with the different tissues, the lesion (as “hot spot”), and the simulated temperature distribution.

2.2. Temperature reconstruction

In general, temperature reconstruction is a process that approximates the original temperature distribution for a given set of sampled values $T_{b_j}$. This enables the extraction of further information to facilitate the detection and/or visualization of the unknown temperature distribution. The proposed method assumes that the temperature distribution can be approximated by a Mixture Model (MM) of known distributions [9], as shown in equation (2).

$$\bar{T}(x,y,z) = a_1D_1(x,y,z,\theta_1) + \cdots + a_KD_K(x,y,z,\theta_K)$$

where $D_i(x,y,z,\theta_i)$ indicate the distributions with parameters $\theta_i$ and $a_i$ ($i = 1, ..., K$) are the coefficients that express the influence of each distribution to the final temperature approximation. The calculation of each weight $a_i$ is derived from the solution of a system of linear equations [10]. The least squares and singular value decomposition methods were employed for finding the unknown coefficients. The Gaussian distribution was used for the modeling of the real temperature distribution $T(x,y,z)$, that has two parameters, the mean value $\mu$ and the covariance matrix $\Sigma$ and is given by the following equation:

$$G(\vec{r}) = \frac{1}{\sqrt{\det(\Sigma)(2\pi)^3}}e^{-\frac{1}{2}(\vec{r}-\mu)^T\Sigma^{-1}(\vec{r}-\mu)^T}$$

where $\mu = (\mu_x \ \mu_y \ \mu_z)^T$ is the mean value vector of grid points inside the antenna’s FOV.
2.3. Testing scenarios

For simulating the concept of an early warning system in detecting a possible breast malignancy, several testing scenarios were considered at different examination periods and for lesions of increasing size. The aim was to detect differences in temperature distribution in the breast, due to lesion presence.

Table 1. Radiometer positions in spherical coordinates

| Position | $\varphi$ ($^\circ$) | $\theta$ ($^\circ$) | Antenna at positions |
|----------|---------------------|---------------------|----------------------|
| 1        | 0                   | 0                   | Set 1 1              |
| 2        | 90                  | 0                   | Set 2 1,2,3          |
| 3        | 90                  | 90                  | Set 3 1,2,3,4,5      |
| 4        | 90                  | 180                 | Set 4 1,2,3,…9       |
| 5        | 90                  | 270                 |                      |
| 6        | 45                  | 45                  |                      |
| 7        | 45                  | 135                 |                      |
| 8        | 45                  | 225                 |                      |
| 9        | 45                  | 315                 |                      |

*a First position is considered the one on top of the hemisphere*

Eleven different lesion sizes (between 0.01 and 1cm in diameter at times $t_0$ and $t_1$ respectively) were considered, at eight (8) different locations. Table 1 presents the various antenna positions around the breast that were tested. Temperature differences at different examination periods were monitored in terms of $L_1$, $L_2$ norms, as shown in equations (4).
\[ L_1 = \| t_1 - t_m \|_1 = \sum_{f_{av}} | t_1 - t_m | \]
\[ L_2 = \| t_1 - t_m \|_2 = \left( \sum_{f_{av}} (t_1 - t_m)^2 \right)^{1/2} \]

3. Results and Discussion

Figures 2a and 2b show the mean temperature differences in terms of \( L_1 \) and \( L_2 \) with varying lesion diameter and radiometer sets of measurements at different locations. All temperatures were normalized to [0-1] interval. Each curve corresponds to the mean temperature difference at different lesion sites. As it can be observed from figure 2a, mean temperature differences (\( L_1 \)) increased non-linearly with increasing lesion diameter. Similar behavior was observed regarding \( L_2 \) temperature differences (see figure 2b). This suggests that an early warning system may be plausible for lesion diameters larger than about 0.4 cm in diameter.

Figure 2a,b. Variation of mean temperature differences (\( L_1 \) and \( L_2 \)) with increasing lesion diameter.

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