Synthetic Array for Radiometric Retrieval of Thermal Fields in Tissues

FERNANDO BARDATI, MEMBER, IEEE, MAURO MONGIARDO, AND DOMENICO SOLIMINI

Abstract—**The feasibility of reconstructing the thermal field in biological tissues from brightness data measured by an array of microwave antennas is investigated through a numerical simulation. The array does not make use of phase information and is synthesized through the Kalman filter algorithm. The obtained results indicate that, by a multispectral technique, such a synthetic array might be able to achieve spatial resolution not only in a transverse direction, but also in depth.**

I. INTRODUCTION

IN HYPERTHERMIA treatment of loco-regional tumors, the temperature of cancerous tissues is raised and maintained above a threshold value by a suitable space and time distribution and the deposition rate of electromagnetic (or acoustic) power. In turn, during the heating process, the surrounding normal tissues should remain at temperature below the value beyond which damage would occur. Monitoring the thermal field is therefore an important aspect of the treatment, and the thermometric instrumentation is relevant to the performance of the hyperthermia system.

In-situ measurement of temperature by implanted sensors, such as electromagnetically nonperturbing thermocouples or optical devices, is being used currently. Research is also underway on the feasibility of measuring temperature by remote sensing techniques. Indeed, the implanted sensors are able to monitor the temperature at a (usually small) number of discrete points. The thermal field, when is needed over the whole cancerous region and the adjacent tissues, is extrapolated from the data according to suitable thermal modeling. A second aspect to be considered is the necessarily invasive nature of the in-situ probes with related discomfort to the patient. Some noninvasive techniques have been suggested, based on the dependence on temperature of tissue parameters such as NMR first relaxation time, speed of sound, ultrasonic emission, low-frequency resistivity [1], microwave complex dielectric constant, and microwave emission [2].

Microwave radiometry is the oldest of these techniques and has undergone both laboratory and clinical experimentation, mainly in connection with breast cancer detection [3]–[5]. The quantity measured by a microwave radiometer is the brightness temperature, which is related to the physical temperature T inside the body by the integral relation

$$T_B(\omega) = \int_{\text{BODY}} W(\omega, \boldsymbol{r}) T(\boldsymbol{r})\, dV \qquad (1)$$

where W is a weighting function that expresses the contribution to the brightness temperature at frequency ω, from a small tissue cell centered at $\boldsymbol{r}$. The weighting function depends upon the nature and geometry of the body tissues, the characteristics of the radiometer's antenna and, apart from interference effects produced by the tissue inhomogeneities, generally decreases with depth. Assuming that W is a known function, the measured brightness temperature carries information on the physical temperature of the tissues. The correlation between the brightness temperature and the temperature measured at selected locations by inserted probes has been demonstrated experimentally [6]. It should be remarked that such an information is of a global nature, the temperature distribution $T(\boldsymbol{r})$ being related to T_B by an integral equation. Determining the thermal field, therefore, requires solving the Fredholm integral equation of the first kind (1) with respect to the unknown function $T(\boldsymbol{r})$, with known data T_B. The possibility of using multispectral radiometry to reconstruct subcutaneous hyperthermic temperature profiles has been considered for a one-dimensional model of biological structures [7]. In this case, data T_B refer to a single direction of observation and to different microwave frequencies. When the number of dimensions is increased, the set of data is made up of brightness temperatures at different frequencies and at diverse directions of observation. Such a set of data can be generated by an array. The increased number of data leads to enhanced processing difficulties deriving essentially from the ill-posed nature of the problem.

In this paper, the feasibility of reconstructing the thermal field within the tissues from the brightness temperatures measured by the elements of a radiometric array is discussed on the basis of a numerical simulation. Although some effort was made to take practical aspects into account, many idealizing assumptions were needed to reduce the considerable complexity of the real problem. Moreover, the analysis refers to particular selections of parameters in the radiometric system. The numerical results that are reported give an indication to the main features of the temperature retrievals achievable by radiometry, though they may not represent the possible performance of an actual system. Similarly, the numerical details referring to the simulation should not be regarded as guidelines to system design.

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II. Model of Emission and Retrieval Algorithm

A commonly used layered model of tissues is assumed: a 2-mm thick skin covers a 1-cm thick layer of fat over indefinite muscular tissue, with plane and parallel boundaries (Fig. 1). Two-dimensional modeling is considered, which assumes thermal variations in the z direction perpendicular to the tissue layering ($z = 0$ on the skin surface), and only in one transverse direction (x-axis). Equal antennas, having identical radiation patterns, are aligned along the x-direction to form the array. Each antenna is assumed to measure the brightness temperature at various microwave frequencies over both horizontal (E-field parallel to the tissue layers) and vertical (H-field parallel to the layers) polarizations of the emitted fields [8]. Indeed, since the emitted radiation is partially polarized, the total brightness results from that associated with two orthogonally-polarized fields [9].

The potential of the radiometric array in retrieving the variations of the thermal field both in depth and in a transverse direction is assessed on the basis of the response to a rectangular pulse of temperature. To this end, the biological structure is truncated both in the x and in the z directions and is subdivided into 70 pixels by considering seven and ten intervals along z and x, respectively. Only this portion of the biological body is assumed to contribute significantly to the brightness temperature at each antenna. The two-dimensional thermal field to be retrieved has been assumed as follows. The temperature of the structure is considered to vary with depth z according to the solution of a one-dimensional bio-heat equation [10], while no variations are supposed in the transverse x-y plane. This temperature distribution will be called thermal background. A 1-K temperature overrise is superimposed onto the thermal background in one pixel whose location can be varied throughout the tissues. The emission from the tissues containing this "hot pixel" is evaluated on the basis of the plane-wave spectrum representation of the field, as discussed in a previous paper [8]. The brightness temperature measured by each antenna is calculated from its radiation pattern and from the plane-wave spectrum corresponding to various positions of the hot pixel in the structure. A geometrical-optics analysis, already proposed in hyperthermia [11], allows the contribution from pixel $P(x, z)$ to the brightness temperature measured by the m-th antenna to be written as

$$\Delta T_{Bpm} = D_p(\theta_m) w_p(\omega_j, \theta_m, z) T(x, z) \Delta x \Delta z \qquad (2)$$

where $D_p(\theta_m)$ is the radiation pattern of the m-th antenna and $w_p(\omega_j, \theta_m, z)$ is the spectral component of the emission in direction θ_m and at frequency ω_j contributed by the pixel $P(x, z)$. The actual expression of D_p depends on the type of antennas, while subscript j denotes the individual frequency from a set of N frequencies at which measurements are considered.

The brightness temperatures T_{Bm} calculated through (2) for the two polarizations and for the set of microwave frequencies are then used as data in the discretized Fredholm integral equation of the first kind (1). The properties of the kernel W introduce strong ill-conditioning and consequent instability, i.e., the noise affecting the data may produce arbitrarily large errors in the solution. A number of methods have been devised to stabilize the solution, including regularization, statistical inversion, and synthetic averaging [12], [13]. The so-called regularization techniques incorporate constraints in the inversion algorithms, while linear mean-square estimators take into account the a priori knowledge of the statistical properties in the solutions. A knowledge of measurement noise statistics can also be a major requirement, as is the case for Backus–Gilbert inversion, where an averaging kernel is synthesized on the basis of a compromise between spatial resolution and stability of the estimate. Kalman filtering, already used in temperature retrieval both from satellites [14] and from ground-based radiometric measurements [15], is suitable for use in hyperthermia. In fact, its recursive implementation scheme allows the temporal evolution of the thermal field, which is generated by the hyperthermia treatment, to be followed with an optimal balance between the a priori information that is obtainable from modeling the electromagnetic heating and the measurements by the elements of the array.

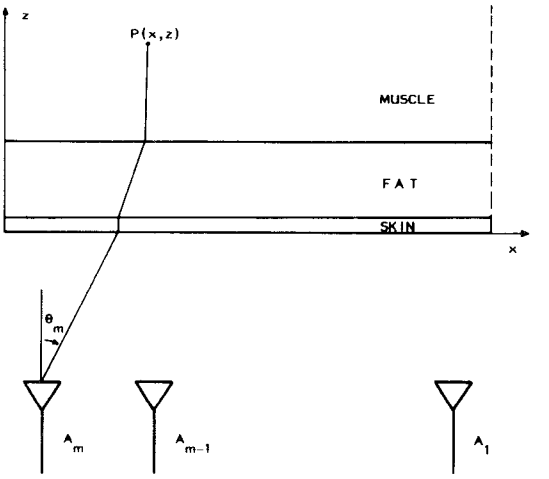

Fig. 1. Model of biological tissues and schematic representation of the antenna array.

III. Results of the Simulation and Discussion

An array of five antennas having identical radiation patterns of the form $\cos\theta$ in the x-z plane has been considered (Fig. 1). Data inversion is less difficult if measures are significantly independent from each other. Therefore, with reference to Fig. 2 of [8], the positions of the antennas have been chosen so that the variations of received power with angle, polarization, and frequency are enhanced, taking into account the limitations imposed by the possible practical feasibility of the system. Several configurations have been tested. The results reported in the following refer to a biological structure 50 cm wide (along the x-direction). The overall length of the linear array is

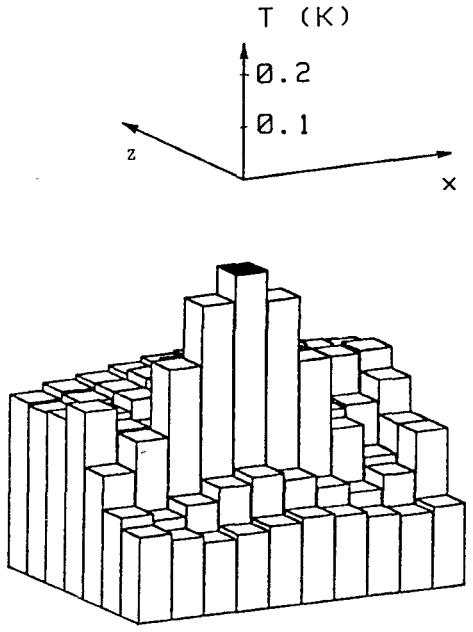

Fig. 2. Pixel-by-pixel reconstruction of 1-K excess temperature located at $P_{5,3}$ through inversion of radiometric data at 10 microwave frequencies in the band 0.975 to 11.5 GHz. The location of the hot pixel is denoted by the black square. The pixels in fat and muscle have size 5 cm×1 cm. The pixels in the skin, denoted by $P_{n,1}$, for $n=1,\cdots,10$, have size 5 cm×0.2 cm. An offset of 0.4 K has been added to each pixel to make easy the readibility of the diagram.

1 m, at a distance of 50 cm from the surface of the skin, and with equally spaced identical antennas. The array is centered with respect to the observed structure.

The brightness temperature measured by each antenna has been calculated by (1) and (2) for both horizontal and vertical polarization at 10 microwave frequencies ranging from 0.975 to 11.5 GHz, using an emission formalism reported elsewhere [8]. In the calculations, use has been made of the microwave complex dielectric-constants values of the tissues found in literature [16]. No variation has been assumed with temperature. The computations have been carried out for monochromatic receiving channels. However, it appears that the weighting functions for finite bandwidth radiometric channels do not differ substantially from the monochromatic case [17]. The calculated brightness temperature data have been corrupted by Gaussian additive random noise with 10^{-4} K standard deviation to simulate measurement noise. Increasing the noise towards more realistic levels resulted in growing instabilities of the reconstructions. The set of noisy synthetic data has been used for inverting the integral equation (1), which has been discretized by assuming T constant in each pixel, to retrieve the temperature distribution $T(x, z)$ within the biological structure. In the following, P_{nk} will denote the pixel $(n-1)\Delta x < x < n\Delta x$, for $n=1,\cdots,10$; $(k-1)\Delta z < z < k\Delta z$, for $k=1,\cdots,7$, where $\Delta x = 5$ cm and $\Delta z = 1$ cm everywhere but for $k=1$ (skin), where $\Delta z = 0.2$ cm.

The retrievals have been obtained through an iterative Kalman filtering procedure. The a priori expected thermal field necessary to initiate the filter has been calculated through the bio-heat equation, as said in the preceding section. Random fluctuations with Gaussian distribution have been superimposed on the average by thermal model parameters from human living tissues to simulate the variability of single individuals. This procedure allowed the error covariance matrix of the a priori estimate to be calculated also. The Kalman filter iterations were stopped when the rms value of the pixel-by-pixel difference between the reconstructed and assumed (background thermal field plus 1-K overrise in one pixel) temperature distributions reached a minimum. The required number of iterations was typically three to four, and the execution time was about 3 min/iteration on a Univac 1100 computer.

The reconstructed thermal pattern reported in Fig. 2 refers to a hot pixel in the muscle, located transversely at the center of the structure and confining with the fat layer (1.2 cm $< z <$ 2.2 cm). The response of the algorithm correctly locates the thermal impulse both in depth and in the transverse direction, although the spread of the temperature overrise points out a rather poor spatial resolution in the transverse direction. Such a loss of resolution occurs when stabilizing inversion techniques are used. In this case, measurements at 10 frequencies (0.975, 1.5, 2.0, 3.0, 4.5, 5.0, 6.0, 7.0, 9.0, 11.5 GHz) and two polarizations were used for a total of 100 data points with a consequent high instability of the inverse problem. It is interesting to note that a reduction in the number of data resulted in an improvement of the retrievals. Fig. 3(a) reports the reconstruction of the same thermal field (as in Fig. 2) by using 7 frequencies (0.975, 1.5, 3.0, 4.5, 6.0, 9.0, 11.5 GHz) out of the 10. A comparison indicates that an improved resolution was attained. Indeed, the reduction in the data yielded a better stability of the inversion, and, in turn, the less severe stabilization requirements allowed an increase of resolution. On the other hand, it is recognized that in ill-conditioned inverse problems, a limiting number of measurements generally exists, beyond which no effective increase in information is obtained [12]. However, a further decrease in the number of frequencies apparently degraded the obtained retrievals, since substantially less information was supplied (data are not reported here). When the hot pixel is deeper in the muscle (3.2 cm $< z <$ 4.2 cm), the higher attenuation lowers the content of emission information, with a consequent degradation in the retrieval algorithm's impulse response, as is shown in Fig. 3(b). The secondary maxima near the lateral boundaries of the structure, which are noted in the reconstructions shown both in Fig. 3(a) and 3(b), are caused by the random noise corrupting the measurements, whose effect is enhanced at the borders by the truncation of the solution. In many real physical inversions and indirect measurements, a major difficulty is to establish the probable reality or the fluctuations due to the intrinsic instability of the solutions. The response to lateral displacements of the temperature impulse can be appreciated from Figs. 3(c) and 3(d), which refer to the case of hot pixels located at the left and right sides of the structure, respectively, and at a depth between 3.2 and 4.2 cm. Note that the used numerical formulation does not take into account any physical symmetry of the

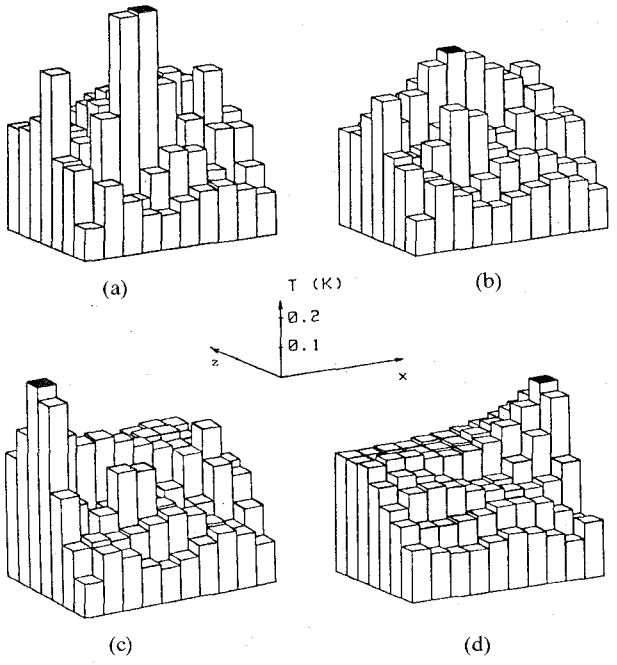

Fig. 3. As in Fig. 2, but for a number of frequencies used in the numerical simulation (7 frequencies out of the set used in Fig. 2). The locations of the hot pixels are: (a) $P_{5,3}$; (b) $P_{5,5}$; (c) $P_{1,5}$; (d) $P_{10,5}$.

structure. Moreover, the simulated random measurement noise affects the individual antennas differently, thus substantially contributing to the dissymmetrization of the results.

IV. Conclusions

The numerical simulation reported in this paper was intended to assess the potential of an array of antennas in retrieving the thermal field inside biological tissues from multispectral microwave measurements. The results indicate that, at least in principle, spatial resolution can be achieved both in a transverse direction and in depth. Such spatial discrimination capability is obtained by processing the brightness data at the antennas through a suitable algorithm which does not make use of phase information. The array, therefore, is not a phased array, but, in a sense, a synthetic array.

In real situations, inhomogeneities and complex shapes of subcutaneous biological structures substantially complicate the electromagnetic modeling. The actual level of noise in practical radiometric systems reduces the accuracy of the temperature reconstructions. The complexity of data processing has to cope with the limitations of the commonly available computing facilities. Additional practical problems, such as the realizability of multifrequency microwave antennas, or the complexity of the radiometric instrumentation, demand further efforts in this kind of study.

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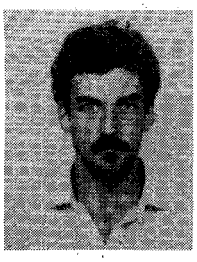

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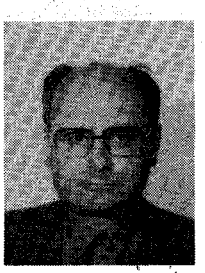

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