MICROWAVE RADIOMETRY FOR MEDICAL THERMAL IMAGING: THEORY AND EXPERIMENT

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ABSTRACT

To ascertain the capability of multifrequency microwave radiometry for imaging an inhomogeneous temperature distribution inside a cylindrical region of the human body an equivalent cylindrical phantom has been constructed. Experiments have been performed with the use of a four-channel radiometer. The physical equipment is evaluated by comparison between measured and modeled data. The effectiveness of a modified algorithm for the solution of the inverse problem of temperature retrieval from radiometric data is discussed.

INTRODUCTION

The temperature distribution within a lossy body may be imaged by externally measuring the electromagnetic microwave radiation emitted naturally by the body itself. A thermal image may be formed in a completely passive non-invasive manner if measurements are made at a number of different frequencies. In the microwave frequency range emission of radiation from the subcutaneous tissues, which, at these frequencies, is directly proportional to the temperature of the tissues, may be received at the skin surface by an antenna. Since this emission is also dependent on frequency, the information carried by measurements at different frequencies may be used to reconstruct the temperature distribution in the tissue. The technique is of promising interest clinically for the monitoring of temperature during hyperthermia treatment of cancer [1-5]. Microwave radiometry has been also used in the diagnosis of disease by detecting pathological temperatures in tissues (see, e.g., [6] for a list of references).

The fine structure of the temperature can, in principle, be obtained by processing the radiometric data obtained at different frequencies and for various positions of the antennas. The theoretical problem of the temperature reconstruction inside bodies characterized by either simple shapes (e.g., homogeneous and layered half-spaces [7]) or complex geometries (a two-dimensional model of a human neck [8]) has received attention in the past. The retrieval has been modeled as the solution of an integral equation whose kernel is the so-called weighting function: the inverse problem is ill-conditioned, therefore special use must be made of regularizing and filtering algorithms. It has been shown that the retrieval of temperature can considerably benefit from some *a priori* information on regularity properties of the temperature function to be retrieved, such as continuity and smoothness, and from the knowledge of the temperature on the surface of the body, which can easily be obtained by means of standard thermometers [7], [9].

To ascertain the capability of multifrequency microwave radiometry for imaging an inhomogeneous temperature distribution inside a cylindrical region of the human body such as a neck, a limb or a thigh, an equivalent circular cylindrical phantom has been constructed. Preliminary investigation [10] has been made with the use of a four-channel radiometer. The thermal structure was a circular cylinder of 3 cm of diameter, at temperature $T + \Delta T$, embedded off-axis in an outer cylindrical region at uniform temperature T, for various values of the eccentricity between cylinders. Both cylinders were filled with the same liquid having the dielectric properties of a muscle, and their temperatures were externally controlled by thermostats. The data were generated by rotating the antennas around the phantom on a plane normal to the axis and by receiving the emission from each position. The results have shown that a thermal difference having the size of the inner cylinder can be retrieved at the expenses of a shift and of a distortion of the original temperature shape. However thermal structures of medical interest usually have a small size, typically 1cm or less. In this paper the results of experiments on hot cylinders of 1 cm diameter are presented, moreover the two following targets are pursued: (i) the evaluation of the physical equipment (phantom and antennas) for radiometric data acquisition through a comparison with theoretical models; (ii) the discussion of a modified algorithm for the retrieval of temperature distributions from radiometric data.

MATERIAL AND METHODS

A 4-channel microwave radiometer is used operating at the frequencies 1.1, 2.5, 4.5 and 5.5 GHz,

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with bandwidths of 200, 500, 700 and 700 MHz respectively [11]. The radiometer works in the automatic gain control (AGC) mode. The AGC mode collects the radiation information from the antenna and then compares it to two reference temperature loads, one being hot (100°C) and the other cold (30°C), to produce a reference voltage level. The load temperatures are controlled by a temperature control unit and are held constant within the radiometer. The antennas are of a rectangular waveguide construction with a solid low-loss dielectric material having a dielectric constant of 30. The antennas are placed in contact with the phantom and the radiation enters the radiometer directly from the antennas. The radiometer output is digitized and processed by a computer. The radiometer operates independently of the computer and runs freely producing output voltages continuously. The phantom is made of a 12 cm diameter plexiglass circular container which is filled with a muscle equivalent saline solution (10 grams of NaCl per liter)[12]. The temperature, T, of the saline solution is kept constant while one or two thin tubes containing the same solution at temperature T+ΔT are revolved through 360° at constant distance from the container wall. The temperatures of the solution in the container and in the tubes are separately maintained constant by continuous forced circulation and are monitored by thermocouples. The antennas are placed flush with the outer surface of the phantom through latex windows orthogonal to each other. The revolution of the inner tubes simulates stationary hot-spots within the phantom while the 4 antennas are scanned around the outer surface collecting data.

The calibration of the antenna-radiometer system in voltage units per degree has been performed by using the above described phantom at a uniform temperature. The solution temperature has been raised by ten centigrade and one tenth of the corresponding voltage output has been assumed to be the calibration factor. During measurements, the antenna temperature has been carefully kept constant.

Denote by Ω the cross-section of the cylindrical body, normal to the cylinder axis, and by $T_a(\vartheta,f_n)$ the radiometric datum measured by the antenna of the channel at frequency f_n (n=1,...,N) when the antenna is positioned at the angle ϑ between the normal to the antenna surface and the radial direction assumed as reference. N=4 in our experiment and the data are collected at M equiangular positions ϑ_m around the cylinder. The dependence of T_a on the physical temperature T(P) at a point $P \in \Omega$ is given by the radiometric equation

$$T_a(\vartheta,f_n) = \int_\Omega W(\vartheta,f_n,P)\, T(P)\, dP \qquad (1)$$

where W is a normalized weighting function whose integral over Ω is unitary, T_a is called the available radiometric temperature [13] of the source which is observed through the antenna at position ϑ. The weighting function determines the contribution of each small sub-region of phantom to the total signal. From the reciprocity theorem it is known that this function is equal to the power deposition pattern when the receiving antenna is used in the active mode to radiate unitary power into the body.

The temperature retrieval from radiometric data has been modelled as the solution of the Fredholm integral equation of the first kind (1). This inverse problem has been shown to be severely ill-conditioned, therefore only a small number of indepedent pieces of information can be extracted from radiometric noisy data [7]. As a consequence the spatial resolution of temperature retrieval is usually poor. The use of a suitably defined space of temperature functions can improve the retrievals. In this paper, as in [10], the temperature space has been assumed to be the space of continuous functions which satisfy a steady-state heat transfer equation together with a Dirichlet condition on the boundary of the observed region. The data space has been also normed by introducing coefficients which weight differently the data according to the channel noise level.

RESULTS

The same experimental situation - hotter tubes embedded off-centre in a larger cylinder - has been repeated for various depths, diameters and temperatures of the hotter tubes. The results of Fig. 1 refer to a tube of 3 cm

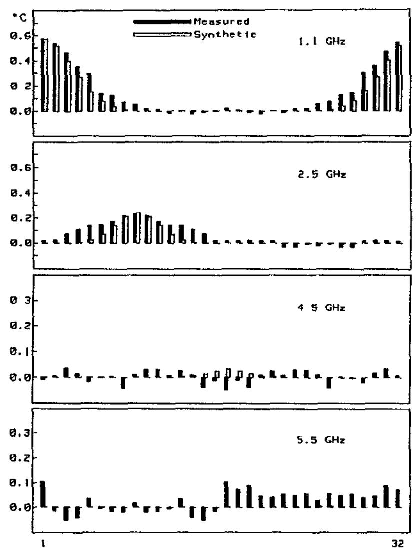

Fig. 1 Bar diagrams of radiometric data for a hot cylinder (ΔT=10°C, 3 cm of diameter) at a distance of 2 cm from the antenna aperture. Data have been collected at 32 equiangular positions around the container wall.

diameter. The data have been collected at M=32 equiangular positions and the temperature of the solution in the tubes was held constant at $\Delta T=10$ °C above the temperature of the surrounding region. At each angular position the signal was sampled for one minute. The average of each observation is recorded in Fig.1 as a function of ϑ_m (black bars), separately for each channel. The corresponding rms value of the noise received by each channel has also been determined. The following values, 0.12, 0.07, 0.14 and 0.09 °C are typical. The signal level reaches a maximum when the hot tube is positioned immediately in front of the corresponding antenna, i.e., at position 1 for channel 1, 9 for channel 2, 17 for channel 3 and 25 for channel 4. In the same figure the synthetic data are also shown (white bars), which have been obtained from a numerical computation of the integral of equation (1) after substitution of the proper functions for W and T. Similar results to those in Fig. 1 were achieved when comparing measured and synthetic data for the smaller inner tube of diameter 1 cm. The weighting functions have been calculated at the radiometer frequencies by solving the electromagnetic problem of the radiation from waveguide into an homogeneous half-space having the dielectric constant of the saline solution. A technique similar to the one used in [14] has been adopted for the computation, the results are shown in Fig. 2.

Temperature reconstructions from measured and synthetic data are displayed in Fig. 3 and 4. They refer to the thermal structure constituted of a couple of inner tubes of diameter 1 cm. Due to ill-conditioning of the inverse problem only a limited number of the available terms (128) could be used in the reconstructions. In particular, only those corresponding to a conditioning number less than 100 (20) were retained in Fig. 3 (Fig. 4). The maximum reconstructed temperature is shown by the black spot within the isothermal contour level curves, which are at intervals of 20 percent of the maximum

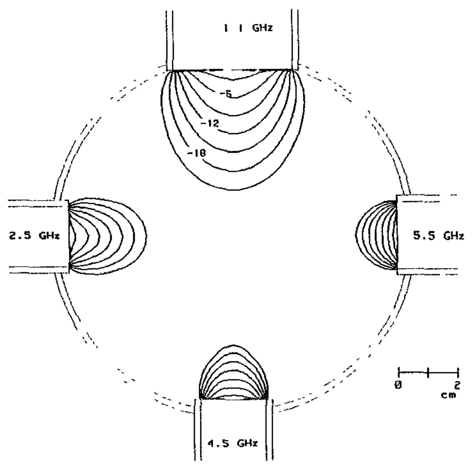

Fig. 2 Contour level plots of the weighting functions for the four channels. Levels are equally spaced on a log scale, with a spacing of 3 dB. For each antenna the weighting function maximum occurs in the middle of the antenna aperture.

value. An agreement between the retrievals from the measured and simulated data can be appreciated, which confirms that both the electromagnetic model of the thermal emission and the experiment have been performed properly. With reference to the position and shape of the hot region to be retrieved, we note that the angular position of the hotter area has been accurately retrieved, while the radial position has been found with less accuracy, the hotter area being generally shifted. Further, the original shape of the temperature function is not retrieved. This behaviour is due to the small number of radial basis functions which are retained after filtering and to the monotonic decrease of the weighting functions with distance from the antennas. It is worth noting that the use of a wider filter such as in Fig. 3 improves the retrieval from synthetic (noiseless) data, whereas it is apparent the opposite behaviour of the reconstruction from measured (noisy) data.

CONCLUSIONS

An experiment has been performed in order to appreciate the potential of multi-frequency microwave radiometry in the monitoring of temperature distributions inside cylindrical regions down to a depth of a few centimeters from the surface. Since the retrieval was founded on knowledge of the electromagnetic emission from tissues as it is received by the antennas in use, the aim of the first part of the experiment was to compare the measured data to those predicted. Then the data were used as the input of an inverse problem, whose solution was written in terms of the singular functions of an integral operator. The agreement between measured and simulated data was fairly good, decreasing, but still satisfactory, when the distance from the outer surface was increased. The hotter tube excess temperature - ideally different from zero in a circular region having sharp boundaries - has been retrieved as a smoother function showing the maximum value in a position shifted along the radial direction.

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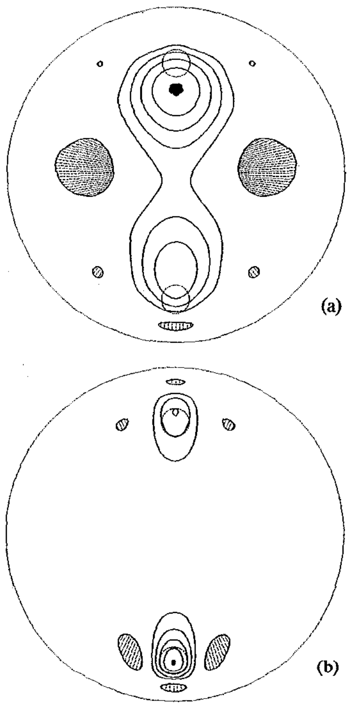

Fig. 3 Temperature retrieval of two hot tubes (diameter 1 cm, distances from tha antenna surface 0.5 and 1 cm) containing saline solution (ΔT=10°C). Retrieval from measured data (a) and synthetic data (b). The number of terms retained in the singular function expansion was 63. Correspondigly, the normalised largest singular value was less than 100. The negative portion of diagrams are indicated by gray shading.

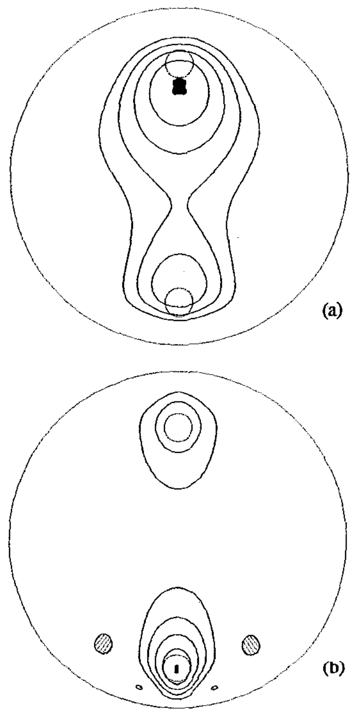

Fig. 4 As in previous figure, for a largest normalised singular value less than 20. 29 terms were retained in the singular function expansion.