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IN VIVO EXPERIMENT FOR THE ANALYSIS OF MULTI-FREQUENCY MICROWAVE RADIOMETRIC DATA

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ABSTRACT

Numerical simulations and laboratory experiments suggested the feasibility of reconstructing temperature distributions inside biological structures from multi-frequency radiometric data. This contribution discusses experimental data in real situations, where the variable geometry and dielectric inhomogeneities in the human body strongly affect the radiometric measurements.

INTRODUCTION

Microwave radiometry is considered to be a tool for measuring non-invasively the temperature of subcutaneous regions of the human body up to a depth of a few centimeters. Single-frequency [1-5] and multi-frequency [6-8] radiometry have originated investigations based both on theoretical simulations and on experiments and clinical validations. The output of a radiometric channel depends on frequency, hence multi-frequency radiometry provides essentially more information than single-frequency operation, and has been especially considered for reconstructing temperature as a function of depth from the body surface. In [6] and [7] the shape (step, exponential) of the temperature profile is assumed to be known, and the determination of the actual values of the curve parameters is attempted by multi-frequency radiometry. In [8] the theoretical feasibility of retrieving temperature distributions of general shapes has been considered. The retrieval is modeled as the solution of an inverse problem involving a Fredholm integral equation of the first kind whose kernel is strictly related to the dielectric properties of the body tissues. However, in real cases, before attempting the solution of the inverse problem, the direct problem must be considered. Hence, a preliminary step to the retrieval process from experimental data is the analysis of the radiometer output signals at various operating frequencies and for various positions of the antennas over the human body, taking into account the actual dielectric inhomogeneities of tissues. Indeed, the understanding of the behavior of the reflection coefficient in each radiometric channel for different geometries of the tissues appears to be of particular relevance [9]

This paper refers to data taken at selected positions around a forearm by a four-channel microwave radiometer whose operation has been already tested in laboratory with the successful retrieval of temperature distributions inside dielectrically homogeneous liquid phantoms [10]. The surface temperature of the region of interest on the forearm has been measured by an infrared thermograph, while the internal structure of the tissues has been determined by echography. Each radiometric channel is characterized by a weighting function and by the mismatch between the antenna and the biological structure. The behavior of the measured radiometric data is then discussed on the basis of the available geometrical and physical information.

EXPERIMENT AND DATA ANALYSIS

The line encircling the cross-section of the forearm where the measurements are performed is about 9 cm from the elbow. Local infrared thermographs were taken to gain information on the temperature of the skin. Indeed the surface data improves the retrieval accuracy [11]. The measured structure has also been probed by an echographic system to determine its actual internal geometry (Fig. 1), whose knowledge is relevant to the design of a proper model of emission.

The radiometric antennas are truncated rectangular (4 cm x 2 cm for the lowest band and 2 cm x 1 cm for the others) waveguides filled with a high-permittivity low-loss dielectric, designed to match both the receiver and a half-space homogeneously filled by muscle. The contacting radiometric antennas are displaced around the forearm cross- section and brightness data are recorded at eight angles of observation, as shown in Fig. 2. In each position the brightness is measured in four radiometric channels, with frequency bands centered on 1.1, 2.5, 4.5, and 5.5 GHz.

The output T of the i-th radiometric channel at frequency f_i is related to the absolute temperature distribution $T(\underline{r}')$ inside the emitting body by the following equation

$$T_{ik} = \int_{V_{ik}} W_{ik}(\underline{r}')\, T(\underline{r}')\, d\underline{r}' + T_{rec}[1 - e_{ik}] \quad (1)$$

where k denotes the position of the antenna on the surface of the body, and $W_{ik}\, Td\underline{r}'$ is the contribution of $d\underline{r}'$ to T_{ik}. V_{ik} is the volume of the body which contributes to T_{ik} and is a function of both k (unless the body has symmetrical properties, which is not our case) and f_i. T_{rec} is the equivalent noise temperature of the receiver loaded with the i-th antenna, and $1-e_{ik}$ is the power reflection coefficient at the interface between antennas and body. Assuming reciprocity between absorption and emission, the weighting function W_{ik} is obtained as the power absorbed by cell at $\underline{r}'$ when the i-th antenna at k-th position is radiating the power temperature e_{ik}. Therefore,

$$\int_{V_{ik}} W_{ik}(\underline{r}')\, d\underline{r}' = e_{ik} \quad (2)$$

In (2) e_{ik} and W_{ik} are average values over the measurement bandwidth of each radiometric channel.

The weighting functions can be evaluated on the basis of the electromagnetic reciprocity from the power deposition pattern of the radiometric antennas which are assumed to radiate into the biological structure, with the constraint of eq. (2). The calculations must be carried out for the various positions of the sensors on the body, because of the variability of the inner biological structures. The method of moments is being considered to this end. On the other hand, a possible alternative procedure is to measure the weighting functions in suitable phantoms simulating the biological tissue arrangements. In our experiment the weighting functions have been measured for the various applicators in water by probing the radiated field by a scanning non-perturbing dipole connected to the receiving port of an hp-8510 network analyzer. The behaviour of an experimental weighting function is shown in Fig. 3. From the measurements it appears that the decay of the weighting functions with depth z is not far from that of a plane wave in a one-dimensional model. This feature looks rather appealing because of the obvious simplicity of such a model

In the attempt to use this ready approach, the thickness of the slab of high water content tissue backed by the bone is to be selected. The effect of the curvature of the boundaries has been taken into account by an equivalent thickness calculated so that the difference between the emissivity of the one-dimensional structure and that of the real structure is minimized. The measurement of the emissivity has been done by measuring the S_{11} parameter of the antenna by means of the network analyzer for the various positions of the sensors and as a function of frequency within each radiometric channel. From these data the emissivity e_{ik} has been obtained by averaging $1 - |S_{11}|^2$ over each channel band for each position k of the sensors. Fig. 4 reports a comparison between the measured emissivity and the one of the equivalent structure, while Fig. 5 shows the equivalent thickness at the various positions around the forearm, together with the actual distance of the bone from the skin surface as deduced from the echographic measurements.

Radiometric data have been generated by using the plane parallel model for comparison with the measured data (Fig. 6) The synthetic data have been obtained under the following hypotheses:

i) the physical temperature is linearly increasing from the surface value obtained by the infrared measurements up to a constant core value of 36° C at a depth of 5 mm;

ii) W_{ik} ($\underline{r}'$) is obtained as the emission of a plane layered muscle-bone structure into a half-space filled by the same dielectric material that fills the antennas [8]. The layers are perpendicular to the direction of observation, and the thickness of the muscle layer, which changes with the position of the antennas, is the one of Fig 5

Both the average value and the variations with angle of the synthetic data are occasionally different from those of the actual experimental data Two effects are the main sources of discrepancy. The varying mismatch of the antennas in the various positions reflects back a fraction of the receiver noise, thus increasing the apparent antenna temperature in the different radiometric channels. In addition, the actual temperature distribution in the forearm tissues differs from the assumed one, in particular in the neighbourhood of vessels, which are indeed rather superficial and concentrated in particular angular positions.

CONCLUSIONS

When attempting the inversion of microwave radiometric data for the retrieval of the body temperature, several effects should be taken into account The eventual geometric complexity of the actual tissue arrangements advices for the use of simpler significant models In several cases a plane parallel geometry is suitable. The determination of the parameters of the equivalent structure is feasible on the basis of the equality of the emissivities. To obtain an adequate precision, a numerical scheme to work out the solution of Maxwell's equations inside bodies of arbitrary geometry is advisable. An important role is also played by the varying mismatch of the radiometric antennas when they scan the various positions over the body. The knowledge of the reflection coefficient seems to be crucial for the correct use of the radiometric data.

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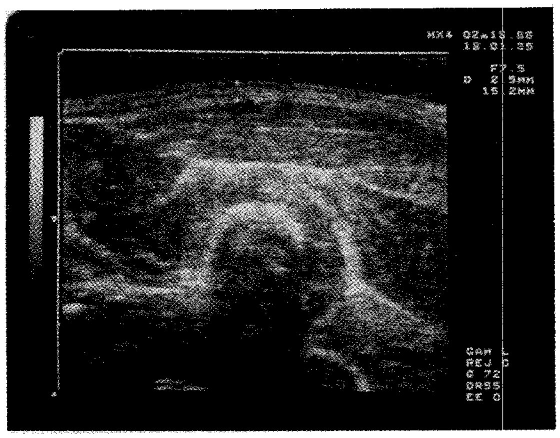

Fig. 1. Echographic image of the forearm section. Note the curvature of the bone.

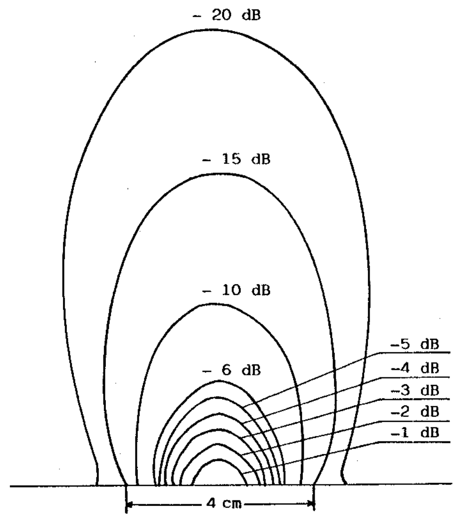

Fig. 3. Behaviour of the weighting function for the radiometric antenna at 1.1 GHz in water.

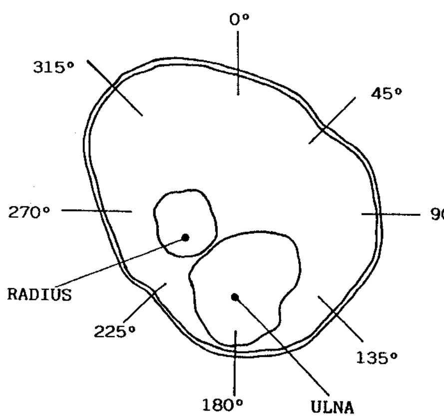

Fig. 2. Schematic representation of the forearm cross-section with the angles of radiometric observation (after [12]).

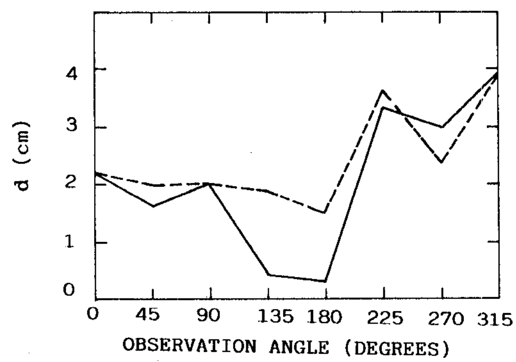

Fig. 5. Thickness of the muscle layer in the plane parallel equivalent structure (dashed) compared with the actual distance of the bone from the surface as obtained by echography (continuous line).

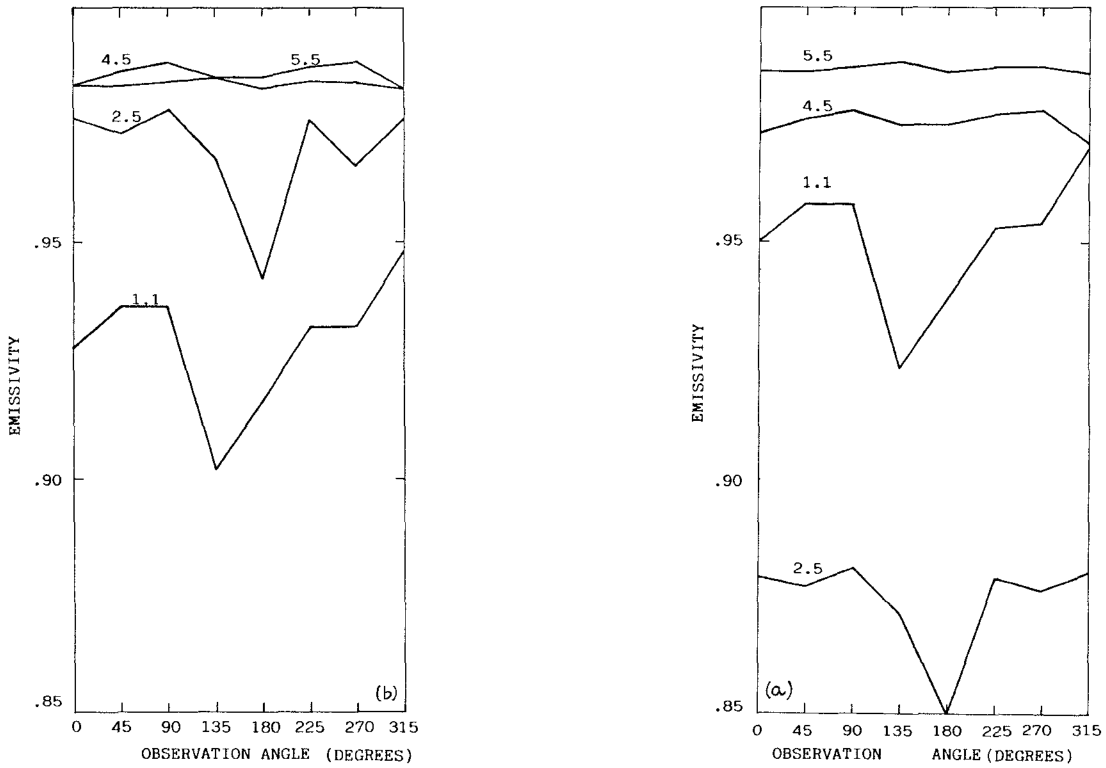

Fig. 4. Emissivity of the actual (a) and equivalent plane parallelstructure (b) as a function of the radiometric observation angle

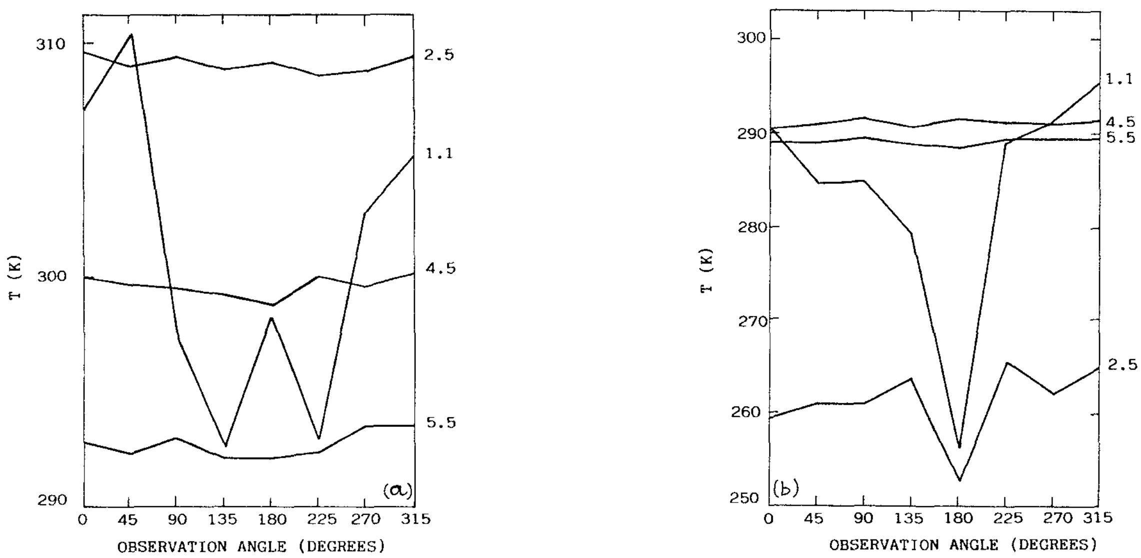

Fig 6. Radiometric antenna temperature T measured on the actual structure (a) and calculated for the plane parallel equivalent model vs observation angle.