A THREE-BAND MICROWAVE RADIOMETER FOR NONINVASIVE TEMPERATURE MEASUREMENT

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Abstract

A three-band radiometer operating at 1.5, 2.5 and 3.5 GHz with a 1-GHz bandwidth has been developed for noninvasive measurement of body temperature. An experiment using a water-bath filled with tap water showed that the instrument could measure the temperature (15 °C) of a subjacent layer (depth > 2 cm), differentiating it from that (22 °C) of the surface layer (depth < 2 cm).

Introduction

The microwave radiometry has been applied to cancer detection (1,2,3) and to temperature measurement during hyperthermia treatments of cancer (4,5). Radiometers used in these and other studies reported so far are based on the single frequency measurement and, consequently, can measure only a weighted average of temperature over a region from the surface to a certain depth. A desired improvement of this technique is to make it possible to measure the temperature inside a body, differentiating it from the surface temperature, by taking measurements at several frequencies.

This paper presents results of such an attempt involving a three-band microwave radiometer and a water-bath experiment.

Radiometer

Fig.1 is a photograph of the three-band radiometer we have built. The radiometer comprises 1-2-GHz and 2-4-GHz Dicke receivers (6) with PIN-diode Dicke switches and a lock-in amplifier. A microcomputer is connected to the radiometer for balancing control and data analysis. The system can be operated either in the conventional Dicke-receiver mode or in the radiation-balance mode (7,8). A single wideband antenna, contact-type dielectric filled waveguide antenna, is used to cover all bands. Measured brightness temperature resolution was 0.05-0.06 °C for a 3-second integration time.

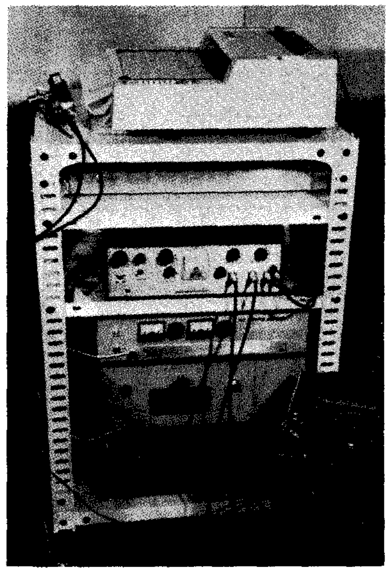

Fig.1. Three-band microwave radiometer.

Water-Bath Experiment

A water-bath arrangement illustrated in Fig.2 was used to test the instrument. First, the instrument was calibrated by recording the instrument output with the antenna placed at a position as shown in the figure while raising the bath water temperature from 10 °C to 40 °C. Second, with the antenna positioned above the plastic container in which cold or hot water was flowing, the electromagnetic-wave-power penetration depth, δ_i (i=1,2,3), was measured by plotting brightness temperature change, ΔT_{Bi} (i=1,2,3), versus d for each band. Measured values for the tap water that we used were: δ_1(1-2 GHz)= 40.6 mm, δ_2(2-3 GHz)=18.6 mm and δ_3(3-4 GHz)=10.6 mm. From theses values, we obtain

$$\delta_i \propto f_i^{-1.60}. \qquad \ldots(1)$$

With these preparations, the brightness temperature change, ΔT_{Bi}, was measured and recorded for each band by shifting the antenna back and forth between the two positions as illustrated in Fig.2.

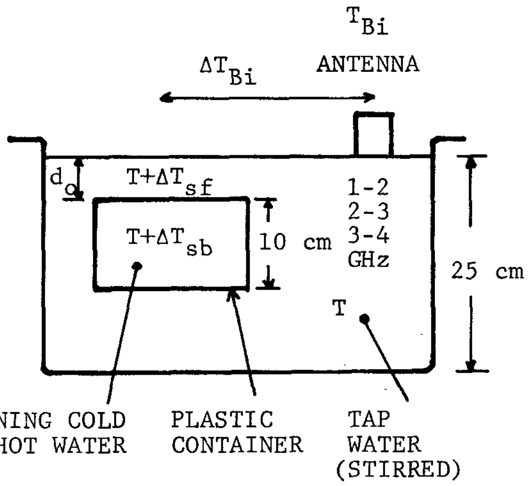

Fig.2. Water-bath arrangement used for calibration and test of the radiometer.

Data Interpretation

ΔT_{Bi} readings thus collected were interpreted with the aid of a simplified temperature distribution model shown in Fig.3. This model enables one to differentiate the temperature inside from that of surface, and can be regarded as a crude model for a certain cases of subcutaneous temperature distributions of practical interest. For this model, one can write

$$\Delta T_{Bi}=\alpha[\Delta T_{sf}\{1-\exp(-d/\delta_i)\}+\Delta T_{sb}\exp(-d/\delta_i)] \qquad \ldots(2)$$

where the thickness of the subjacent layer was assumed sufficiently large. ΔT_{sf} and ΔT_{sb} are the temperature elevations in the surface layer and in the subjacent layer, respectively, above the background temperature T. In equ.(2), $\alpha = 1$ effectively for our water-bath experiment, since the effect of antenna mismatch entered both calibration and measurement. For actual measurements on biological objects, the radiation-balance measurement ensures $\alpha = 1$. In addition,

$$d/\delta_i = (d/\delta_1)(f_i/f_1)^n \qquad \ldots(3)$$

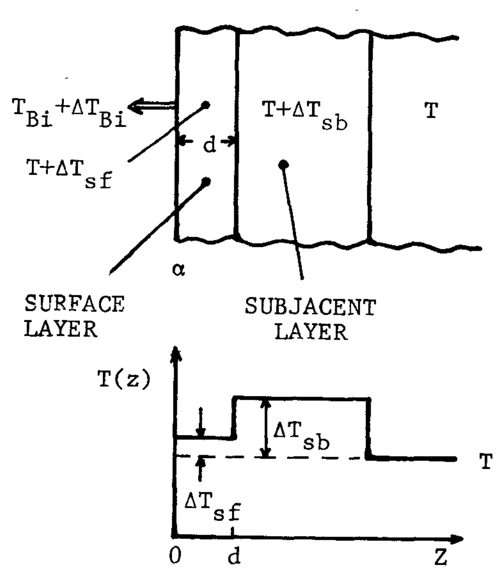

Fig.3. A simplified temperature distribution model used for data interpretation.

with n = 1.60 in view of equ.(1). The value of n will probably vary for different objects, depending on their material and structure.

Hence, ΔT_{sf}, ΔT_{sb} and d/δ_1 are unknown parameters of the model that can be determined uniquely from three independent measurements of ΔT_{Bi} (i=1,2,3). This gave us a prime motivation to study capability of three-band radiometer.

Using a least-square-fitting method, we estimated the model parameters from sets of ΔT_{Bi} (i=1,2,3) collected through a number of measurement runs. Typical results are summarized in Table 1. Runs 1 through 4 are measurements on cold objects and runs 5 through 11 on hot objects. Runs 1 and 2 as well as runs 7 through 10 are intended to represent repeated measurements on almost identical temperature distributions. Agreement between the estimated temperatures and the corresponding thermister readings is fair. The thermister readings of ΔT_{sb} were taken at the outlet of the plastic container and probably had errors of ±0.5 °C. The depth d_o in Table 1 is the distance from the antenna aperture to the top of plastic container wheras the estimated d the distance to the boundary between two layers of different temperatures, which tends to come closer to d_o for higher flow rate of water in the container.

Conclusion

A three-band microwave radiometer technique based on temperature distribution model parameter estimation has been described. Results of water-bath experiment showed that it was possible to measure surface layer temperature, subjacent layer temperature and depth of boundary between the layers with a reasonable accuracy using this technique. Preliminary measurements taken on the pork meat were promising, and we are planning animal experiments simulating hyperthermia conditions.

Acknowledgment

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Table 1. Summary of Water-Bath Experiment

RUN	DEPTH*	THERMISTER**			RADIOMETER**			ESTIMATION**			
No.	d_o(mm)	T	ΔT_{sf}	ΔT_{sb}	ΔT_{B1}	ΔT_{B2}	ΔT_{B3}	ΔT_{sf}	ΔT_{sb}	d/δ_1	d(mm)
1	10	22.3	0	-8.8	-3.25	-0.93	-0.34	-0.1	-8.7	1.0	40
2	10	22.5	0	-8.8	-3.30	-0.96	-0.34	-0.2	-8.7	1.0	40
3	20	21.7	0	-8.0	-2.30	-0.61	-0.21	-0.1	-6.7	1.1	44***
4	30	33.0	0	-23.0	-10.35	-3.30	-1.45	-0.5	-24.7	0.9	37
5	10	22.9	0	6.0	2.03	0.63	0.30	0.1	4.8	0.9	37
6	15	23.1	0	6.2	2.50	0.55	0.21	0.1	8.1	1.2	49
7	15	23.1	0	8.7	2.95	0.73	0.37	0.2	8.5	1.1	45
8	15	23.1	0	8.7	3.07	0.77	0.34	0.2	8.8	1.1	45
9	15	23.1	0	8.7	3.00	0.62	0.29	0.1	10.6	1.3	53
10	15	23.1	0	8.6	3.05	0.71	0.34	0.2	9.7	1.2	49
11	20	23.0	0	8.8	2.89	0.48	0.09	0.0	11.7	1.4	57

* Distance from antenna aperture to the top of container in Fig.2.
** Temperatures are given in °C.
*** High flow rate of cold water in the container.