A THREE-BAND MICROWAVE RADIOMETER SYSTEM FOR NONINVASIVE MEASUREMENT OF THE TEMPERATURE AT VARIOUS DEPTHS

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ABSTRACT

An experimental three-band (1.5,2.5,3.5±0.5GHz) radiometer system and a data analysis procedure have been developed for noninvasive measurement of the temperature at various depths in a biological body. Using them, we made temperature measurement experiments on the abdominal region of rabbits. The results of the experiments demonstrate the feasibility of the multifrequency radiometry for this purpose.

INTRODUCTION

The microwave radiometry has been studied for the cancer detection based on thermal anomaly in the tissue (1,2) and for the temperature monitoring during hyperthermia treatment of cancer (3,4, 5,6). The radiometers actually built for these purposes so far measure an average temperature from the body surface to a certain depth, except for the three-band radiometer reported in (5,6) that can measure a surface-layer temperature and a subjacent-layer temperature separately. Since the temperature-versus-depth profile can be obtained from the multifrequency radiometer measurement, in principle, interests in this area have increased recently (7,8).

This paper describes an experimental three-band radiometer system and a data analysis procedure developed for noninvasive measurement of the temperature at various depths in a biological body. The results of temperature measurement experiments performed by using them on the abdominal region of rabbits are also presented.

RADIOMETER SYSTEM

Figure 1 shows a photograph of the experimental system consisting of a radiometer (left) and a microcomputer (right). A block diagram of the system is given in Fig.2. The radiometer comprises the 1-2-GHz and 2-4-GHz Dicke receivers (9), and operates at 1.5,2.5,3.5 GHz with a 1-GHz bandwidth. A contact-type dielectric-filled waveguide (25.4 mm × 34.2 mm) antenna shown in Fig.3 is used. The antenna has two separate apertures electrically in order to cover the 1-2-GHz and the 2-4-GHz bands, but has a single aperture mechanically to be able to look at the same lateral region of an object at all the frequencies. The temperature of the reference noise source, referring to Fig.2, is controlled by the microcomputer so as to keep the output of the lock-in amplifier zero: the radiometer is operated in the radiation-balance mode (10,11). In this mode of operation, the noise temperature of the reference noise source is equal to the brightness temperature of an object, and hence, the surface emissivity, α, can be regarded as effectively unity. The control voltage that controls the temperature of the reference noise source is used as the output signal of the instrument. The instrument output signal is calibrated for each band against the temperature of the stirred-water in a bath, and the calibration data are stored in the computer memory. Measured value of the brightness temperature resolution of the system is about 0.05 °C for an integration time of five seconds.

The microcomputer is used for the system control including the frequency-band selection and the noise source temperature control, the data analysis and the display.

Fig.1. An experimental radiometer system consisting of a three-band radiometer (left) and a microcomputer (right).

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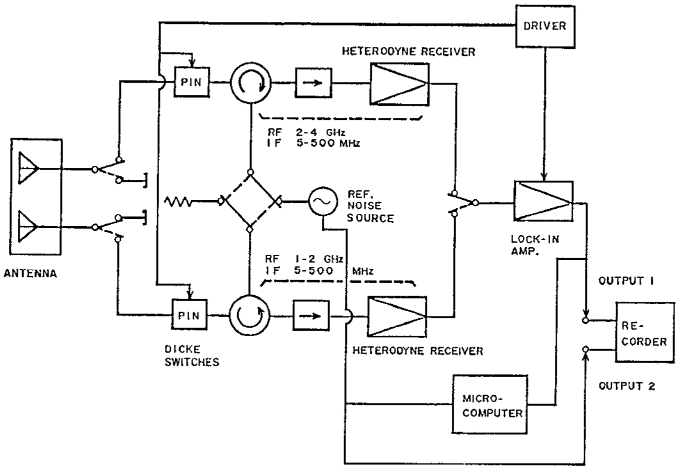

Fig.2. A block diagram of the three-band radiometer system. The system operates at 1.5,2.5,3.5 GHz with a 1-GHz bandwidth in the radiation-balance mode.

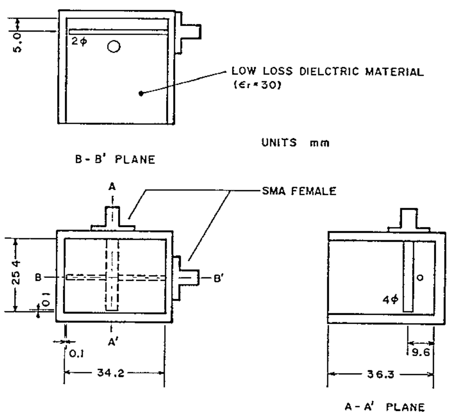

Fig.3. Contact-type dielectric-filled waveguide antenna.

DATA ANALYSIS

The radiometer system measures the brightness temperatures, T_{Bi}, at the frequencies, f_i= 1.5,2.5, 3.5 GHz (i=1,2,3), with a 1-GHz bandwidth. A set of T_{Bi} (i=1,2,3) readings is used in the present study, in which we restrict ourselves to a one-dimensional treatment of the inverse problem, to solve simultaneous equations of either (1) or (2) for T_0, ΔT, d_T ;

$$T_{Bi} = T_0 + \Delta T \left[1 - \frac{1}{1 + \delta_i/d_T} \right] \qquad (1)$$

$$(i = 1,2,3)$$

$$\begin{aligned} T_{Bi} = T_0 + \Delta T \Big[1 - \frac{1}{1 + \delta_{si}/d_T} & + \exp(-d_s/\delta_{si}) \Big\{ \Big(\frac{1}{1 + \delta_{si}/d_T} - \frac{1}{1 + \delta_{fi}/d_T} \Big) \exp(-d_s/d_T) \\ & + \exp\{-(d_f - d_s)/\delta_{fi} + d_f/d_T\} \times \Big(\frac{1}{1 + \delta_{fi}/d_T} - \frac{1}{1 + \delta_{mi}/d_T} \Big) \Big\} \Big] \end{aligned} \qquad (2)$$

$$(i = 1,2,3)$$

Equation (1) is obtained for a uniform tissue model by substituting an exponential temperature (T) versus depth (z) profile,

$$T(z) = T_0 + \Delta T \{ 1 - \exp(-z/d_T) \} \qquad (3)$$

which is assumed to exist in the tissue, into the formal solution of the equation of radiative transfer (12),

$$T_{Bi} = \alpha \int_0^\infty \{T(z)/\delta_i\} \exp\Big(- \int_0^z dz^*/\delta_i\Big)\, dz \qquad (4)$$

$$(i = 1,2,3)$$

with $\alpha = 1$,

assuming the power penetration distance in the tissue at f_i, δ_i, is constant. Equation (2) is obtained likewise for a three-layer tissue model consisting of the skin ($\delta_i = \delta_{si}$ for $0 \leq z < d_s$), the fat ($\delta_i = \delta_{fi}$ for $d_s \leq z < d_f$), and the muscle ($\delta_i = \delta_{mi}$ for $d_f \leq z < \infty$). Values of the power penetration distance used in our data analysis are listed in Table 1.

Table 1. Values of the power penetration distance used in the data analysis.

Tissue / Penetration Distance / Freq.	Skin δ_{si}(mm)	Fat δ_{fi}(mm)	Muscle δ_{mi}(mm)
1.5 GHz	12.1	70.2	12.1
2.5 GHz	5.3	56.1	5.3
3.5 GHz	3.1	42.9	3.1

EXPERIMENT

Using the radiometer system and the data analysis procedure, we made a series of temperature measurement experiments on the abdominal region of rabbits (3 kg). A view of the experiment is presented in Fig.4. The radiometer system is calibrated prior to start taking measurements. With the antenna placed in a position, all the steps of the measurement, including the T_{Bi} taking, the data analysis and the display of results are made automatically. One cycle of these steps takes 1-2 minutes, depending on the stability of T_{Bi} readings.

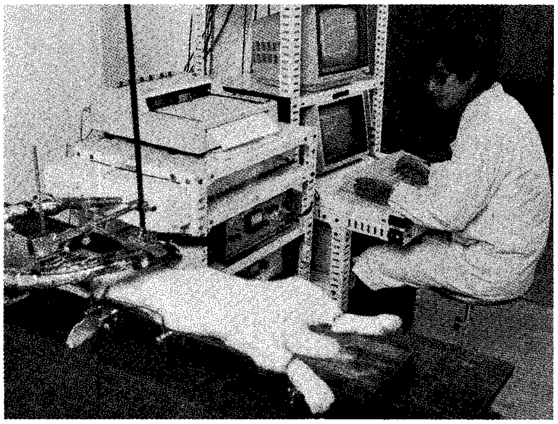

Fig.4. A view of the temperature measurement experiment. The antenna is placed on the abdominal region of a rabbit.

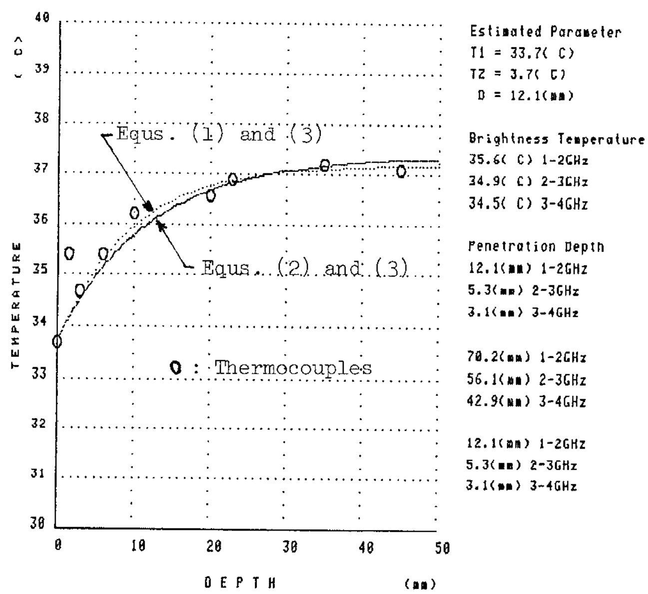

Fig.5. A computer print-out of the estimated temperature-versus-depth profiles. Smooth curves: radiometer measurements. Open circles: thermocouple measurements.

A typical result is presented in Fig.5 in the form of computer print-out, where the tissue temperature is plotted along the ordinate in °C and the depth from the body surface along the abscissa in mm. The open circles represent the readings taken with thermocouples placed in the tissue. The smooth curves with light and dark lines are the T-versus-z profiles estimated by equations (1) and (3) (uniform tissue model) and by equations (2) (3) (three-layer tissue model), respectively. In the three-layer tissue model calculation, $d_s = 5$ mm and $d_f = 6$ mm are used on the basis of anatomical observation. Since the fat layer is thin in the abdominal region of the rabbit, difference between the two estimations is not appreciable. Fig.6 shows twelve examples of the T-versus-z profiles estimated from radiometer readings. These examples are drawn from the results of three different measurement runs, intending to show the accuracy and the scattering of the estimations obtained by our system at present. We consider that the agreement between the radiometric measurement and the direct measurement with thermocouples is fairly good.

CONCLUSIONS

We have developed an experimental three-band microwave radiometer system and a data analysis procedure for noninvasive measurement of the temperature at various depths in a biological body. Using them, we made temperature measurement experiments on the abdominal region of rabbits. The results of the experiments show that the radiometric measurement agrees fairly well with the direct thermocouple measurement, provided that the temperature distribution can be approximated by an exponential distribution. The results demonstrate the feasibility of the multifrequency radiometry for this purpose.

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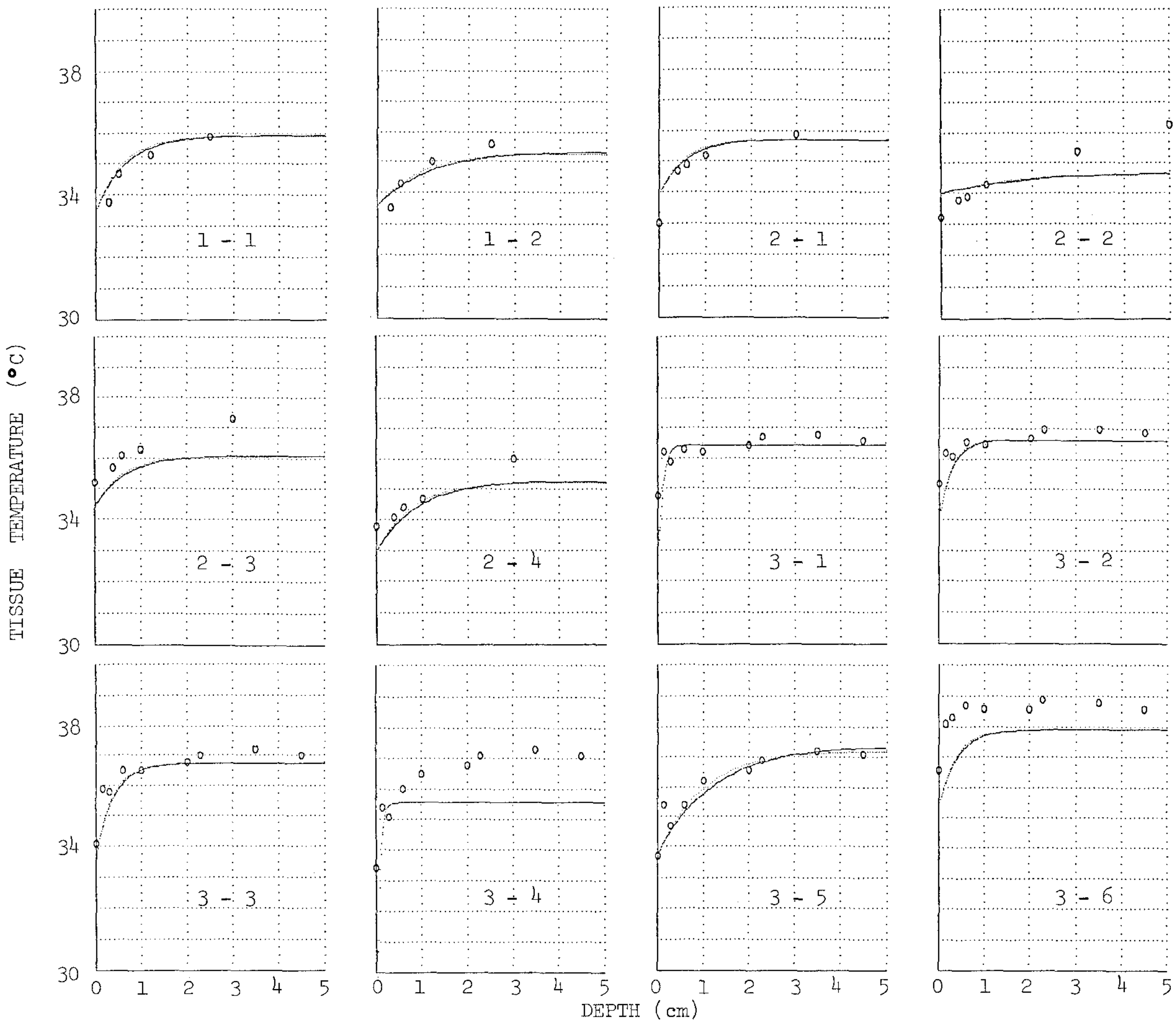

Fig.6. Typical examples of the radiometric estimations of T versus z profiles in the abdominal region of rabbits. The examples are drawn from three different measurement runs. Smooth curves: radiometric estimations. Open circles: direct thermocouple measurements.