EFFECTS OF WATER-FILLED BOLUS ON THE PRECISION OF MICROWAVE RADIOMETRIC MEASUREMENTS OF TEMPERATURES IN BIOLOGICAL STRUCTURES

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ABSTRACT

An assessment is made of the degradation that is caused by a water-filled bolus in the precision of tissue temperatures measured non-invasively by a five-band microwave radiometry scheme. The precision is expressed in terms of the confidence interval of tissue temperature estimated from a set of five brightness temperatures measured with an experimental instrument operating at center frequencies, 1.2, 1.8, 2.5, 2.9, 3.6 GHz, with a 0.4-GHz bandwidth. Results show that the degradation due to a bolus having a thickness of about 1 cm is small when it is filled with the deionized or distilled water. A conclusion of the present study is that the use of water-filled bolus is permissible for the microwave radiometric measurement, which bears a practical importance when the technique is used in combination with the electromagnetic heating for hyperthermic treatment of cancer.

INTRODUCTION

Microwave radiometry has been applied to non-invasive measurement of subcutaneous tissue temperatures for cancer detection(1,2), for temperature monitoring during hyperthermic treatment of cancer(3,4) and other diagnostic purposes(5). The problem of retrieving temperature-versus-depth profiles in a biological body has been studied theoretically(6-9) and experimentally(10-13). A method was described in (13) that was capable of estimating temperature profiles from brightness temperatures measured with a five-band radiometer, where effects of random measurement errors were accounted for by the confidence interval of tissue temperature. This method is used in the present study to examine effects of a water-filled bolus placed between a radiometer antenna and an object. The presence of the bolus is undesirable for the radiometric measurement because it attenuates the signal from the object and generates the thermal radiation, but it is required for the surface cooling during the electromagnetic heating of lesion for hyperthermia.

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ANALYSIS

A. Antenna-Bolus-Tissue Model

The antenna-bolus-tissue structure system is represented by a plane parallel layered model, comprising the lossless dielectric (antenna), water, skin, fat and muscle. The equation of radiative transfer is solved for this model under one dimensional approximation. The solution can be put in a symbolic form,

$$T_{Bi,model} = L_i[T(z);\delta_{Wi},\delta_{Si},\delta_{Fi},\delta_{Mi}] \qquad (1)$$

where $T_{Bi,model}$ is the brightness temperature for the model, L_i an integral operator defined by the solution of radiative transfer equation, $T(z)$ the temperature profile, z the depth into tissue with the coordinate origin at the water-skin interface, and δ_{Wi}, δ_{Si}, δ_{Fi}, δ_{Mi} are power penetration distances in the water, skin, fat and muscle, respectively. The suffix i refers to the frequency of observation, f_i. In eq.(1), the thermal radiation from the water layer and the absorption in it of the thermal radiation signal coming from the tissue structure are taken into account. Effects of multiple reflections at the skin-fat and fat-muscle interfaces are also taken into account by a coherent approach.

B. Temperature Profile Model

To facilitate analysis, we introduce a temperature profile model function of a form,

$$T(z)=T_W, \qquad z<0, \qquad (2a)$$

$$T(z)=T_0+\Delta T_1(1-\exp(-z/a)+\Delta T_2(z/b)\exp(-z/b), \qquad z\geqq 0. \qquad (2b)$$

Eq.(2) has a typical shape shown in Fig.1, and is capable of representing gradually varying profiles with a broad peak (or valley) in tissue. We treat T_0, ΔT_1, ΔT_2, a and b as unknown model parameters to be determined from measurements, since the temperature of water in bolus, T_W, can be measured directly with probes such as thermocouples. Independent measurements of the brightness temperature at five different frequencies are sufficient to determine the five model parameters. Values of the power penetration distances in tissues at respective frequencies are assumed known in the present treatment, but in practice are determined from a number of separate phantom measurements in which temperature profiles are directly measured.

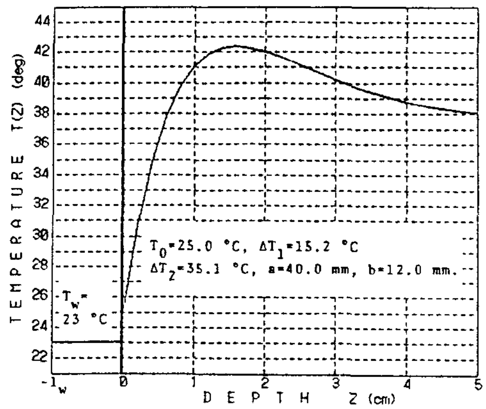

Fig.1. Temperature profile model described by eq.(2).

C. Temperature Profile Estimation

Temperature profiles are estimated using the procedure described in (13), which gives a basic equation,

$$\sum_{i=1}^{5}\left[\frac{(T_{Bi,model}-T_{Bi,meas})-\varepsilon_{i,min}}{C\,\Delta T_{Bi,min}}\right]^2 \leqq 1 \qquad (3)$$

where $T_{Bi,meas}$ and $\varepsilon_{i,min}$ are measured values of the brightness temperature and minimum errors in the least-square fitting of model to measurements, respectively, at f_i (i=1,2,..,5). Effects of random errors in the $T_{Bi,meas}$ measurements are taken care of by the denominator, where $\Delta T_{Bi,min}$ are minimum detectable brightness temperatures or the resolution of the radiometer and C is the parameter that sets the confidence level of estimation; C=2.46 at a 70%-confidence level.

Combining eqs.(1) through (3) and carrying out numerical computation, one obtains temperature-versus-depth profiles, where the corresponding confidence interval of estimation gives a range of tissue temperatures at a value of depth, z.

EXPERIMENT

A. Arrangement

Experiments on the radiometric temperature profiling were made using an arrangement illustrated in Fig.2, where a muscle equivalent agar phantom in plastic container was placed in a hot water-bath at about 40 °C. A box made of thin (1 mm) plastic boards was placed on the top of phantom in which temperature controlled water (23 °C) was circulated. A waveguide antenna filled with a dielectric material (ε_r=40) was placed in the circulating water as shown in the figure, where the distance from the antenna aperture (15.6 mm x 20.4 mm) to the top surface of phantom was set at 1 cm. The water layer between the antenna aperture and the phantom was intended to simulate a water-filled bolus.

Radiometric measurements were made with an experimental instrument operating at center frequencies, 1.2, 1.8, 2.5, 2.9, 3.6 GHz, with a 0.4-GHz bandwidth. Measured values of $\Delta T_{Bi,min}$ of the instrument (integration time = 5 sec.) are given in Table 1(A). Several thermocouple probes were placed in the phantom for comparison and in the circulating water for measurement of T_W. The circulating water tested in the experiments was the deionized water prepared by filtering the tap water with a polymer resin filter and the distilled water of a pharmaceutical grade.

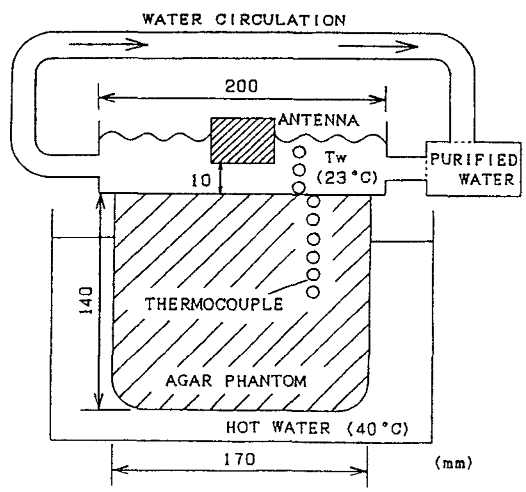

Fig.2. An arrangement used in the radiometric temperature profiling experiments.

B. Results

Typical results obtained with using the deionized water are given in Fig.3, where the tissue temperature given in °C and the distance from the phantom surface in the depth direction given in cm are plotted along the vertical and horizontal axes, respectively. The solid curve represents an estimated temperature profile which fits a particular set of $T_{Bi,meas}$ (i=1,2,..,5). The profile is subjected to random fluctuations due to random errors in the $T_{Bi,meas}$ measurements. Magnitudes of the fluctuations are expressed in terms of the confidence interval of tissue temperature estimation. The region with intervals a-a' in Fig.3 represents a region of confidence intervals estimated at a 70%-confidence level for the experimental results given above. The precision of estimation is defined by one half of confidence intervals at a 70%-confidence level in the present study.

In order to show the degree of degradation due to the presence of the water layer, a similar confidence interval estimation was made by computer simulation in which the water layer thickness was made to vanish while the tissue temperature profile given by the solid curve in the figure was kept unchanged. Results are represented by the region with confidence intervals b-b' in Fig.3, where the degradation due to the water layer is indicated by the areas of heavy shading. Open circles are thermocouple temperature readings for comparison.

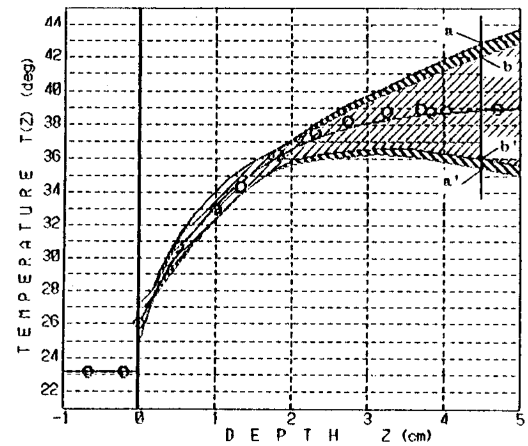

Fig.3. Typical results of a microwave radiometric temperature profiling experiment made with a 1-cm thick layer of deionized water between the antenna aperture and the phantom.

A similar experiment was made with the distilled water circulated in the space between the antenna aperture and the phantom, referring to Fig.2. Typical results are given in Fig.4, where the solid curve, the shaded regions with confidence intervals a-a' and b-b' represent a profile which fits a set of $T_{Bi,meas}$, regions of confidence intervals at a 70%-confidence level with and without the 1-cm thick layer of distilled water between the antenna aperture and the top surface of phantom, respectively. The degradation caused by the distilled water layer is indicated by the areas of heavy shading.

These results show that the degradation in the precision of tissue temperature estimation can be kept small when proper precautions are taken, indicating that the use of a water-filled bolus is permissible for microwave radiometric measurements of tissue temperatures.

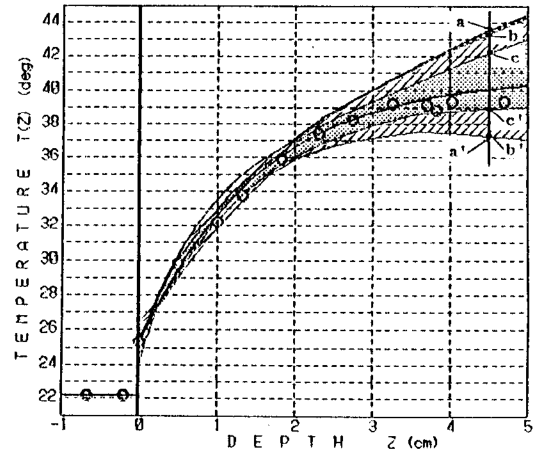

Fig.4. Typical results obtained with using a 1-cm thick layer of distilled water between the antenna aperture and the top surface of phantom.

EFFECT OF INSTRUMENT RESOLUTION

The numerical results presented above regarding the precision are based on $\Delta T_{Bi,min}$ values given in Table 1(A). These values were obtained on an experimental radiometer used in the experiments with a 5-second integration time, as mentioned earlier. The precision of estimation improves as the brightness temperature resolution of the instrument improves, according to eq.(3).

Computer simulation was made to assess the improvement expected when the brightness temperature resolution was improved to 0.03 K at all the frequencies of measurements, as given in Table 1(B), where the same experimental data that used for a-a' in Fig.4 were used. Results are represented by the shaded region with confidence intervals c-c' in Fig.4. The brightness temperature resolution of about 0.03 K is expected with a 5-second integration time for a radiometer currently under construction that employs a modern low noise amplifier (NF = 1.2 dB, G = 35 dB) at its front end when it is operated at around the room temperature.

Table 1. Radiometer brightness temperature resolution. (A)Experimental radiometer. (B)Improved design.

f_i(GHz)		1.2	1.8	2.5	2.9	3.6
$\Delta T_{Bi,min}$(K)	(A)	0.07	0.06	0.06	0.06	0.07
	(B)	0.03	0.03	0.03	0.03	0.03

A relationship between the precision and the depth deduced from confidence intervals c-c' in Fig.4 is summarized in Table 2.

Table 2. Precision of tissue temperature estimation deduced from Fig.6.*

Depth(cm)	1	2	3	4	5
Precision(K)	±0.2	±0.4	±0.7	±1.2	±2.0

*Conditions of estimation:
Brightness temperature measurements in five bands over 1 - 4 GHz range with $\Delta T_{Bi,min}$ = 0.03 K.
With 1-cm thick bolus filled with distilled water.
One-D approximation in uniform, muscle equivalent tissue.

CONCLUSION

A feasibility study was made on a five-band microwave radiometry scheme for non-invasive measurement of tissue temperature in the presence of a water-filled bolus between radiometer antenna and object. A temperature profiling technique previously developed was used to analyze effects of the bolus on the precision of tissue temperature estimation, where the precision was defined by one half of the confidence interval of estimation at a 70%-confidence level. Experiments were performed on an agar phantom using an experimental five-band microwave radiometer with a 0.06-0.07-K resolution, where a 1-cm thick water layer was introduced between the radiometer antenna and the phantom to simulate the bolus. The water tested in the experiments was the deionized water and the distilled water. The confidence intervals were calculated for the experimental data as a function of the depth with and without the presence of water layer, respectively. Results indicated that the degradation in the precision due to the water layer was small for the both kinds of water, with the distilled water giving smaller degradation of the two. The precision was also estimated using a 0.03-K resolution to find that it was about ±1.2 K at a 4-cm depth in a uniform muscle-equivalent tissue structure.

A conclusion may be drawn from the present study that the use of a water-filled bolus is permissible for the microwave radiometric measurement of tissue temperature, provided that the bolus thickness is kept at about 1 cm or less and the distilled or the deionized water is used in the bolus.

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REFERENCES

(1) A.H. Barret, P.C. Myers and M.L. Sadowsky, "Detection of breast cancer by microwave radiometry," Radio Science, Vol.12, No.6(S), pp.167-171, Nov.1977.
(2) K.L.Carr,A.M.El-Mahdi and J.Shaeffer,"Dual-mode microwave system to enhance early detection of cancer," IEEE Trans. Microwave Theory and Tech., Vol.MTT-29, No.3, pp.256-260, 1981.
(3) M.Chive, M.Plancot, Y.Leroy, G.Giaux and B.Prevost, "Microwave (1 and 2.45 GHz) and radiofrequency (13.56 MHz) hyperthermia monitored by microwave thermography," Proc. of the Twelfth European Microwave Conf., pp.547-552, 1982.
(4) F.Sterzer, R.Paglione and F.Wozniak, "Self-balancing microwave radiometer for non-invasively measuring the temperature of subcutaneous tissue during localized hyperthermia treatments of cancer," 1982 IEEE MTT-S International Microwave Symposium, Digest, pp.438-440.
(5) F.Sterzer, "Microwave radiometers for non-invasive measurements of subsurface tissue temperatures," Journal of Automedica, Vol.8, No.4, pp.203-211, 1987.
(6) F.Bardati,M.Mongiardo and D.Solimini,"Inversion of microwave thermographic data by the singular function method," 1985 IEEE MTT-S International Microwave Symposium, Digest, pp.75-77.
(7) F.Bardati,M.Bertero,M.Mongiardo and D.Solimini, "Singular system analysis of inversion of microwave radiometric data: application to biological temperature retrieval," Inverse Problems, Vol.3, pp.347-370, 1987.
(8) F.Bardati,M.Bertero,M.Mongiardo and D.Solimini, "Singular system analysis for temperature retrieval in microwave thermography," Radio Science, Vol.22, No.6, pp.1035-1041, 1987.
(9) S.D.Prionas and G.M.Hahn, "Noninvasive thermometry using multi-frequency-band radiometry. A feasibility study," Bioelectromagnetics, Vol.6, pp.391-404, 1985.
(10) S.Mizushina,H.Oh-ishi and Y.Hamamura, "A three-band microwave radiometer for noninvasive temperature measurement," 1984 IEEE MTT-S International Microwave Symposium, Digest, pp.145-147.
(11) S.Mizushina,Y.Hamamura and T.Sugiura, "A three-band microwave radiometer system for noninvasive measurement of the temperature at various depths," 1986 IEEE MTT-S International Microwave Symposium, Digest, pp.759-762.
(12) Y.Hamamura, S.Mizushina and T.Sugiura, "Non-invasive measurement of temperature-versus-depth profile in biological systems using a multiple-frequency-band microwave radiometer system," Journal of Automedica, Vol.8, No.4, pp.213-232, 1987.
(13) S.Mizushina,Y.Hamamura,M.Matsuda and T.Sugiura, "A method of solution for a class of inverse problems involving measurement errors and its application to medical microwave radiometry," 1989 IEEE MTT-S International Microwave Symposium, Digest, pp.171-174.