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A SELF-BALANCING MICROWAVE RADIOMETER FOR NON-INVASIVELY MEASURING THE TEMPERATURE OF SUBCUTANEOUS TISSUES DURING LOCALIZED HYPERTHERMIA TREATMENTS OF CANCER

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ABSTRACT

The use of a self-balanced microwave radiometer in localized rf and microwave hyperthermia treatments of cancer is described. Initial clinical observations are presented.

INTRODUCTION

When treating tumors with localized hyperthermia it is of great importance to the clinician to accurately know the temperature of the tissues that are being heated. Unfortunately, however, measuring tissue temperatures during localized hyperthermia treatments is difficult. Skin temperatures can be non-invasively measured with either thermocouples, thermistors, or fiber optic thermometers, but measurements of the temperature of subcutaneous tissues with any of these temperature sensors usually require invasive procedures that most clinicians prefer to avoid if at all possible. Dicke-type radiometers can non-invasively measure the average temperature of subcutaneous tissues, but the readings of Dicke radiometers depend not only on the temperature of the tissues being measured, but also on the mismatch between the antenna of the radiometer and the tissues. Since there is substantial variation in the dielectric constant of various healthy and malignant tissues, Dicke radiometers have to be constantly recalibrated, a procedure that is not practical in a clinical environment.

Self-balancing radiometers overcome the major limitation of Dicke radiometers by automatically compensating for variations in the dielectric constants of the tissues whose temperature is being measured.[1,2] These radiometers appear to be well suited for non-invasively measuring average tissue temperature in a clinical environment, particularly if the same antennas or applicators are used to heat the tissues with rf or microwaves and to receive thermal noise from the heated tissues.[3] We report here on such a self-balancing radiometer and its use in conjunction with localized hyperthermia treatments of cancer using rf and microwave heating.

LOCALIZED HEATING OF TISSUES WITH RF OR MICROWAVE RADIATION

A convenient method for producing localized hyperthermia (sustained local heating to temperatures of about 42-43.5°C) is to use contact applicators to broadcast rf or microwave energy into the tissues to be heated. The rf or microwaves travel through the tissues of the body in the form of exponentially decaying waves, giving up energy to the tissues via dielectric heating.

Figure 1 shows a block diagram of the apparatus used to induce localized hyperthermia with radiated rf or microwaves. Power produced by a generator is matched by means of a tuner into an applicator that radiates the power toward the tumor to be treated. Two power meters are provided, one for measuring the power leaving the generator, and a second one for measuring the power reflected back to the generator. The depth to which the rf or microwaves that are radiated by the

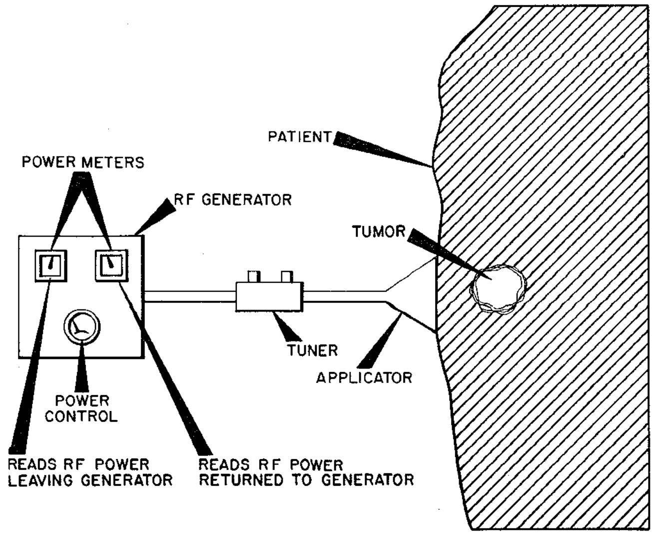

Fig. 1 Apparatus for producing localized hyperthermia with rf or microwave radiation.

applicator can penetrate into the patient and heat the tumor is primarily a function of the dielectric properties of the tissues shielding the tumor from the applicator and of the rf or microwave frequencies used. In general, the lower the water content of the shielding tissues, the deeper the penetration of a wave at a given frequency. Waves penetrate much deeper into fat (low water content) than into muscle (high water content). Also, at the frequencies of interest, the lower the frequency, the deeper the penetration into tissues with a given water content. The approximate useful depths for localized hyperthermia treatments using a single applicator are listed in Table I.

TABLE I. Approximate Useful Depth for Hyperthermia Treatments with Single Radiating Applicator

Frequency (MHz)	Depth (cm) H	Depth (cm) L
30	10	>20
100	5	>20
1000	3	15
2500	2	10
5000	1	5

H = Tumor shielded from applicator by tissues with high water content, such as skin and muscle.

L = Tumor shielded from applicator by tissues with low water content, such as fat and bone.

Figure 2 shows four rf and microwave hyperthermia contact applicators that we are using with the appratus of Fig. 1.[4-6] The applicators shown in Fig. 2a-2c operate at a microwave frequency (2450 MHz); the applicator of Fig. 2d operates at a relatively low rf frequency (27 MHz). The microwave applicators make it possible to accurately focus the microwave energy on the tumors to be treated, but their use is limited to treating cutaneous and subcutaneous tumors, tumors within or in the

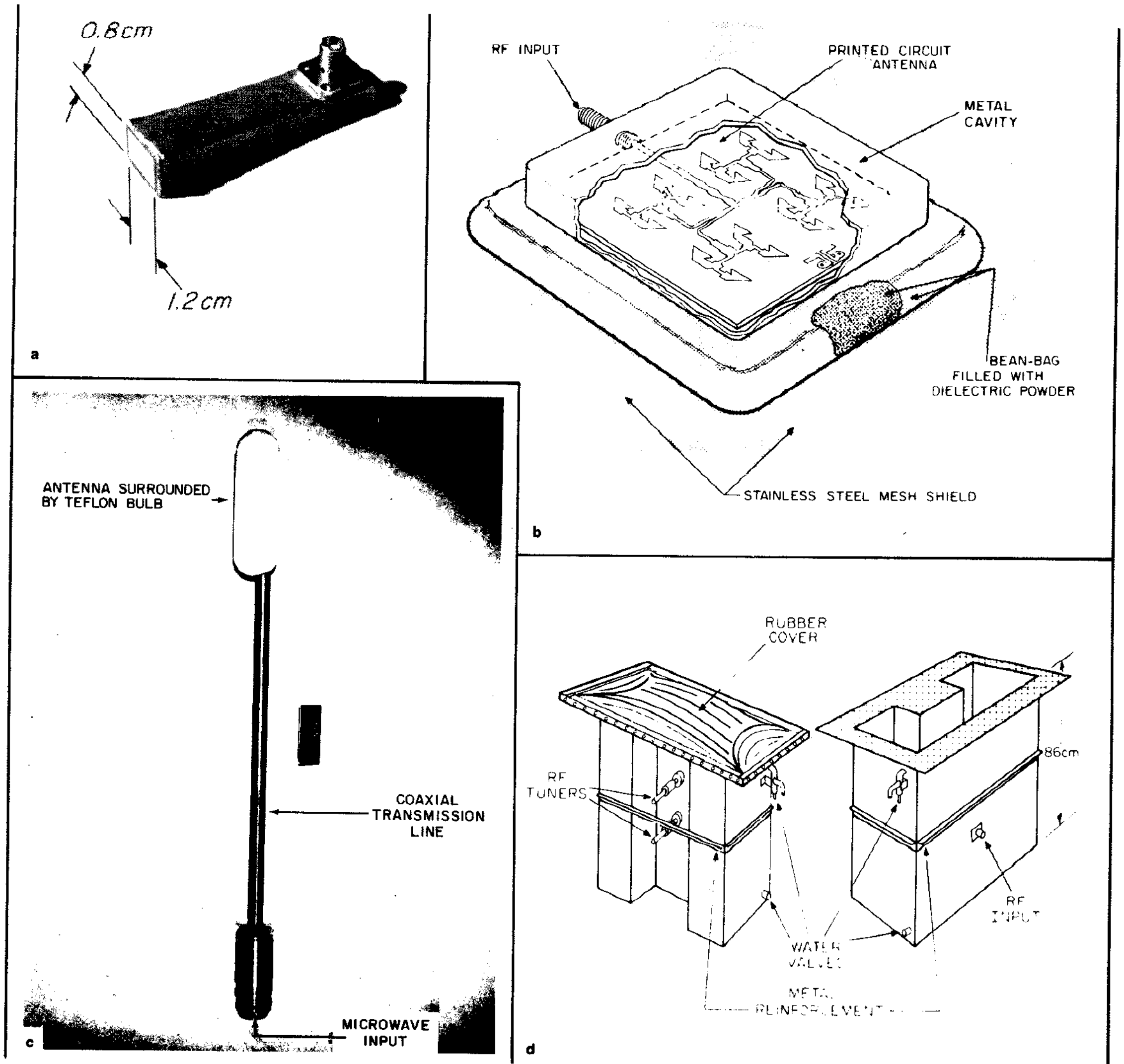

Fig. 2. Photographs of several applicators developed by us for use with apparatus of the type shown in Fig. 1: (a) 2450 MHz waveguide applicator filled with solid dielectric (used for treating small superficial lesions); (b) 2450 MHz "bean-bag" applicator with printed circuit antenna (used for treating large superficial lesions and breast tumors); (c) 2450 MHz coaxial applicator (rectal applicator for treating prostate cancer); (d) 27 MHz water-filled waveguide applicator (used for treating deep-seated tumors).

vicinity of natural body cavities, and tumors in the breasts. The rf applicator can be used to treat deep-seated tumors, but focusing is relatively poor (the wavelengths in tissues at 27 MHz are greater than 1 meter). The rf or microwave power levels required to raise tissues to hyperthermic temperature vary from about 1 W for the applicator of Fig. 2a to several hundred watts for the applicator of Fig. 2d.

MEASUREMENT OF SUBCUTANEOUS TISSUE TEMPERATURES WITH THE RADIOMETER

The self-balancing radiometer used in our work operates over the frequency range from 2350-2550 MHz. The low-noise amplifier of the radiometer uses bipolar transistors as the active elements. Switching is done with latching ferrites, and a solid-state diode is used in the variable noise source. Temperature readout is in degrees celsius on a liquid crystal display. The time constant of the radiometer can be adjusted over a wide range, but for most clinical use a time constant of a fraction of a second produces adequate accuracy (i.e. a fraction of a degree celsius). The 2450 MHz contact applicators shown in Fig. 2a-2c are used as antennas. Most of the thermal microwave noise power received by the antennas of the radiometer emanates from a layer of tissues roughly 1/2 to 1 cm thick that is located just below the contact area of the antennas. The actual thickness of the tissue layers making most of the contributions to the radiometer reading depends on the water content of the tissues: The lower the water content, the thicker the tissue layer contributing most of the received noise power.

The switching arrangement shown in Fig. 3 was built to enable us to use one applicator in a dual mode. In one mode, the applicator is used to direct the power from a 2450 MHz generator into the tissues to be heated. In the other mode, the applicator serves as the antenna of the radiometer and receives the thermal radiation from the heated tissues.

When heating is done with contact applicators operating at frequencies other than 2450 MHz, tissue temperatures are measured by removing the contact applicator after heating, and then measuring the thermal noise power emitted by the heated tissues with the radiometer. The ceramic-filled waveguide applicator of Fig. 2a usually serves as the antenna of the radiometer.

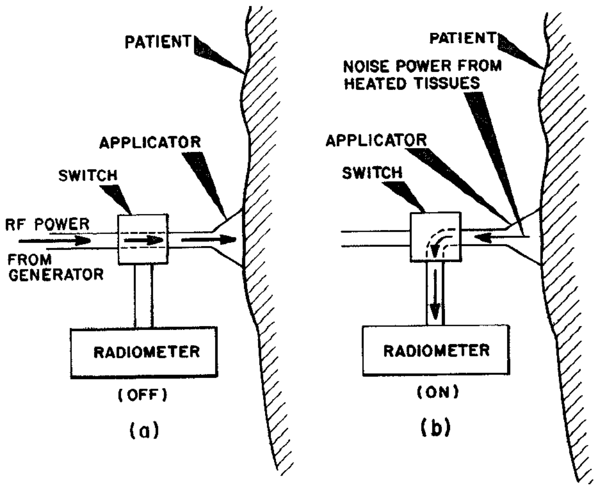

Fig. 3. Switching arrangement for using the same applicator for both heating with microwaves and for receiving thermal microwave radiation: (a) switch in position for heating; (b) switch in position for measuring thermal radiation emitted by the heated tissues.

INITIAL CLINICAL OBSERVATIONS

From comparisons between skin temperatures measured with thermocouples and corresponding radiometer readings we have reached the following conclusions:

1. During localized hyperthermia treatments with contact applicators, skin temperatures are not reliable as indicators of subcutaneous temperatures. This is because skin temperatures, unlike subcutaneous temperatures, are strongly influenced by factors such as the temperature of the contact applicator, the intimacy of contact between the applicator and the skin, the amount of perspiration, etc. This observation has obvious implications for any study attempting to compare the effectiveness of various localized hyperthermia treatment regimes.

2. During localized hyperthermia treatments with contact applicators, subcutaneous temperatures are often significantly higher than skin temperatures. This effect is probably due to several factors including cooling of the skin by the applicators, the high vascularity at hyperthermic temperatures of healthy skin, skin cooling due to perspiration, etc. One implication of this observation is that it might be adequate in some patients to raise the skin temperature to only about 41.5°C, since the corresponding temperature of subcutaneous tumors is likely to be within the hyperthermic range (42-43.5°C).

3. After localized hyperthermia treatments, subcutaneous tissue temperatures remain longer at elevated temperatures than do skin temperatures. This observation has important implications when planning localized hyperthermia treatments followed after a short interval by ionizing radiation therapy.

CONCLUSIONS

Self-balancing radiometers operating in one microwave frequency band are useful for making non-invasive measurements of average subcutaneous tissue temperature during localized hyperthermia treatments of cancer. The major limitations of radiometers of this type are that only average rather than point temperatures are measured, and that the depths to which tissue temperature are averaged are relatively shallow. It should be possible to make progress in overcoming these limitations by developing self-balancing radiometers that can operate at multiple frequency bands in both rf and microwave spectral regions.

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