MICROWAVE APPLICATORS FOR LOCALIZED HYPERTHERMIA TREATMENT OF MALIGNANT TUMORS

by

Robert W. Paglione and Fred Sterzer
RCA Laboratories
David Sarnoff Research Center
Princeton, NJ 08540

and

Jozef Mendecki, Esther Friedenthal and Charles Botstein
Montefiore Hospital and Medical Center
111 East 210th Street
Bronx, NY 10467

Summary

Three types of microwave applicators have been developed for treating malignant tumors in humans: waveguide applicators, conformal "bean-bag" applicators using printed circuit antennas, and coaxial applicators. These applicators operate at a frequency of 915 or 2450 MHz and can raise the temperature of tumors to the hyperthermic range of 42.5 to 43.5°C. Encouraging results have been obtained with these applicators in initial clinical trials involving approximately 50 patients.

Introduction

Hyperthermia has been shown to be an effective therapy in the treatment of cancer.[1,2,3] When used in conjunction with ionizing radiation, hyperthermia produces several additional therapeutic advantages: 1) the vasodilation resulting from the hyperthermia causes radio-resistant hypoxic (poorly oxygenated) cells, located within the center of the tumor, to become better oxygenated and therefore, more sensitive to the ionizing radiation; 2) cells in the S-phase of the mitotic cycle, the phase most resistant to ionizing radiation, are particularly sensitive to heat and therefore hyperthermia can supplement the destructive effects of the ionizing radiation; and 3) hyperthermia may impair the regeneration of malignant cells that have been partially damaged by ionizing radiation.

Hyperthermia can be produced in living tissues by a variety of methods. It can be induced in the whole body or in regions of the body, or it can be induced locally. We will describe equipment designed to produce localized hyperthermia using microwaves and present results obtained in several clinical cases.

Localized Heating With Microwaves

In a typical localized hyperthermia treatment, the temperature of the tumor mass is raised from a normal body temperature of 37°C to an elevated temperature of 42.5 to 43.5°C and held there for one-half to one hour. This treatment is usually repeated at two-day intervals. The power densities required to produce this heating depend on the type and size of the tumor, its location, the blood circulation in and around the tumor, etc. Typical power densities have been experimentally found to be 1 to 2 watts per square centimeter of surface area upon which the electromagnetic radiation impinges. Thus, depending on the particular tumor, powers ranging from a few to hundreds of watts may be required.

Applicators

The applicators that produce localized microwave hyperthermia must be capable of handling the power needed to raise the temperature of the tumor or tumors to be treated to the hyperthermic range. The applicators must also minimize the amount of microwave power delivered to healthy tissues and must not be physically uncomfortable for the patient who must undergo one or several treatments. The radiation into free space from the applicator must be kept to a minimum to protect the patient and the personnel who administer the treatment from unnecessary exposure to microwave radiation. The applicator must also be rugged and in some cases, it must be able to be sterilized or autoclaved.

We have developed three types of microwave applicators based on the above design considerations: waveguide applicators, conformal "bean-bag" applicators using printed circuit antennas, and coaxial applicators. All of the applicators operate at 915 ±13 MHz or at 2450 ±50 MHz.

Waveguide Applicators

Waveguide applicators are constructed using short sections of rectangular waveguides that are closed at one end with a metallic short circuit and have a coaxial connector attached to the broad wall for introduction of microwave power. In some applicators the waveguide is filled with air and in others it is filled with a solid dielectric. In operation, the microwave power is coupled into the waveguide through the coaxial connector and the open end of the applicator is pressed against the tumor to be treated. Figure 1 is a photograph of a typical waveguide applicator. This applicator operates at 2450 MHz and is filled with a low-loss, high dielectric constant, solid ceramic material. The dielectric constant of the ceramic material is approximately equal to the dielectric constant of muscle tissue. This material was incorporated into the applicator design to reduce the overall size of the applicator and to reduce reflections at the applicator/tissue interface. The distance between the 3 mm coaxial connector and the short-circuited end of the applicator is optimized for a maximum input VSWR of 1.5:1 when the applicator is in contact with typical body tissues. The input VSWR is approximately 10:1 when the applicator is radiating into free space.

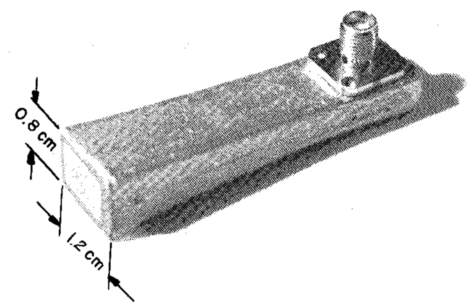

Fig. 1 Waveguide applicator filled with solid dielectric. The applicator is designed for operation at 2450 MHz.

This type of applicator is particularly useful for treating small, relatively flat tumors on the surface of the body. Air-filled waveguide applicators are well-suited for treating small surface tumors that protrude somewhat above the skin.

Conformal Applicators

The conformal "bean-bag" applicator, shown in Figure 2, consists of a Teflon-fibreglass printed-circuit board with a multiplicity of dipole antennas printed on both sides, a metal back cavity, a plastic bag, and a metallic screen. One-half of each dipole antenna radiates outward from the applicator; the other half radiates into the metal back cavity. The printed circuit board is positioned in the metal back cavity so that the microwaves radiating into the back cavity will be reflected back through the printed circuit board and constructively add with the outwardly radiating microwaves to produce a coherent beam of radiating energy. Microwave energy is delivered to the individual dipoles through a corporate feed. This feed can also be designed to tailor the heating pattern of the applicator by distributing more power to certain dipoles than to others.

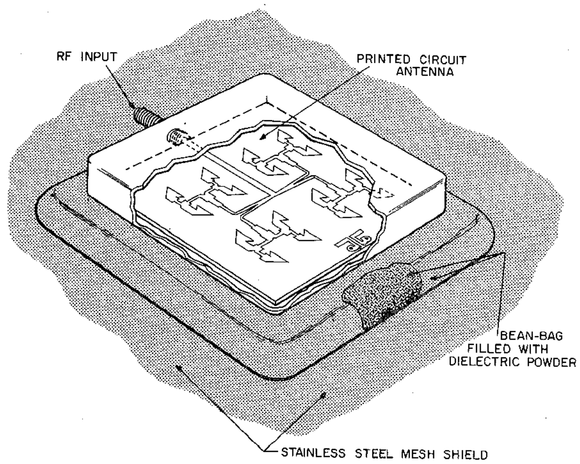

Fig. 2 "Bean-bag" applicator designed for operation at 2450 MHz.

The spaces in front of and in back of the antenna board and the plastic bag are all filled with a low-loss powder of high dielectric constant. This powder serves a two-fold purpose: 1) the dipoles are resonant at approximately 10.5 GHz, and the dielectric constant of the power effectively reduces their resonant frequency to 2450 MHz; and 2) the powder in the plastic bag acts as a cushion that conforms to the contours of the body.

The metallic screen is made of stainless steel wires woven into a fine mesh and the perimeter of the screen is weighted with a silicon rubber compound. When the applicator is being used, the screen is spread out over the treatment area to minimize the stray-field radiation.

In operation, the "bean-bag" is placed on top of the lesion or lesions to be treated (the plastic bag tends to conform to the contours of the lesions and the body), and the microwave power is fed into the applicator via a flexible coaxial cable.

Coaxial Applicators

Coaxial applicators are useful for treating tumors that are located in or near natural body cavities. Figure 3 is a photograph of a 2450 MHz coaxial applicator that was specifically designed for treating cancer of the prostate gland. The applicator consists of a length of semi-rigid 50-ohm coaxial transmission line with a microwave connector at one end and a Teflon bulb covering a dipole antenna at the other.

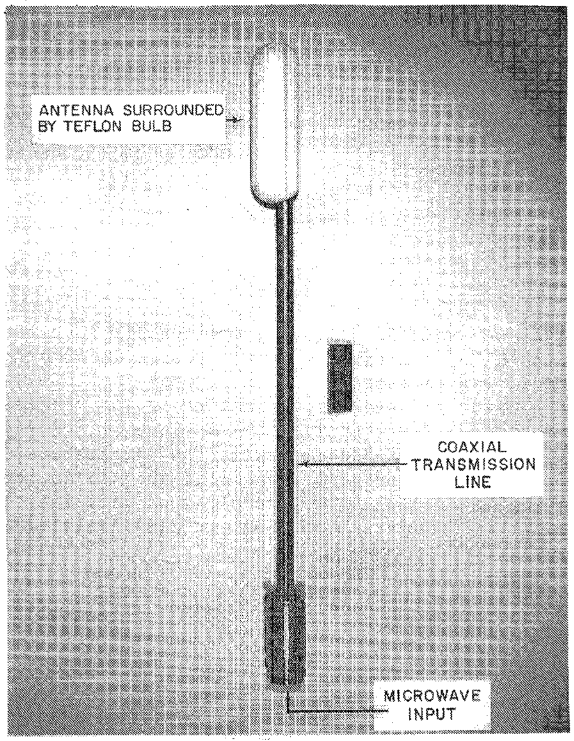

Fig. 3 Coaxial applicator designed for operation at 2450 MHz.

The dipole antenna is made by removing a quarter-wavelength section of the outer conductor from the end of the coaxial line, and by adding a quarter wavelength metallic choke to reduce the leakage of microwave power along the outer conductor of the coaxial line (See Figure 4).

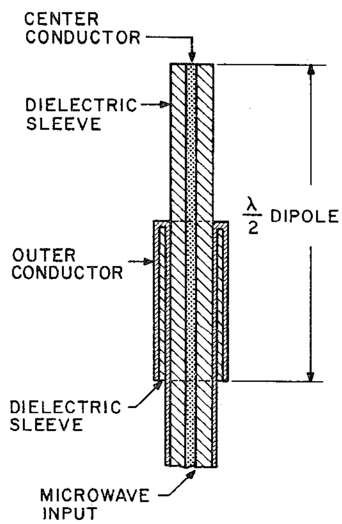

Fig 4. Cross-section of the dipole antenna of a coaxial applicator.

The dipole antenna is enclosed in a Teflon bulb that has a pear-shaped cross-section. The antenna is positioned in the neck of the bulb and is equidistant from the surface in the neck area only -- the distance is greater in all other areas. The applicator is positioned in the rectum of the patient with the neck of the Teflon bulb facing the prostate gland. Since the antenna is closest to this surface and since tissues have a high dielectric constant, most of the microwave power will be absorbed by those tissues that are in the direction of the prostate gland.

Temperature Distributions Produced by Hyperthermia Applicators

The temperature rise produced in living tissues by microwave heating is a strongly nonlinear function of the incident microwave power. This fact is illustrated in Figure 5, which shows the temperature measured in the rectum of an anesthetized mouse, as a function of the microwave power density obtained using the 2450 MHz waveguide applicator of Figure 1. In this experiment the waveguide applicator was placed on the abdomen of a mouse, approximately 0.5 cm above the rectum. A thermocouple was inserted into the rectum to measure the temperature rise. Note that with 0.5 W/cm^2 there is almost no heating, with 0.8 W/cm^2 the temperature rises to only 37°C, while with 1.5 W/cm^2 a temperature of 42°C is reached in only 60 seconds. At the lower power densities, the heat generated by the microwave radiation can be carried away by the blood flow with only a small increase in temperature. At a power density of 1.5 W/cm^2, even the maximum blood flow through the blood vessels is insufficient to maintain an equilibrium temperature and, therefore, the temperature increases rapidly as a function of time.

Figure 6 shows temperature versus time curves measured in the thigh of an anesthetized dog that was heated with a 2450 MHz "bean-bag" applicator. Three thermocouples were inserted into the mass of the posterior thigh muscle of the dog under the center of the "bean-bag" applicator to depths of 1, 2 and 3 cm, respectively. A fourth thermocouple was placed under the skin, and a fifth thermocouple was placed on the surface of the skin. The figure shows that in equilibrium the temperature under the skin is higher than on the skin surface. Furthermore, in the muscle the temperature decreases monotonically with distance from the skin; at a distance of 2 cm from the skin, the temperature is more than 2°C lower than the temperature under the skin. Because of this substantial drop-off in temperature at a depth of 2 cm, a single 2450 MHz "bean-bag" (or waveguide) applicator is generally useful only for treating tumors that do not extend more than 1.5 to 2 cm below the surface of the body. The treatment depth can, however, be extended somewhat by artificially cooling the skin underneath the applicator.

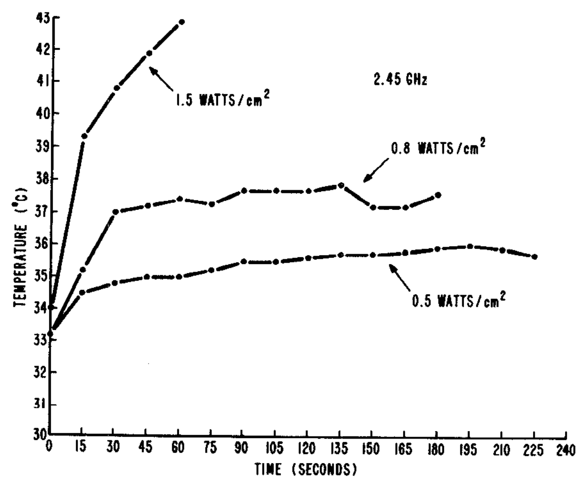

Fig. 5 Rectal temperature of a mouse as a function of time during local hyperthermia.

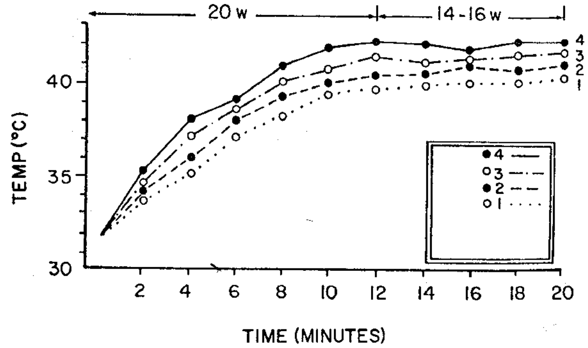

Fig. 6 Temperature in the thigh of a dog versus time during local hyperthermia.

More uniform temperature distributions to greater depths than those of Figure 6 can be obtained by heating with two applicators placed on opposite sides of a tissue volume. Figure 7 shows the temperature distribution that was obtained when the left gluteus major of a 36 kg anesthetized dog was heated from opposite sides with two "bean-bag" applicators. The distance between the two applicators was approximately 5 cm, and the temperature over this entire distance was nearly uniform.

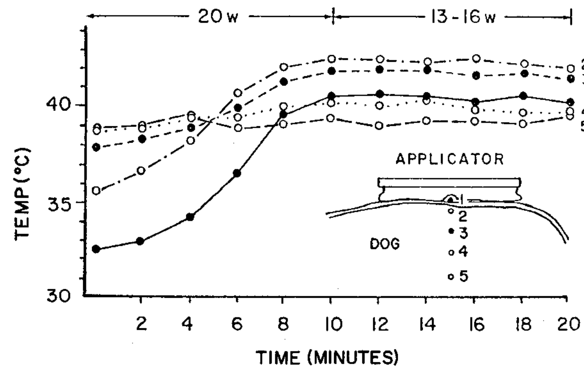

Fig. 7 Temperature in left gluteus major of a dog versus time during local hyperthermia.

Figure 8 represents an X-ray photograph of the hind portion of a male dog with a coaxial applicator inserted in the rectum opposite the prostate gland and a small catheter inserted in the urethra. The coaxial applicator that was used in this experiment was similar to the one shown in Figure 3. The temperature in the urethra of the dog (the prostate gland surrounds the urethra), after heating with 2450 MHz microwave power, was measured at several locations. The experiment was then repeated with a similar although somewhat longer applicator that operated at 915 MHz.

Figure 8 shows the temperature readings at various points along the urethra obtained with these two frequencies. It can be seen that the temperature of the prostate could be raised into the hyperthermic range (approximately 42.5-43.5°C). The temperature difference between the hottest part of the rectal wall and urethra was only slightly more than 1°C. As expected, heating with 915 MHz produced a slightly more uniform temperature distribution than heating with 2450 MHz. No damage to the rectal wall of the dog was produced by heating with either frequency.

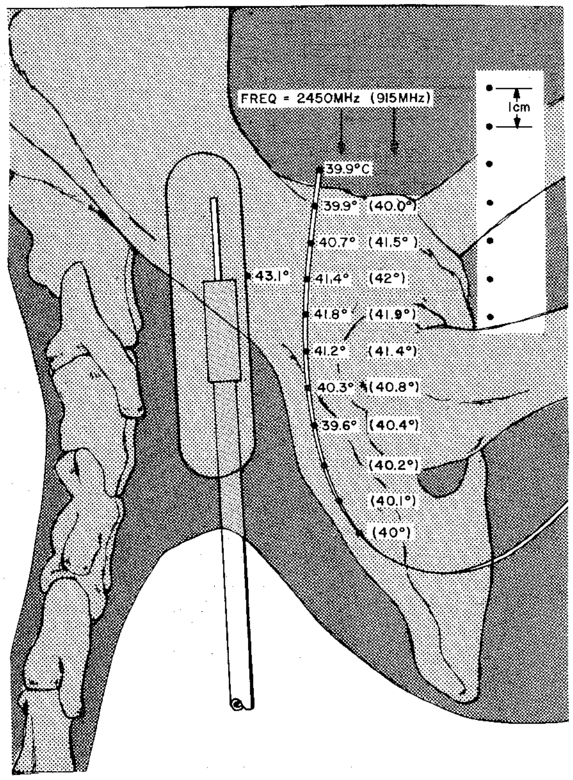

Fig. 8 Temperatures in the urethra of a dog during local hyperthermia.

Clinical Results

A variety of cancers in humans have been treated with localized hyperthermia. In some cases localized hyperthermia was used alone, but in the majority of cases the localized hyperthermia treatment was combined with reduced doses of X-ray radiation. The types of cancers treated so far include basal cell carcinomas, malignant melanomas, primary and metastatic breast cancers, prostate cancers, and liposarcomas. Results obtained to date are encouraging,[4] indicating that hyperthermia is likely to become an important tool in the treatment of cancer.

Acknowledgement

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