Development of a 915-MHz Direct-Contact Applicator for Therapeutic Heating of Tissues

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Abstract—**The design of a 915-MHz diathermy dielectric-loaded applicator with a TE_{10}-mode aperture field distribution is described. The lightweight porous dielectric used for loading the applicator allows for the transmission of refrigerated air through the cavity to provide surface cooling so therapeutic temperatures can be produced in deep tissues without excessive heating of surface tissues. The design is based on theoretical calculations previously developed by the authors which predict optimal size of the aperture and field distribution that would provide the best heating patterns in deep layers of tissue. Experimental evaluations of the heating of tissues of models and human beings are discussed.**

I. Introduction

IN PREVIOUS STUDIES [1]–[5], the authors have discussed the superiority of 915-MHz UHF fields over conventional diathermy shortwave and higher microwave frequencies in providing deep therapeutic heating of tissues. In those studies, the authors also pointed out the advantages of using a square-aperture source with a TE_{10}-mode field distribution for providing the most uniform and optimal patterns of heating. The authors further pointed out that the optimal size for such source is approximately 13-cm square. A practical applicator for providing the source was built and tested in experiments that confirmed the results of theoretical studies; the tests were conducted both in the laboratory on tissue models [3] and in the clinic on human subjects [6], [7].

Since the time of publication of the previous papers, the authors have had many requests for details of the design details of the applicator. In this paper, we discuss the applicator and provide a complete description of the design. The 13-cm square aperture can provide a TE_{10}-mode field distribution at the point of contact between the applicator and the tissue to be treated. The applicator also includes a unique means for providing surface cooling to the tissue during its operation. The cooling helps to eliminate undesirable surface heating while at the same time enhancing and providing more uniform heating of deep tissue.

A companion paper in this issue [8] evaluates the applicator under practical conditions in the clinic. The applicator is not only useful as a new and improved modality of diathermy [6], but has some distinct advantages over other therapeutic heating techniques in the induction of hyperthermia as an adjunct to cancer treatment [9]. The applicator has also proved very useful in the exposure of laboratory animals in connection with studies on biological effects of electromagnetic radiation [4], [10], [11], and has been used in diagnostic experiments involving microwave measurements of volume changes of the heart [4] and lungs [12]. The analysis leading to the details of the design are included in the final section.

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II. Analyses and two Early Designs of the Applicator

The authors have previously discussed some of the fundamental problems in designing applicators for electromagnetic heating [2], [5]. At high frequencies where applicators of convenient size may be used to focus microwave energy on selected areas of the body, the depth of penetration is so shallow that the energy cannot be directed efficiently into deeper tissues. On the other hand, at lower frequencies where greater depth of penetration is obtained, the size of an applicator that is required to provide a directed beam becomes too large for practical clinical use. Therefore, compromise must be made in the choice of frequency and size of applicator so that a reasonable depth of penetration of energy can be achieved while, at the same time, the applicator can be restricted to a convenient size and mass for clinical use.

Theoretical expressions have been developed for calculating the deep-heating patterns in planar tissue layers as produced by a direct-contact aperture source [2]. The expressions, numerically evaluated on a digital computer, may be used to select an aperture size and source distribution to provide the best subcutaneous heating patterns in deep layers of tissue. It was found that the minimum ratio of fat-to-muscle heating is achieved through the use of a simple TE_{10}-mode aperture of one wavelength in width and between one and two wavelengths in height. The ratio of deep-to-superficial heating produced by a direct contact source of this size is significantly greater than that for a plane-wave source under the same conditions. It was also shown that with reduction in aperture size, the ratio would decrease so that superficial heating could become

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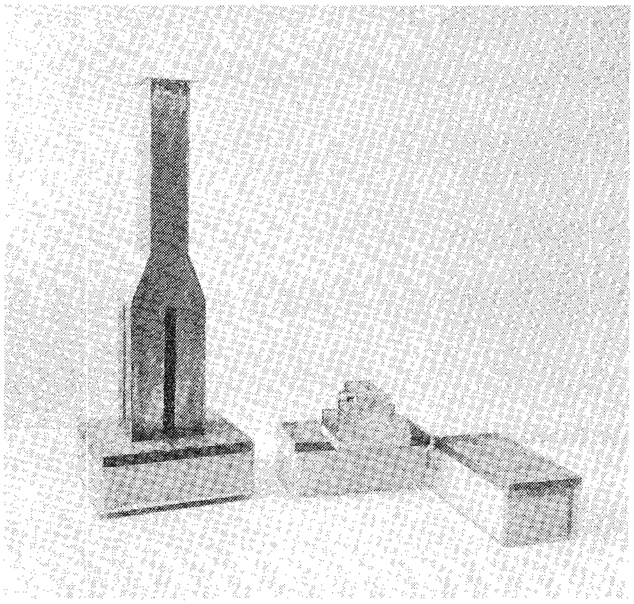

Fig. 1. Waveguide applicator, prototype cavity applicator, and fat-muscle tissue models.

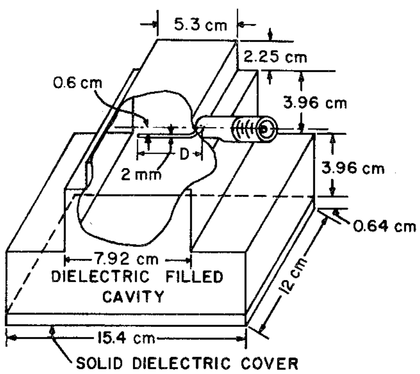

Fig. 2. Prototype 915-MHz diathermy applicator.

dominant—and far in excess of that produced by a plane-wave source.

Theoretical expressions were verified by exposing a tissue model with a TE_{10}-mode waveguide source and by measuring patterns of heating by thermography [3]. The waveguide applicator consisted of a 12-×6-cm waveguide with a 64-cm tapered transition that increased its size to a 12-×16-cm cross section. The applicator is shown in Fig. 1 as positioned on top of one of the tissue models. The waveguide was loaded with aluminum-oxide sand (dielectric constant ~4) to reduce the cutoff frequency of the waveguide below 915 MHz. This large sand-loaded applicator was designed in an attempt to produce the same type of field distribution as that obtained with the waveguide. The applicator is illustrated to the reader's right in Fig. 1 and in Fig. 2, and consisted of a cavity with transitions from a coaxial connector and probe to a 12× 7.75-cm waveguide and step transitions to a 12×15.4-cm aperture. The applicator was also loaded with aluminum-oxide sand to lower the cutoff frequency so that microwave energy could be transmitted through the cavity to the aperture. Theoretical analysis indicated that the optimal patterns of deep heating could be obtained if a

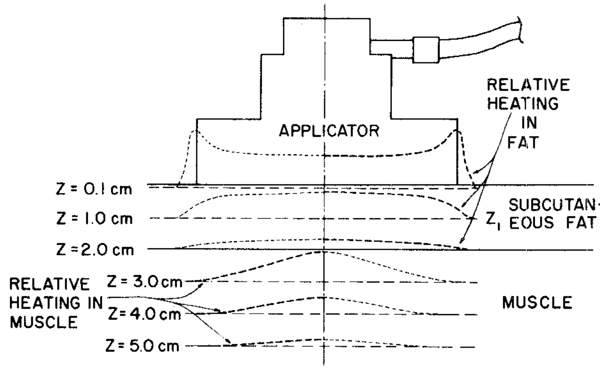

Fig. 3. Cross section of tissue model exposed to applicator and the associated SAR patterns.

TE_{10}-mode aperture distribution could be maintained across the aperture of the applicator.

The two applicators depicted in Fig. 1 were studied both from a theoretical and from an experimental standpoint by use of theoretical expressions and the thermographic technique described previously. Experimental measurements were made on planar tissue models that consisted of 2 cm of synthetic fat on the top and several centimeters of synthetic muscle on the bottom, as is shown under the experimental applicators in Fig. 1. The model on the left side of the figure was assembled while the model on the right was separated to permit thermographic observation [3]. The information of interest was the specific absorption rate (SAR) or the rate of heating produced in the tissue model. The theoretical and experimental patterns of heating in the tissue models were compared for the various applicators.

In the analysis, we shall consider a coordinate system with the z axis along the axis of the applicator and perpendicular to the tissue layers, and the x–y axis in the plane of the applicator's aperture with x oriented in the direction of the electric field vector along the long dimension of the applicator. The relative SAR's and heating patterns were calculated theoretically and measured experimentally along the x axis for various values of z, as depicted in Fig. 3 by the short-dash curves. The long-dash curves illustrate the lines along which the SAR's were determined. Since the SAR curves were symmetrical due to the symmetry of the applicator, theoretical computer plots were made only for the bold-faced portions of the curves, as shown in the figure.

Fig. 4 illustrates thermographs of the cross section of the model after it was exposed to the two applicators. Thermographic techniques have been explained previously by the authors [3]. In Fig. 4, the thermograms are oriented 90° with respect to the model shown in Fig. 3. A C scan (two-dimensional picture of the entire model area heated with intensity proportional to temperature) taken in the x–z plane is shown in the upper left portion of Fig. 4. One small division of the scale corresponds to 2 cm. The horizontal midline, the small subdivision in the photograph, corresponds to the z axis through the geometric center of the aperture perpendicular to the flat interface of

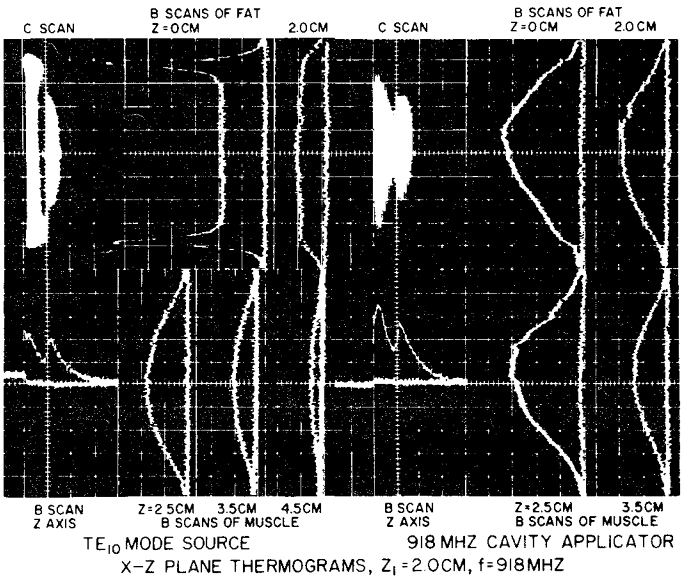

Fig. 4. Thermograms of plane layered tissue model exposed to 12×16-cm waveguide aperture source and cavity applicator (input power: 650 W for 15 s).

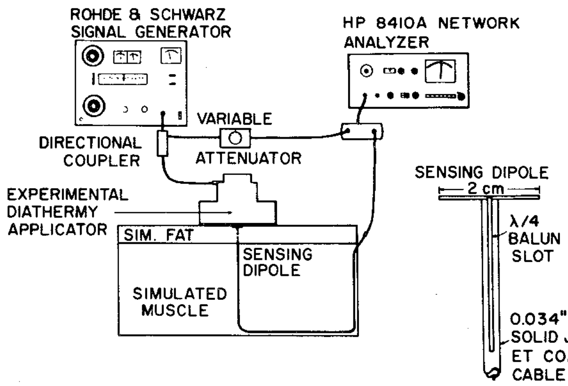

Fig. 5. Apparatus for measuring aperture-source distribution of applicators.

the tissue model. The vertical midline with the small subdivisions corresponds to the fat–muscle interface. Photographs of the B scan (vertical deflection proportional to temperature) are also taken in the x–z plane corresponding to the depths $z=0$ and $z=2$ in the positions depicted in Fig. 3. The temperature scale corresponds to 0.5°C per division. The temperature changes between the scans taken before and after exposure were produced at a power input of 650 W to the applicator when applied for 15 s. The family of B scans in the lower right of the figure was recorded for larger values of depth z, which corresponds to the deeper muscle region. The B scan at the lower left of the figure is a scan taken along the z axis of the applicator. Note the discontinuity due to the difference in dielectric properties of the media. Also, one may note the corresponding hot spots resulting from rapidly diverging fields near the edge of the aperture for the waveguide applicator at $z=0$ and $x=\pm 8$ cm.

The thermographic data for the cavity applicator are shown on the right side of Fig. 4. Note in this case that

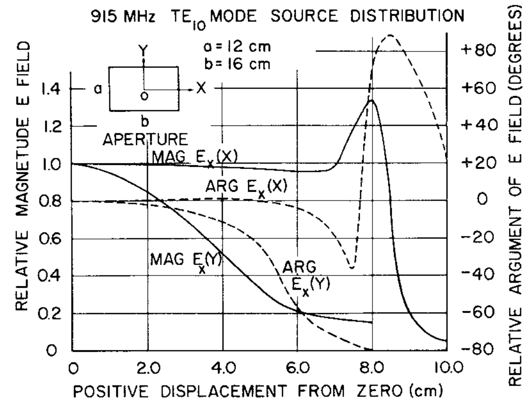

Fig. 6. Magnitude and phase of the electric field at the aperture of a TE_{10}-mode waveguide source in contact with the tissue model.

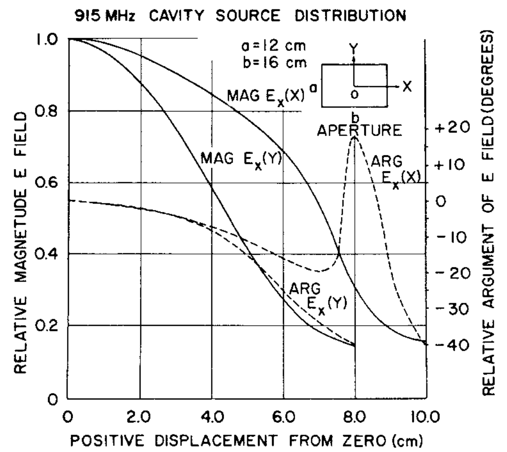

Fig. 7. Magnitude and phase of the electric field at the aperture of a prototype cavity-applicator source in contact with the tissue model.

heating at the edge is eliminated due to the presence of the plastic radome at the applicator's aperture, which separated the metal edges from the synthetic tissue. The heating in the fat for this case, however, is no longer uniform and is greater than that obtained for the waveguide aperture. Since it was believed that this was due to higher order modes appearing in the cavity applicator as a result of the abrupt transitions from the probe feed to the large aperture, an apparatus shown in Fig. 5 was set up for measuring the aperture field distribution when it was in contact with the tissue model. The aperture-field distributions were measured by implanting a small sensing dipole at the surface of the simulated fat layer and comparing the signal picked up by the dipole to that fed to the experimental diathermy applicator by means of a network analyzer. The aperture-field distribution could easily be scanned by moving the applicator to various positions over the sensing dipole. The results for the 12-×16-cm waveguide applicator are shown in Fig. 6, and those for the small cavity applicator are shown in Fig. 7. The figures illustrate that both the magnitude and the phase of the electric field vector in the x direction vary along the x and y axes. For the waveguide source, note that the magnitude and phase are relatively constant along the x

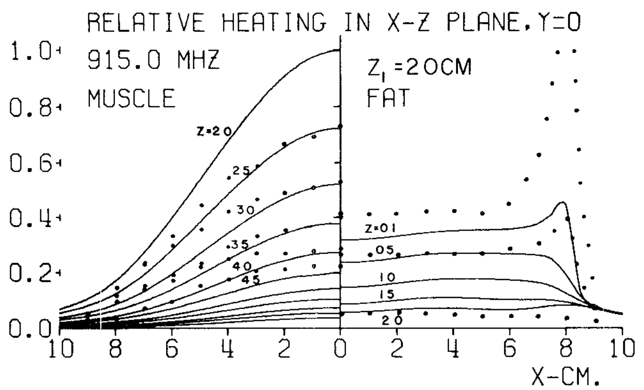

Fig. 8. Comparison between theoretical and measured SAR patterns in tissue model exposed to TE_{10}-waveguide source.

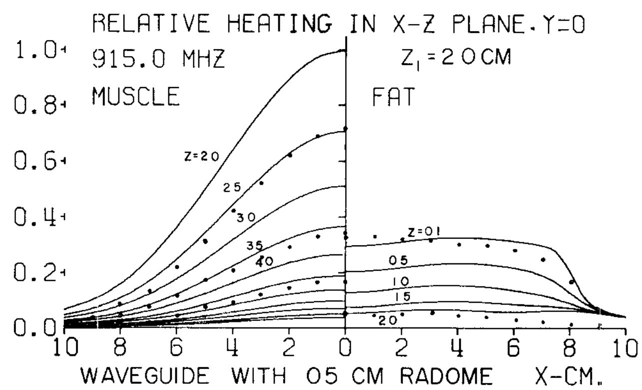

Fig. 9. Comparison between theoretical and measured SAR patterns in tissue model exposed to TE_{10}-waveguide source with 0.5-cm thick radome.

axis while the magnitude varies as a cosine function and the phase is constant along the y axis, which is as expected for a TE_{10}-mode distribution. Note, however, that there are discontinuities in both phase and amplitude near the edge of the applicator due to the fringing fields and the interaction between the probe and the metal walls of the applicator. For the cavity source, however, there are variations both of phase and of magnitude in all directions, indicating the presence of higher order modes.

Fig. 8 illustrates theoretical and measured SAR patterns in the tissue models after exposure to the TE_{10} waveguide source. The solid lines are the values of the theoretical SAR calculated for the x–z plane, which correspond to the bold portions of the curves of Fig. 3. The SAR patterns in the positive x direction for the fat are shown and for the muscle in the negative x direction. The dots correspond to the SAR as calculated from the experimental thermographic data (conversion of temperature change to SAR, taking into account thermal properties of the model tissue). The undesirable hot spots near the edges of the applicator as seen in Figs. 4 and 8 were eliminated by the addition of a 0.5-cm thick dielectric plate (radome) to the waveguide applicator as suggested by previous studies [2], [3]. The results for the radome-clad waveguide are shown in Fig. 9 which represents a nearly optimal set of SAR patterns for the frequency and size of applicator.

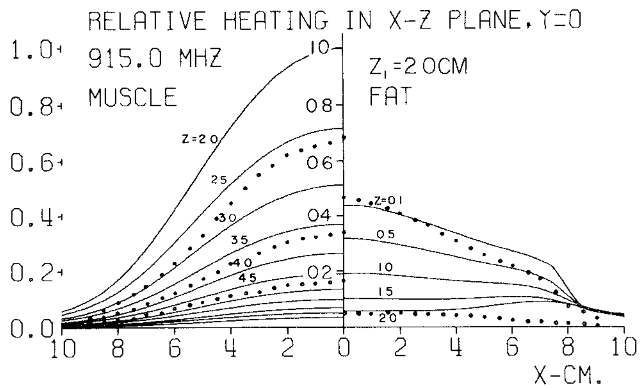

Fig. 10. Comparison between theoretical and measured SAR patterns in tissue model exposed to TE_{10}-waveguide source with prototype cavity applicator.

The theoretical patterns of heating for the prototype cavity applicator, as based on the aperture-field distributions that is plotted in Fig. 7, were compared to those calculated from the thermographic measurements in Fig. 10. The figure clearly illustrates that the nonuniform and higher SAR's in the layer of fat are indeed due to the nonuniform aperture distribution and are caused by the higher order modes in the prototype cavity applicator.

In order to eliminate this problem, a new cavity applicator was designed with special provisions for eliminating the excitation of higher modes. This was accomplished by eliminating the abrupt transitions from the smaller feed guide to the large aperture that contacts the tissue to be treated. From the theoretical studies, the heating pattern was nearly optimal for aperture widths from 12 to 16 cm. The aperture was designed to be 13-cm square and fed by two separate waveguides that were formed by a bifurcation resulting from a metal wall placed at the center of a square cavity. Since it was also shown previously that the deep patterns for therapeutic heating could be improved through surface cooling [6], a unique forced-air cooling system was designed as an integral part of the applicator. The description and details of the applicator's design are discussed in the following section.

III. Details of the Air-Cooled Applicator

A much improved applicator was fabricated and is illustrated by the sketch in Fig. 11 and the photograph in Fig. 12; this applicator is based on experience gained from conducting experiments and from calculations described in the previous section. A three-dimensional view of the applicator with its walls removed is shown at the upper left-hand corner of Fig. 11. The remaining sketches in the figure illustrate the front, side, top, and back views of the applicator. The drawing illustrates that two separate waveguides are combined to form a 13-cm square aperture source for producing a TE_{10}-mode field distribution.

The applicator consists of a transition from a coaxial connector to a stripline power splitter that supplies power to the two independent waveguides by excitation loops. The heavy aluminum-oxide sand used in the previous

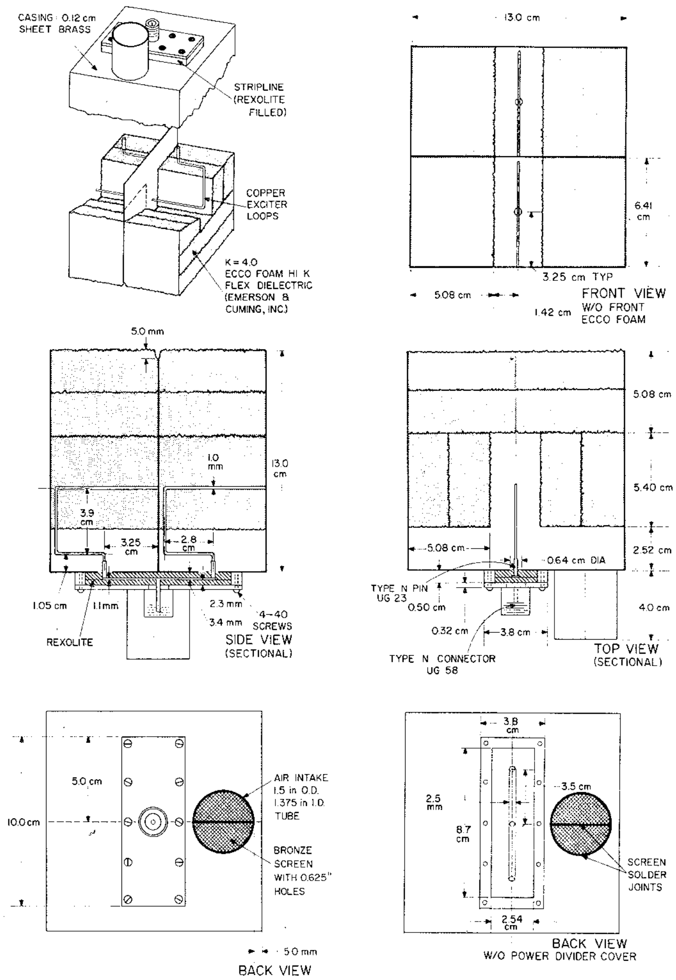

Fig. 11. Design details of air-cooled applicator.

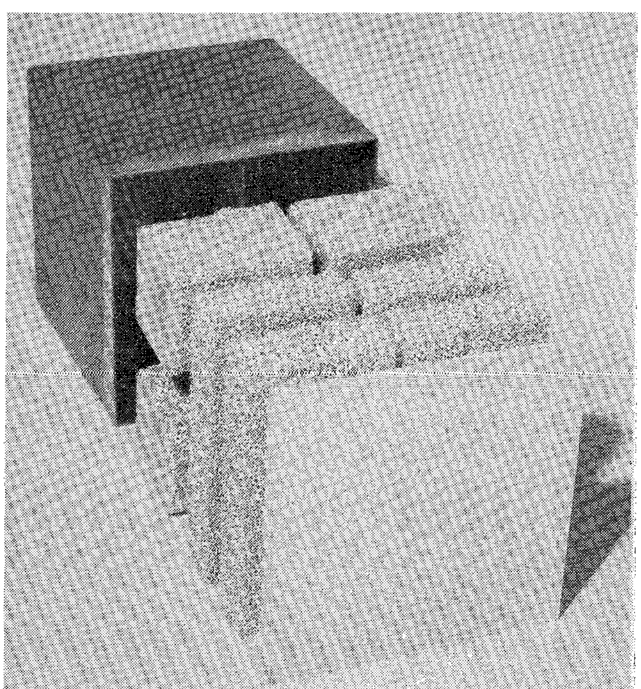

Fig. 12. Photograph of 915-MHz air-cooled applicator.

TABLE I
INPUT VSWR TO AIR-COOLED 915-MHz DIATHERMY APPLICATOR IN CONTACT WITH HUMAN THIGH FOR SUBJECTS WITH VARIOUS THICKNESSES OF SUBCUTANEOUS FAT.

SUBJECT	VSWR	FAT LAYER (cm)
5	1.80	0.6
4	1.59	0.8
1	1.63	1.3
7	1.33	1.9
2	1.30	2.0
8	1.29	2.1
6	1.33	2.2
3	1.44	2.3

applicators was replaced with a lightweight Emerson and Cuming, Inc., Ecco Foam material. The foam has a dielectric constant of 4 and is of extremely low density, which significantly reduces the mass of the applicator. The foam is also porous, which allows cooling air to be blown through the applicator and onto the surface of tissue being treated. The size and shape of the loops were adjusted to provide minimum reflection at the coaxial feed section when the applicator was in direct contact with the human thigh. Table I illustrates variations in voltage standing-wave ratio (VSWR) for the applicator in contact with a human thigh based on tuning the applicator for minimum VSWR when it is in contact with a 2-cm thick layer of fat.

A metal screened airflow aperture was built into the back of the applicator so that forced cooled air could be directed through the porous dielectric material. The acrylic radome shown in Fig. 13 was placed at the aperture of the applicator to eliminate the hot spots in the tissue due to the metal walls of the cavity and to allow cooled air to be directed across the surface of the tissue with which it is in contact. A system of holes and ridges were built into the radome to allow the most efficient flow of air over the surface of the tissue.

Fig. 14 illustrates the input VSWR to the applicator as a function of the applicator's distance from the thigh of human volunteers. The applicator was oriented with the E field perpendicular to the femur. Three volunteers were used with fat thicknesses varying from 1.3–2 cm. The results show that the applicator is reasonably matched for this position from direct contact with the tissue to a distance of 3 cm. When the applicator was turned 90° so that the E field was parallel to the femur, the results in Fig 15 were obtained. Although the VSWR was somewhat higher in this case, the applicator was still reasonably matched at distances of 0–2 cm from the tissue surface. The applicator was tested continuously under high power conditions up to 600 W and it performed satisfactorily with negligible heating of the dielectric material and the metal hardware.

Fig. 16 illustrates the useable bandwidth of the applicator in terms of VSWR when in direct contact with the human thigh. In this case, the applicator was well-

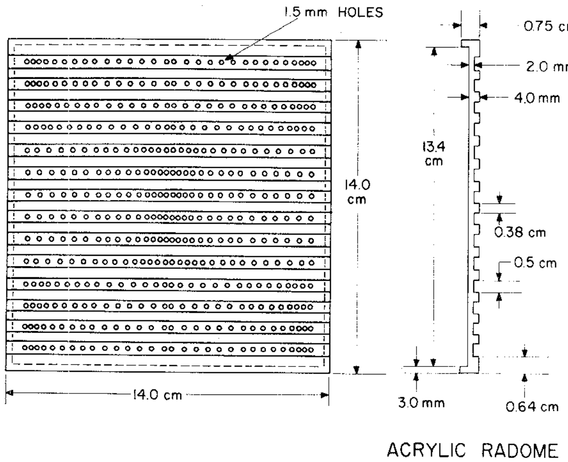

Fig. 13. Radome for air-cooled applicator.

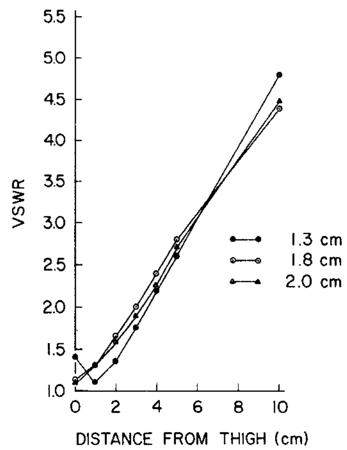

Fig. 14. Input VSWR to applicator in contact with human thigh with E field perpendicular to femur for different subcutaneous fat thicknesses.

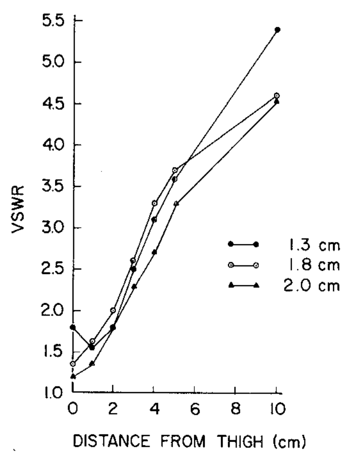

Fig. 15. Input VSWR to applicator in contact with human thigh with E field parallel to femur for different subcutaneous fat thicknesses.

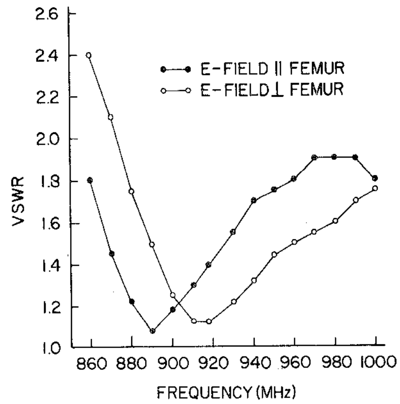

Fig. 16. Input VSWR to applicator in contact with human thigh with E field perpendicular to femur, as a function of frequency for a subcutaneous fat thickness of 1.8 cm.

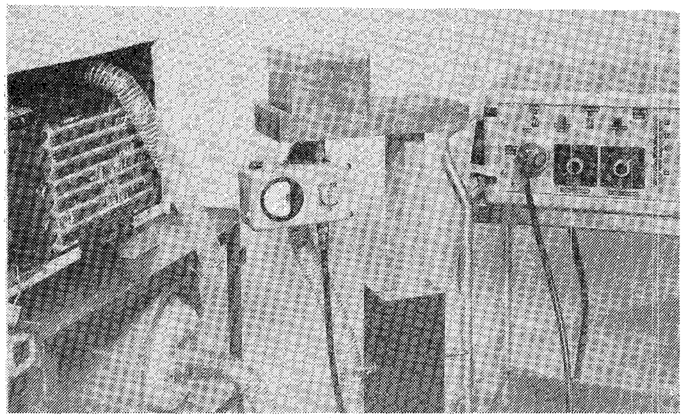

Fig. 17. Photograph illustrating the 915-MHz air-cooled diathermy applicator connected to microwave sources for clinical testing.

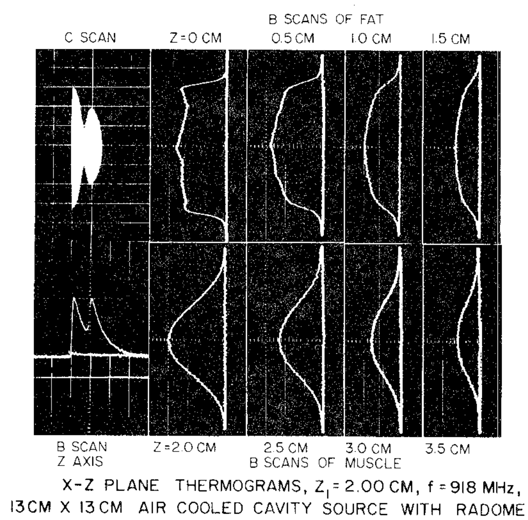

Fig. 18. Thermograms of plane-layered tissue model exposed to 13- × 13-cm air-cooled cavity with radome.

matched over the range 880–940 MHz, more than adequately covering the 915 ± 13-MHz ISM band.

Fig. 17 illustrates how the applicator was connected for testing in the clinic. Air for cooling was provided by a small portable air conditioning unit that was attached to the applicator by a flexible hose. The cooling unit contains controls for varying the air temperature and the rate of flow.

Previous results [6], [7] indicate that with 1 W of input power, the applicator can produce a maximum SAR of

3.25 W/kg in the muscle. Therefore, an input power of 50 W is sufficient to produce an SAR between 150 W/kg in the muscle, an SAR that is more than adequate for typical clinical use.

Fig. 18 illustrates thermographic measurements made in the tissue model after it is heated by the applicator. The patterns closely resemble the ideal patterns obtained with the radome-covered TE_{10}-waveguide source that is illustrated in Fig. 9. Thermographic results of additional testing of the applicators associated with clinical use are discussed in detail in the companion paper [8].

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Evaluation of a Therapeutic Direct-Contact 915-MHz Microwave Applicator for Effective Deep-Tissue Heating in Humans

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***Abstract*—A 13-cm square direct-contact microwave applicator which operates at 915 MHz was evaluated in tissue models and human volunteers to determine its therapeutic effectiveness. It was found that the applicator with radome- and forced-air cooling selectively elevates temperatures in muscles (1–2 cm) to 43–45°C. At this higher range of temperature, certain physiologic responses such as an increase in blood flow are produced. The applicator may also be used to heat malignant tumors of muscle.**

I. Introduction

IT HAS BEEN demonstrated that microwave radiation at 915 MHz can produce local vigorous therapeutic responses when used clinically to heat deep tissue [1]. In the clinical use of diathermy, it is essential that the highest temperatures in the distribution occur at the anatomical site to be treated. Thus the heating modality to be used—which may be microwave, shortwave, or ultrasound energy—and the technique of application must be selected according to the specific site of pathology to be treated and heating pattern desired [1]. These criteria are well documented for therapeutic application in the realm of rehabilitative medicine [2]. It is also likely that these heating modalities will be useful in treating cancer.

To ensure that vigorous physiological responses are elicited, temperatures on the order of 43–45°C must be produced in the tissue. When these temperatures are pro-

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