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The Performance of a New Direct Contact Applicator for Microwave Diathermy

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***Abstract*—A direct contact applicator, specifically designed for microwave diathermy at the Industrial, Scientific, Medical (ISM) frequency of 2.45 GHz was evaluated by studying near-field patterns in free space, thermographic heating patterns in phantoms of simulated fat and muscle tissue, and associated leakage radiation. The main features are a circular waveguide with a short conical flare horn output section surrounded by an annular choke and two sets of dual posts to generate far-field circular polarization. The significant near field components of the therapeutic beam are in a transverse plane, parallel to the aperture. Heating patterns on the exposed surface of muscle phantoms and inside fat-muscle phantoms are spatially similar and relatively uniform. The leakage level is 0.8 mW/cm^2 per 100 W of forward power for direct contact and 4 mW/cm^2 per 100 W of forward power for a 1-cm air gap between aperture and planar phantoms. The uncertainty of these leakage measurements is ±2 dB. This investigation demonstrates the technical feasibility of a safe and effective direct contact microwave diathermy applicator operating at 2.45 GHz. The applicator is a viable candidate for hyperthermia applications.**

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I. Introduction

PRESENT clinical practice in microwave diathermy uses spaced applicators for high power therapy [1]. Since the product performance standard, proposed by the Bureau of Radiological Health (BRH), requires minimum exposure of operator as well as unprescribed tissue of patient, direct contact applicators are desirable. They are inherently safer as they can readily reduce unwanted radiation. To demonstrate the technical feasibility for a safe and effective design, Transco, in accordance with BRH specifications [2], developed a prototype direct contact applicator operating at the ISM (Industrial, Scientific, Medical) frequency band of 2450±50 MHz. This applicator became part of a BRH microwave diathermy system prototype, constructed to demonstrate the feasibility of the provisions of a draft microwave diathermy product performance standard.

Three important considerations guided the design of the applicators.

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1) The structure should be as simple and as small as possible for a specified aperture size to facilitate its clinical use.

2) The center region of the near-field pattern should be uniform and circularly polarized to prevent steep temperature gradients in the heating patterns.

3) Under loaded conditions with phantoms of simulated fat and muscle tissue, the leakage around the applicator should be as small as possible and meet the leakage requirements of the proposed BRH standard of 5 mW/cm^2 at a 5-cm distance from applicator surface.

The main design features of the direct contact applicator are described first, then maps of the free space fields, internal and surface heating patterns as well as leakage of the applicator, are evaluated to characterize its performance. It is concluded that the technical feasibility of a safe and effective commercial design is demonstrated.

II. Design Features

Fig. 1 shows a general view of the applicator while Fig. 2 gives an internal view with coaxial input probe and phasing posts. The applicator, operating at the ISM frequency band of 2450 ± 50 MHz has an aperture diameter of 15.2 cm. The far field beamwidth is 55.5° and the maximum input power carrying capability is 300-W CW. The housing, with a diameter of 9.5 cm., consists mainly of a circular waveguide. At its output end, the conical flare horn section with a diameter of 12.9 cm. is surrounded by an annular choke to control leakage. The waveguide is fed by a coaxial probe with a Type *N* connector at its input. This probe is shown vertically in Fig. 2. Two sets of dual posts, opposite to each other, are placed in the forward part of the guide at 45° to the probe (see Fig. 2) to generate a circularly polarized field. A resistive card is mounted at the center of the back plate (see Fig. 2), normal to the coaxial probe, to minimize any mismatch resulting from tissue loading. Design of the sets of polarizing posts was based on information given in Jasik [3]. Basically, the metallic probes are oriented at 45° to the incident field in the waveguide. The field component parallel to the posts is delayed 90° with respect to the component that is orthogonal to the posts. Since the bandwidth is narrow, only two sets of posts are necessary to give the required phase shift. Broader bandwidths would require more sets of posts with less penetration into the guide. By adjusting the lengths and spacings of the polarization posts as well as the annular choke depth, circular polarization over the beamwidth and a sharp drop-off of power at $\pm 90°$ from the beam maximum was obtained in the far field.

III. Mapping of Free Space Fields

Spatial variations of the free space field components in front of the applicator were measured using the near-field mapping facility at the BRH [4]. The miniature, isotropic BRH probe with three orthogonal dipoles and a fiber optic telemetry system [5] was used to obtain values of the detected squared electric field E (E^2 corresponds to an "equivalent far-field power density") for field components in a transverse plane, parallel to the aperture plane, as well as the longitudinal component normal to this plane. The plots of Figs. 3–6 were obtained by scanning the tip of the probe in a transverse plane $x-y$ at a spacing of 5 mm from the applicator aperture. Because of the steep gradients at this small spacing only the center dipole of the probe was used in three successive orthogonal orientations to obtain the three components of the total field [4]. The transverse field was obtained from the measured x and y components.

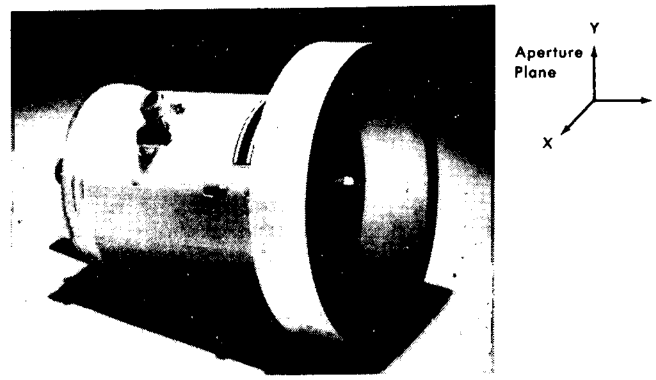

Fig. 1. General view of applicator.

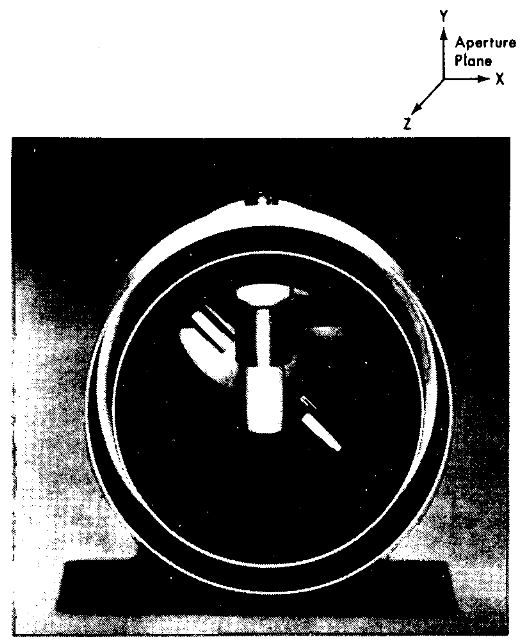

Fig. 2. Internal view of applicator with coaxial input probe and phasing post.

Fig. 3 shows a three-dimensional plot of the spatial distribution of the total field. In accordance with the indicated coordinate system, the transverse plane is the horizontal plane $x-y$ with E^2 in the vertical direction. The maximum power density at the center of the therapeutic beam is 15.7 mW/cm^2 per W of forward power and the minimum in front of the outside diameter of the choke is 0.13 mW/cm^2 per W of forward power. Fig. 4, a half section of the total field (Fig. 3), shows a low-level ridge near the edge of the plot. This ridge has a maximum

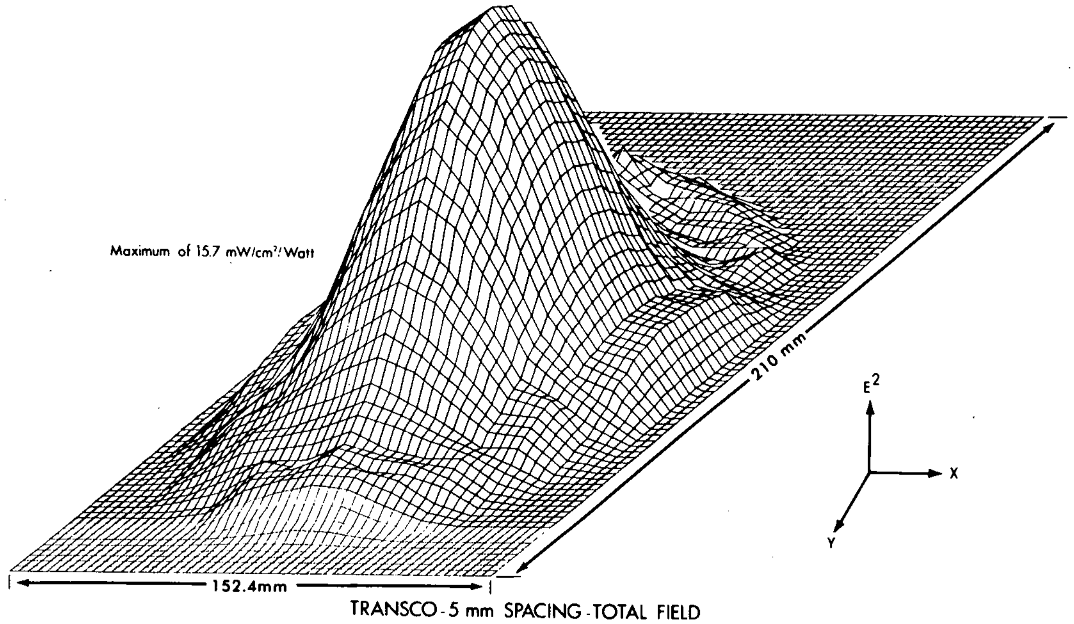

Fig. 3. Plot of total field.

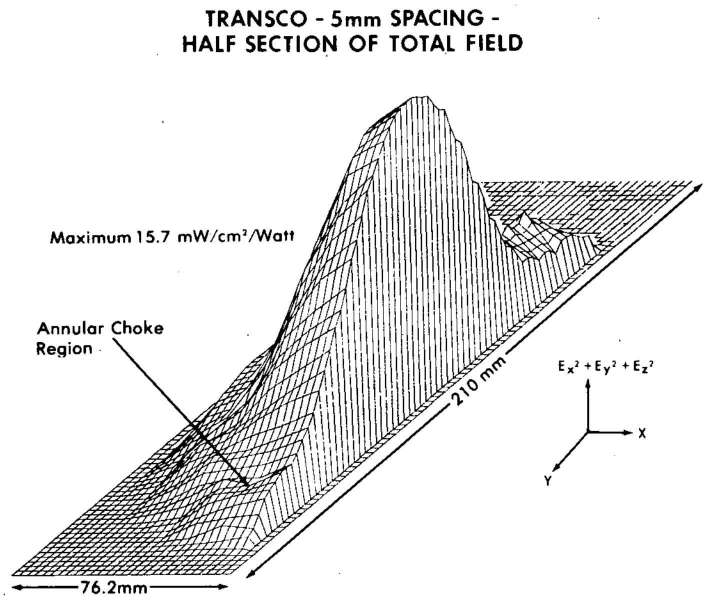

Fig. 4. Plot of half section of total field.

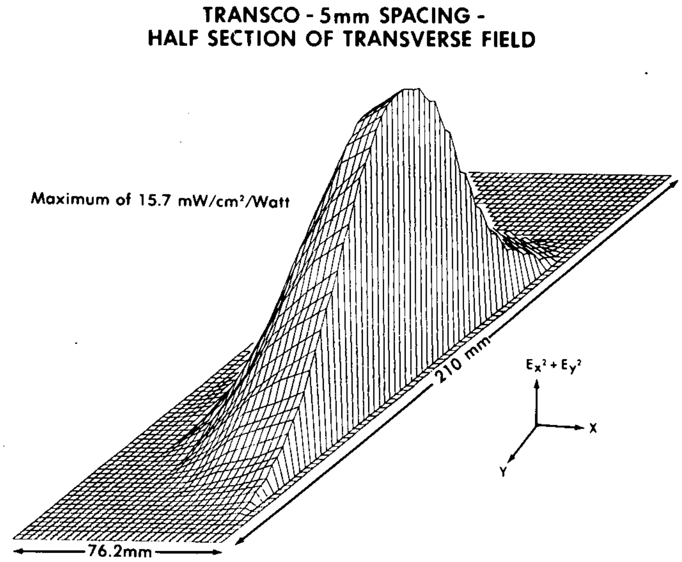

Fig. 5. Plot of half section of transverse field.

of 2.45 mW/cm^2 per W in the vicinity of the rim of the conical flare section. The power density gradually falls off in the ring between the conical flare section and the annular choke.

Comparing the three-dimensional plot of the transverse field of Fig. 5 with the total field plot of the previous figure, one notes that the two plots are identical in the main beam. This is in agreement with the analysis of the data which shows that the longitudinal field component is negligible but for the ridge region where the total field is essentially the longitudinal field component. In other words, only transverse field measurements are needed for describing the therapeutic beam for planar tissue treatment while the longitudinal field plays a major role in determining the level of the leakage fields. For planar anatomical geometry, the transverse field is the main contributor to induced heating in muscle. Due to the boundary conditions and the high dielectric constant of muscle, the heating induced by the longitudinal component is negligible, although for high intensities it could be a hazard at grazing incidence [4]. Only for curvilinear anatomical geometry, need the longitudinal component be considered as a contributor to microwave heating because of focusing [6]. As will be seen in Section IV, the phantoms considered in this study are planar.

Fig. 6 shows transverse field isopower density contours at intervals of 2.5 mW/cm^2 per W of forward power for the therapeutic beam with contour 1 representing the 2.5 mW/cm^2 per W level. The contours, in agreement with Fig. 3, indicate a generally symmetric pattern. Minor deviations from a circular curvature of the top portions of the lower valued contours are due to the very steep near temperature rise. The "normal" profile was obtained by rotating the planar phantom 90° counterclockwise from its horizontal position (the steep temperature gradient at the left of the normal profile occurs at the air–fat interface) and setting the white scan line again in the region of maximum heating. From this profile, the position p of the maximum heating and the depth of penetration d can be determined. The distance p is measured from the fat–muscle interface, and d is defined [6] as the distance between the fat–muscle interface and the depth at which the temperature decreases by 50 percent from the maximum temperature in the simulated muscle tissue. With the direct contact applicator placed symmetrically over the phantom midplane, Fig. 9 gives a w of 7.6 cm, a p of 1.2 cm, and a d of 2.2 cm. With the applicator moved 3.8 cm from the separation midplane along the z-axis (indicated in Fig. 8), Fig. 10 gives a w of 7.2 cm, a p of 0.8 cm, and a d of 2 cm. The results determined from Figs. 9 and 10 suggest that the microwave-induced heating only decreases gradually with distance from the central region of the applicator, indicating relatively uniform heating. Instead, heating patterns of spaced applicators presently in clinical use are highly nonuniform [8]. (Computer analysis techniques to obtain three-dimensional maps of the entire temperature profile induced in phantoms are being developed at BRH.)

The data of Fig. 11 showing surface heating patterns, was obtained with a forward power setting of 130 W for 10 s. A spacing of 1 cm between the aperture and polyethylene film on top of the simulated muscle tissue was used to minimize surface cooling due to the two front circular polarization metal posts. The "horizontal profile" in the lower photograph corresponds to the scan line of the thermogram in Fig. 11 while the "vertical" profile was obtained by rotating the muscle phantom 90° in its vertical position. The value of w for the horizontal is 7.3 cm and for the vertical case is 6.6 cm, giving an average diameter of the heating pattern of about 7 cm instead of 7.6 cm for the case of Fig. 9. This demonstrates that surface and internal temperature profiles have similar spatial configurations. This simularity might be useful for a clinical noninvasive evaluation of applicator designs.

V. Leakage Measurements

Leakage measurements for various direct contact applicators were discussed in detail in [6]. They were obtained by positioning the applicator on top of the phantom as shown in the upper sketch of Fig. 8 and using a commercially available isotropic probe (Narda 8300) to measure leakage. With a probe-applicator spacing of 5 cm (foam sphere of probe in contact with applicator surface) and with a ±2 dB uncertainty in the measurement, the maximum leakage for direct contact loading was 0.8 mW/cm^2 per 100 W of forward power and 4 mW/cm^2 per 100 W of forward power with an air space of 1 cm between applicator and phantom. These radiation levels confirm the effectiveness of the flange choke design to control microwave leakage and meet the leakage requirements of the microwave diathermy standard, proposed by BRH.

VI. Final Comments

The technical feasibility of commercially developing a safe and effective microwave diathermy applicator for the ISM frequency band of 2450±50 MHz is demonstrated. The performance characteristics are a transverse field pattern for its therapeutic beam, a relatively uniform heating pattern and low leakage radiation. Preliminary testing of this applicator without resistive card matching, to determine net power delivered to treatment area, indicates very similar performance. Plans for clinically testing have been made. This applicator is also a viable candidate for hyperthermia. The design is being modified by Transco to operate at the lower ISM frequency of 915 MHz in approximately the same size package.

The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the Department of Health, Education, and Welfare.

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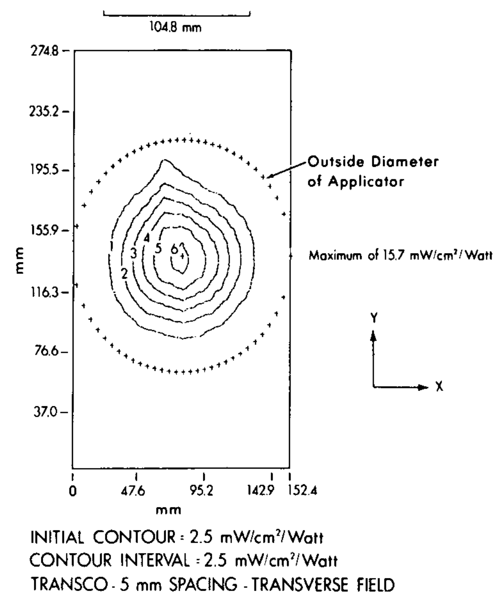

Fig. 6. Plot of isopower density contours of transverse field.

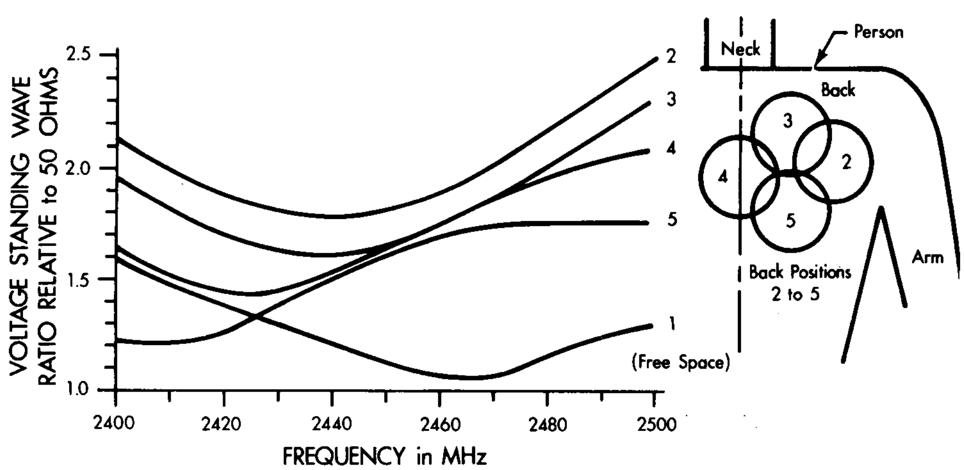

Fig. 7. Plot of input impedance data.

field gradients at 5 mm from the aperture. A slight error in positioning the tip of the probe in a transverse plane parallel to the proximate aperture is critical. Note that the spacing of contours 5 and 6 is somewhat wider than for the other contours, suggesting a relatively broad peak in the center portion of the therapeutic beam. The circular contour with the crosses indicates the diameter of the choke.

The data was analyzed to map the polarization in the transverse plane at 5 mm from the aperture of the applicator. "Axial ratio" values of polarization were obtained from the ratios of vertical to horizontal field components in this transverse plane. Since, as previously discussed, the isocontours of Fig. 6 are somewhat unsymmetrical (the tip of the probe cannot be maintained exactly at 5 mm from the aperture during the whole range of vertical scanning), the polarization plots are markedly more unsymmetrical than the isocontours of Fig. 6 because small errors in the transverse field components can significantly alter the value of their ratio. Even though the polarization results have a large uncertainty due to probe position errors, they indicate that within a centrally located circular region of about 2.3-cm radius, the axial ratios of polarization ranges from 0.5 to 1.5.

Fig. 7 shows input impedance data of the applicator. At four locations on the back of a person and for the unloaded condition of free space radiation, the VSWR is generally less than 2.5 for the ISM frequency band of 2450 ± 50 MHz with a value of 2 in the vicinity of 2450 MHz. (For a typical clinical spacing of 5 cm between a conventional Type B applicator and the back of a person, the VSWR is about 2.8).

IV. Heating Patterns

The experimental setup for measuring internal heating pattern was previously described in detail [6]. The upper sketch of Fig. 8 shows the microwave heating of a planar phantom with the Transco applicator. The lower sketch shows the subsequent heating pattern measurement with a

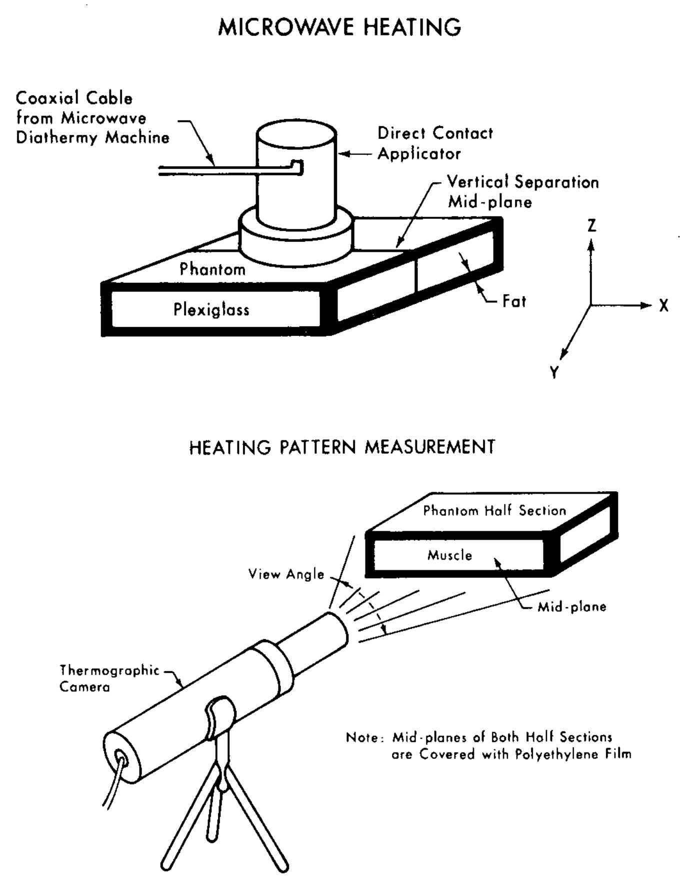

Fig. 8. Experimental setup.

thermographic camera viewing the separation midplane of a planar phantom. This phantom consists of simulated fat and muscle tissues prepared in accordance with a procedure developed by Guy [7]. The thickness of the top and bottom fat layers is 0.8 cm.

The experimental setup for determining surface heating patterns uses a planar phantom composed only of muscle tissue with a polyethylene film on top of it. Heating is induced in this phantom by placing the applicator on top of the film. The subsequent heating pattern measurement is made by positioning the phantom vertically so that the thermographic camera views the heated muscle surface through the polyethylene film.

The heating patterns shown in Figs. 9–11 consist of thermograms and selected profiles, discussed in detail in reference [6]. The upper photographs are thermograms showing the spatial configuration of the microwave heating. From the white scan lines positioned in the region of maximum heating, the temperature profiles in the lower photographs are obtained.

The data in Figs. 9 and 10 was obtained with a forward power setting of 130 W for 10 s. For the "parallel" temperature profile, the white scan line was positioned parallel to the fat–muscle interface in the region of maximum heating inside the simulated muscle layer. The width w of the heating pattern is determined from the parallel temperature profile. It is defined [6] as the width of the trace for which the temperature rise is half the maximum

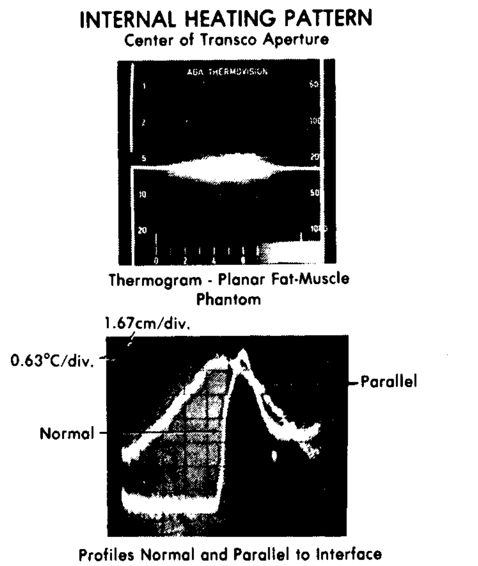

Fig. 9. Internal heating pattern at center of applicator.

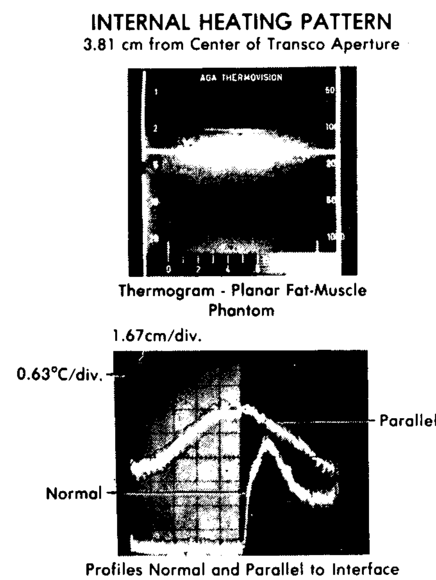

Fig. 10. Internal heating pattern 3.8 cm from center of applicator.

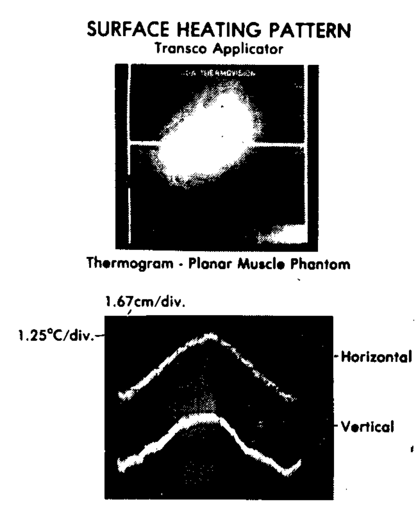

Fig. 11. Surface heating pattern.