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ENERGY DEPOSITION PATTERNS WITHIN LIMB MODELS HEATED WITH A MINI ANNULAR PHASED ARRAY (MAPA) APPLICATOR

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SUMMARY

A series of experiments has been carried out in order to characterize a MAPA applicator prior to possible clinical implementation. The energy deposition patterns were determined in several human limb models of different complexities.

The maximum energy deposition observed in a homogeneous cylindrical phantom was found to be at the middle of the applicator. For more realistically shaped, homogeneous limb models, the point of maximum energy deposition was shifted towards a smaller cross-sectional region; this was also the case for isolated human legs. Furthermore, significant heating was observed in the bone of the isolated legs. Such phenomena illustrate the limitation of using classical 2-D numerical models for predicting the energy deposition patterns in heterogeneous bodies.

INTRODUCTION

A series of experiments has been carried out to characterize a MAPA applicator from the BSD Medical Corp. This applicator, which is composed of an array of eight cylindrically arranged dipoles operating in the frequency range 100 to 200 MHz, is designed to heat deep tissues within a limb for therapeutic purposes.

Our main aim was the determination of the energy deposition patterns within different limb models in order to improve the ability to predict and control heating in a clinical situation.

METHODS

Several phantom models of increasing complexity were used to evaluate the influence of a number of basic parameters. The first model was a thin-wall Plexiglas cylinder of 12.7 cm diameter filled with an aqueous solution of 40% sucrose and 1.8% sodium chloride. This solution simulated the dielectric properties of muscle in the frequency range employed in this study (1). The second and the third models were life-size, thin-wall realistically shaped shells filled with the same aqueous "muscle-equivalent" solution used in the first model. These models, respectively, a single human female leg, constructed from polyacrylamide, and a lower half of the male body, made of gauze reinforced latex, were used to determine the effect of anatomical shapes on the energy deposition patterns. To avoid problems with heat transfer by convection, energy deposition patterns were measured with either a small, unidirectional, implantable Electric-field probe (1mm OD) from BSD Medical Corp. or a larger isotropic Electric-field probe (19 mm OD) from Holaday Industries, Inc. (Model IME-03). Typically, the BSD probe was used within the cylindrical model on a cartesian grid (spacing of 2x2 cm) to map the energy deposition $|E_z|^2$ in a transverse plane at the middle of the applicator length and along the axis. The electric field on this plane and along the axis is assumed to be mainly axially oriented (E_z) for reasons of symmetry. The Holaday probe was used to make scans of the energy $|E|^2$ deposition along several lines parallel to the axis of the anatomically-shaped phantoms. The position of the phantoms within the MAPA and the inclusion of a cylindrical bone phantom (thin-wall glass tube filled with N-propanol) within the muscle region were also investigated.

Due to the compositional and geometrical complexity of a real human limb, it is questionable as to whether any of these "simple" phantoms can adequately represent the clinical conditions of human hyperthermia treatment. Therefore, we developed a new type of limb phantom which consists of a "fixed", amputated human extremity. Within one hour of a therapeutic hemipelvectomy, the lower, non-tumor bearing portion of a leg was detached from the tumor bearing thigh and pelvis by cutting just above the patella. Sixteen radio-opaque catheters (16 ga.) were inserted into the leg at various locations to permit subsequent insertion of temperature probes for the determination of the energy deposition patterns. The catheters were positioned in four transverse planes of the leg. Computerized tomography (CT) scans were taken to determine the exact postions of the catheters. The limb was fixed overnight in an aqueous solution of 50% ethanol and then stored in 80% ethanol. Prior to each experiment, the leg was transferred to an aqueous solution of 0.9% saline for one day.

The leg was placed inside the MAPA with the temperature probes in place, and the operating frequency was chosen to be the lowest frequency corresponding to a minimum reflection using the tuner supplied by the manufacturer. This was determined to be 120 MHz and corresponded to a reflected power level of less than 5 percent. Temperature was measured by high impedance lead thermistors manufactured by BSD Medical Corp. A power of 200 W was applied for a 3 minute period, during which the temperature at each location was recorded every ten seconds. After the 3 minute heating period, each probe was moved manually 1cm and the power was applied again for another 3 minutes. The variation of temperature with time at each location was recorded at a total of 133 points.

RESULTS

The $|E_z|^2$ energy deposition pattern in the cylindrical homogeneous muscle-equivalent phantom centered inside the MAPA appears both axially and azimuthally symmetric. In addition, the $|E_z|^2$ energy on the transverse cross-section at the middle of the applicator length is more uniform at lower frequencies (Fig. 1). The greater uniformity at lower frequencies is consistent with calculations of the incident electric field using with a simple numerical model. In this model, expressions for the incident field close to a thin-wire dipole (2) were used to determine the total electric field of the eight dipoles in an unbounded homogeneous medium (water) (Fig. 2). Lateral displacement of the phantom within the MAPA alters the resultant energy deposition pattern significantly. The inclusion of a coaxial "bone-equivalent" layer moves the contours outward in such a manner that the energy at the surface of the bone corresponds to that value which had been present on the axis.

The importance of model shape became apparent during our studies with the single female leg phantom. The energy deposition pattern does not appear axially symmetric as it is with the cylindrical model. The variation in cross-sectional area caused the pattern to be slightly skewed so that the point of maximum energy deposition was shifted toward a smaller cross-section (Fig. 3). Heating was also observed at the ankle which was outside of the applicator.

Earlier experiments (3) using a mannequin-shaped model showed that certain types of applicators can produce substantial heating at locations other than those intended for treatment. For this reason, we conducted experiments with a full-size half-mannequin. The deposited RF-energy appears to be mostly confined to the leg under treatment. No significant energy deposition was found either in the untreated leg or in the pelvic area. The dependence of the energy deposition pattern upon the cross-sectional area variation of the leg was also observed with this model.

In the experiments on the amputated leg, the specific absorption rate (SAR) and the electric field strength were calculated from the time rate of temperature rise at different anatomical locations including inside the bone. The heating pattern was skewed from the middle of the MAPA length to a nearby region with a smaller cross-section, as observed previously with the other anatomically shaped phantoms. The point of maximum heating was also not located along the axis unlike the case for the cylindrical phantom. A significant temperature rise was measured inside the bone and the fat as well as inside the muscle. The heating observed within the bone seems particularly noteworthy since the energy deposition in this medium is usually considered to be very small (4, 5). Bone heating was reduced when the leg was shifted away from the MAPA axis (Fig.4).

CONCLUSIONS

These experiments with different limb models show that the MAPA should be able to heat the deep portions of a human extremity. They reveal some important limitations with respect to the control of the energy deposition pattern in a clinical situation:

1) The variation with axial position of a limb's cross-sectional area may skew the energy deposition patterns and cause the point of maximum heating to occur in a region with a smaller cross-section rather than at the middle of the applicator.
2) Heating may occur in some anatomical structures where it would not usually be expected (i.e. bone). It seems that this heating may be associated with the fact that the local electric field may have a significant non-axial component due to the cross-sectional variation of the limb and also to end effects of the applicator. The orientation of the electric field at various tissue interfaces must then be considered a factor in controlling the energy deposition pattern. This illustrates a severe limitation for the clinical use of 2-D instead of 3-D numerical models to predict the energy deposition patterns within realistic structures.

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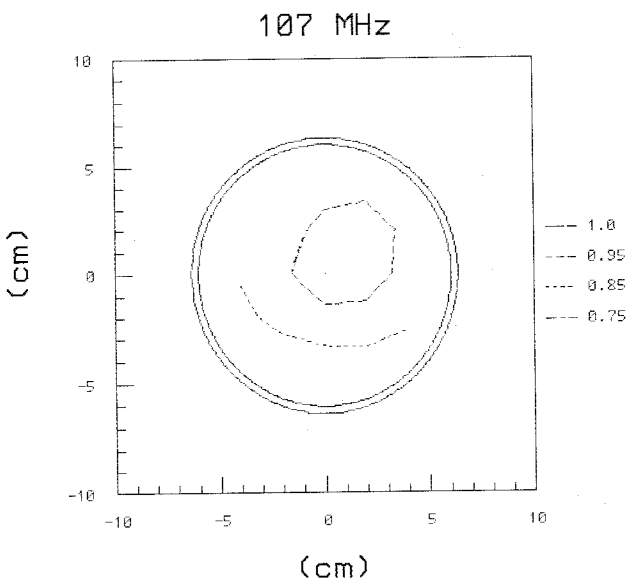

Figure 1: Energy ($|E_z|^2$) deposition pattern in a homogeneous cylindrical (12.7 cm ID) phantom determined experimentally at 107 MHz on the transverse plane at the middle of the MAPA applicator.

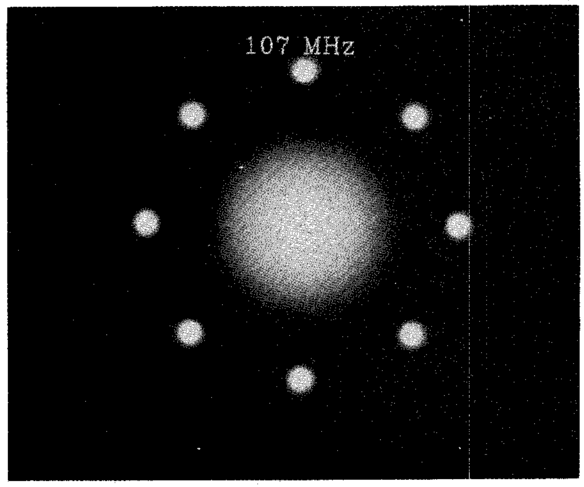

Figure 2: Total energy deposition calculated from the incident electric field of 8 thin-wire dipoles at 107 MHz. The diameter of the eight dipole set-up is similar to that of the MAPA (30 cm).

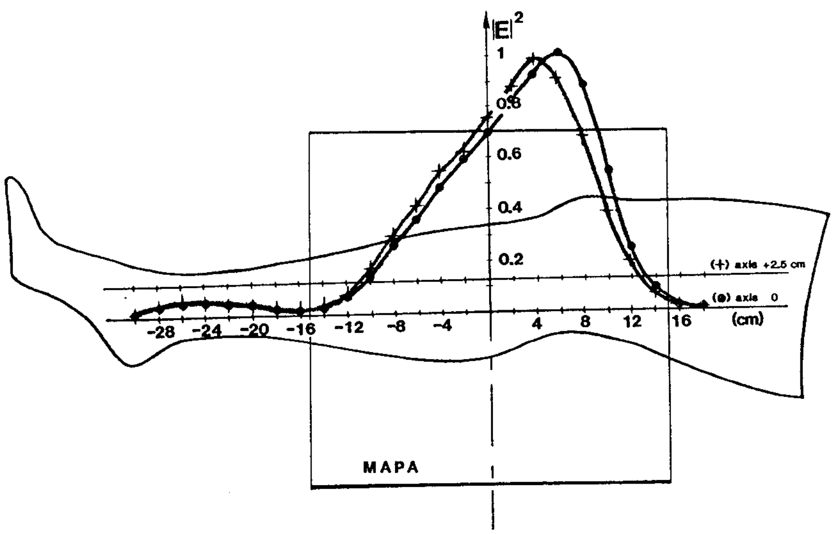

Figure 3: Axial variation of the total energy ($|E|^2$) deposition in a homogeneous thin-wall single-leg phantom. The point of maximum energy deposition is shifted toward a smaller cross-section.

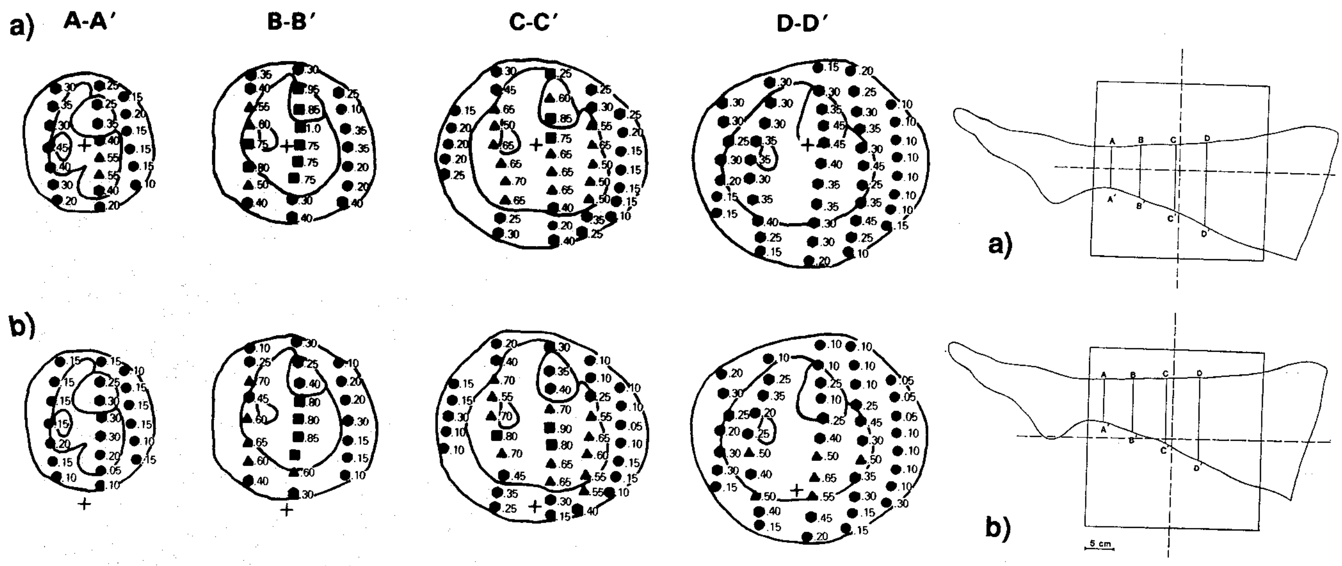

Figure 4: Experimentally measured time rate of temperature rise divided by net power and represented as a fraction of the maximum value for different cross-sections (see diagram);
a) leg "centered" on the MAPA axis represented by "cross" symbol.
b) leg shifted of axis by 6 cm.