Optimization of Helical Coil Applicators for Hyperthermia

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Abstract —**Numerical solutions have been used to optimize helical coil applicators in order to maximize the ratio of axial to surface heating within coaxial muscle cylinders. It is shown that this optimization requires significantly larger values of pitch angle and frequency than those which have been specified thus far for experimental applicators. The maximum ratio of axial to surface heating is obtained with a linear helix, which is a limiting form of the helix, defined to have a pitch angle of 90°. Calculated ratios of axial/surface heating with a linear helix are as large as 2.54 (at 352 MHz) for a muscle cylinder with a radius of 4 cm, and 1.26 (at 82 MHz) for one with a radius of 8 cm. The relationship of the linear helix to the annular phased array and the resonant cylindrical cavity applicator is discussed.**

I. Introduction

Hyperthermia offers considerable promise as an adjunct to cancer therapy, but there has been difficulty in obtaining the desired temperature profiles in deep-seated tumors [1]. The annular phased array (APA) [2] has been used to obtain deep heating noninvasively, and the helical coil [3] and resonant cylindrical cavity [4] have also been considered for this purpose. The relationship of the APA to the resonant cylindrical cavity has already been noted [4]. This paper will show that optimization of the helical coil applicator, in the sense of maximizing the ratio of axial to surface heating, leads to a different device that is closely related to both the resonant cylindrical cavity and the APA.

II. Description of the Applicators Considered in This Paper

Resonant helical coils have been used as RF applicators in experiments with fat-muscle models of the human arm and thigh [3]. These helices had pitch angles between 1° and 4°, and were operated at frequencies from 13.56 to 67 MHz. Thermographic measurements have shown that it is possible to obtain a pattern of energy deposition that is approximately uniform over a transverse plane through the muscle-simulating regions of the models. Focused heating (e.g., at the axis) has not been observed with the experimental helical coil applicators.

The resonant cylindrical cavity, consisting of a conducting cylinder with circular end plates, has also been considered for use as an RF applicator for hyperthermia [4]. Theoretical analyses have been used to determine the heating pattern if such a device was filled with homogeneous muscle tissue. The TM_{0M0} modes were chosen, for which the electrical field has axial orientation and is independent of both the azimuthal and axial coordinates. When these modes are used with a lossless dielectric, the magnitude of the electrical field intensity is maximum on the axis and has local maxima at $M-1$ other radii, with zero at the outer cylindrical surface. The maximum on the axis can be understood since these modes are equivalent to a superposition of plane waves converging on the axis. The analysis showed [4] that for the TM_{010} mode it is possible to obtain a local maximum in the energy deposition on the axis of a muscle-filled cavity.

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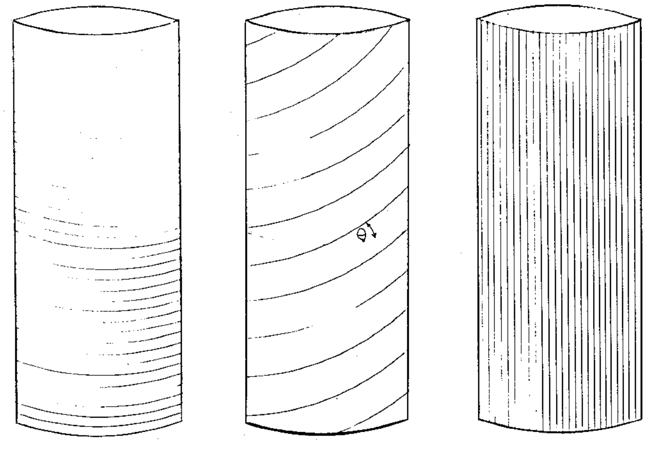

Fig. 1. Helical coil with limiting forms.

Limiting forms of the helix, at the extreme values for the pitch angle, will be referred to as the "circular helix" (0° for azimuthal current flow) and "linear helix" (90° for axial current flow) respectively. Fig. 1 shows a helical coil as well as both of these limiting forms. A center-fed linear helix having a length equal to one-half wavelength (for the propagation on the helix) may be considered to be a limiting form of the APA, having a large number of dipole elements that are fed with equal currents. The linear helix is also closely related to the resonant cylindrical cavity applicator. Since the flow of current in the cylindrical shell of the cavity is axial, the shell could be replaced by a series of parallel conductors having axial orientation, which would be a suitable configuration for the linear helix. Helical coils (including their two limiting forms) do not have end plates, so the fields are dependent upon axial location and the radial electric field is nonzero at locations away from the transverse central plane. In this respect helical coils are more closely related to the APA than to the cylindrical cavity applicator.

III. Optimization of Helical Coil Applicators

Numerical solutions used in the optimization were computed with procedures which have been described previously [5]. Homogeneous or layered cylindrical models of a human limb were used with a coaxially located helical coil in air. Only azimuthally symmetric modes were considered; fringing of the fields at the ends of the coil was neglected; and the helical winding was approximated by a cylindrical shell which conducts only at the pitch angle (sheath helix approximation). Patterns of energy deposition have been calculated for a transverse plane through the center of the axis of the coils, which is the plane for which the deposition is a maximum [3].

The numerical procedures used in these calculations have been shown [6] to correctly predict the resonance conditions and heating patterns observed in experiments with helical coil applicators [3]. The values of frequency and pitch angle for the experimental applicators were quite suitable for the sheath helix approximation (spacing between consecutive turns being small relative to helix radius and wavelength). It is possible that a large

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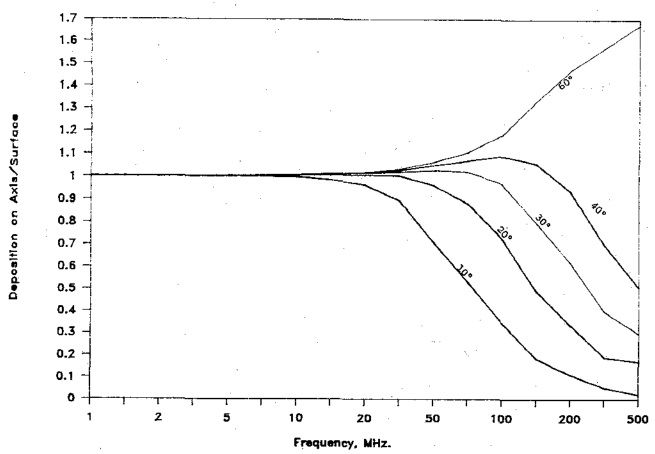

Fig. 2. Relative SAR on the axis of a muscle cylinder as a function of frequency for helical coils with various pitch angles. Helix radius = 5 cm, muscle radius = 4 cm.

TABLE I
MAXIMUM RATIO OF AXIAL/SURFACE SAR WITH A 4 CM RADIUS MUSCLE CYLINDER USING HELICES HAVING DIFFERENT PITCH ANGLES

Pitch Angle (degrees)	Helix Radius = 5 cm Frequency (MHz)	Helix Radius = 5 cm SAR Ratio	Helix Radius = 4 cm Frequency (MHz)	Helix Radius = 4 cm SAR Ratio
0	0.0	1.000	0.0	1.000
10	4.2	1.002	6.1	1.003
20	18.0	1.007	25.0	1.013
30	51.0	1.028	65.0	1.046
40	108.0	1.092	125.0	1.137
50	180.0	1.245	202.0	1.335
60	467.0	1.687	418.0	1.810
70	371.0	2.084	361.0	2.194
80	354.0	2.420	352.0	2.442
90	352.0	2.543	350.0	2.524

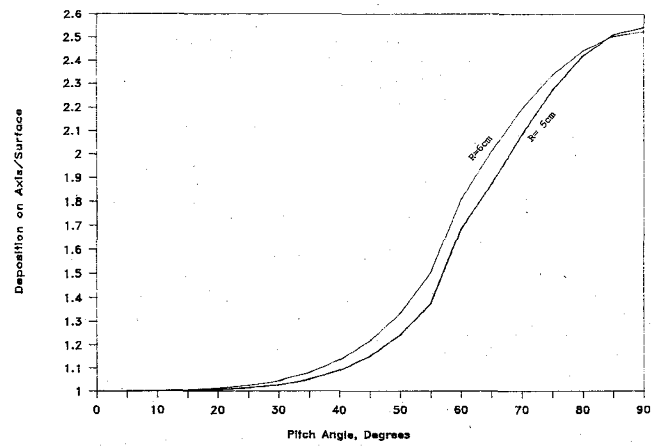

Fig. 3. Relative SAR on the axis of a muscle cylinder using the optimum frequency for helical coils with various pitch angles. Helix radii = 5 and 6 cm, muscle radius = 4 cm.

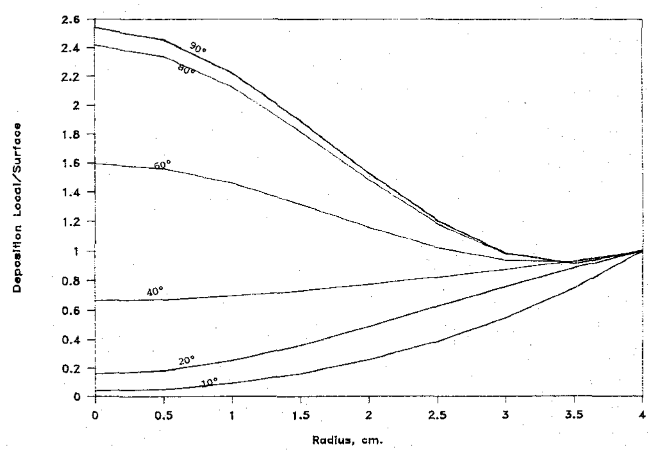

Fig. 4. Relative SAR in a muscle cylinder as a function of radial location for helical coils with various pitch angles. Helix radius = 5 cm, muscle radius = 4 cm, frequency = 352 MHz.

number of parallel conductors, or metallic tape, would be required to construct an applicator that would give results approximating the computed values if significantly larger values of pitch angle and/or frequency were used.

It is recognized that a variety of different criteria could be used as the basis for optimization, but for the purposes of this paper it was chosen to maximize the ratio of axial to surface heating. This choice was made because of the need for applicators suitable for the treatment of deep-seated tumors.

Fig. 2 shows the relative rates of energy deposition on the axis of a 4-cm-radius muscle cylinder for helical coils having a radius of 5 cm. The ordinate used in both Figs. 2 and 3 is the ratio of the specific absorption rate (SAR, defined as the rate of energy deposition per unit mass) on the axis to that near the surface of the cylinder. For each value of the pitch angle there is a frequency at which the ratio of axial to surface SAR is greatest. The values of these maxima, and the frequencies at which they occur, increase monotonically with the pitch angle. For example, the greatest SAR ratio is 1.007 at 18 MHz with 20°, and 1.092 at 108 MHz with 40°. The maxima would not be measurable within the range of parameters that has been used in experiments with helical coil applicators [3]. Since greater SAR ratios were found at the peak in each successive curve in Fig. 2, as the pitch angle was increased, larger values of pitch angle were used in the calculations which follow.

Fig. 3 gives the relative SAR on the axis of a 4-cm-radius muscle cylinder as a function of the pitch angle, for helices having radii of 5 and 6 cm. Multiple solutions were used in order to determine the optimum frequency for each value of the pitch angle, and the maximum SAR ratios are shown in the figure. The series of maximal SAR ratios in Fig. 3 has a maximum for the linear helix and a minimum for the circular helix. These results suggest that the optimum helix is a linear helix, which may be considered to be a different device. Values of optimum frequency used in the figure varied from approximately 0 MHz for the circular helix to 350 MHz for the linear helix, as shown in Table I.

Fig. 4 shows the relative SAR in a transverse plane through the center of a 4-cm-radius muscle cylinder heated with helices having a radius of 5 cm and 6 different values of pitch angle. A frequency of 352 MHz was used, which was found to be optimal for a pitch angle of 90° with these radii. This figure shows that

TABLE II
MAXIMUM RATIO OF AXIAL/SURFACE SAR FOR MUSCLE CYLINDERS WITH LINEAR HELICES

R Muscle (cm)	R Helix (cm)	Frequency (MHz)	SAR Ratio
4.0	5.0	352.0	2.54
4.0	6.0	350 0	2.52
6.0	7.0	171.0	1 54
6.0	9.0	169.0	1.54
8.0	9.0	82.0	1.25
8.0	12.0	82.0	1.26
10.0	11.0	45.0	1.17
10.0	15.0	45.0	1.17

TABLE III
HELICAL COIL APPLICATORS WITH A MODEL OF THE HUMAN UPPER ARM

Frequency, MHz	420	420	10	10
Pitch Angle, degrees	90	20	90	20
Mean Relative SAR in Tissue Layers:				
Bone	0.17	0.01	0.06	0.06
Muscle	1.77	0.61	1.01	1.01
Fat	0.40	0.22	0.08	0.08
Skin	(1.00)	(1.00)	(1.00)	(1.00)

Outer radii of the tissue layers = 1.2 cm for bone, 3.4 cm for muscle, 3.9 cm for fat, and 4.0 cm for skin. Helix radius = 5 cm.

relatively shallow penetration is obtained with this high a frequency unless the pitch angle is large. Stability of the optimum (linear helix) is shown in that the relative SAR on the axis is decreased by only 4.8 percent when the pitch angle is changed from 90° to 80°.

Another series of calculations was made in which the optimum values of frequency and pitch angle were determined for muscle cylinders of four different sizes, using helical coils having two different radii with each muscle cylinder. Table II summarizes the optimal solutions. In each case the linear helix gave the maximum ratio of axial/surface SAR. The values of relative SAR on the axis necessarily decrease monotonically with increasing size of the muscle cylinder due to increased losses in the dielectric. The helix radius has little effect on either the optimum frequency or SAR ratio. This is because the spacing between the helix and the muscle cylinder is a small fraction of a wavelength in air, so it has little effect on the radial flow of energy within the system. The value of the phase velocity, and hence the length required for resonance at a given frequency, does depend on the spacing. In earlier work this dependence was predicted for helical coils having smaller pitch angles, and was confirmed experimentally [7]. Such dependence was attributed [7] to the difference in dielectric loading due to the change in fill-factor for the coils.

An inhomogeneous bone/muscle/fat/skin model of the human upper arm was used earlier [5], [6] in calculations for helical coil applicators having parameters similar to those used in experiments [3]. This model consists of a cylinder of bone (radius = 1.2 cm), with coaxial layers of muscle, fat, and skin having outer radii of 3.4, 3.9, and 4.0 cm, respectively. In the earlier calculations the magnitude of the electrical field intensity was found to decrease monotonically for decreasing values of the radial coordinate. The SAR, which is also dependent on the electrical conductivity, was found to have relatively low values in the fat and bone. This decrease is due to the lower value of electrical conductivity in fat and bone, as compared to that in muscle and skin [8].

Table III gives the results of calculations made for the inhomogeneous model of the human upper arm with four different helical coil applicators. Each helix has a radius of 5 cm. A linear helix with a frequency of 420 MHz was found to give the maximum ratio of mean SAR in the muscle to that in the skin. This solution also provided a maximum (but small) value for the relative SAR in the bone. Results in the second column of Table III show that the penetration at such a high frequency (420 MHz) is significantly reduced when a smaller pitch angle is used.

Previous calculations [6] suggest that increasing the pitch angle of a helix within the range of 1° to 4° at a fixed (low) frequency increases the depth of heating in tissues. This effect has been attributed to the increased magnitude of the axial (relative to azimuthal) component of the electric field. Values in the last two columns of Table III show that changing the pitch angle from 20° to 90° has little effect on the relative values of SAR at low frequencies. It should be noted that the depth of heating would be markedly decreased for pitch angles much less than 20°.

IV. DISCUSSION AND CONCLUSIONS

It has been shown that optimization of the helical coil applicator, in the sense of maximizing the ratio of axial to surface heating, leads to the linear helix which may be considered to be a different device. While other criteria could be used for optimization, this choice was made because of the need for applicators for the treatment of deep-seated tumors.

The linear helix is closely related to both the resonant cylindrical cavity and the APA. For the same frequency of operation all three applicators would produce similar heating patterns on a transverse plane through the center of the axis. End plates, required with the resonant cylindrical cavity, would not be needed with the linear helix. For this reason the linear helix, like the APA, would have a radial component of the electric field at locations away from the transverse central plane. The APA requires a feed structure to obtain the necessary current distribution for the radiating elements. It may be simpler to feed the resonant cylindrical cavity and the linear helix since they each have one feed point, but it would not be possible to steer the heating pattern electronically, as may be done with the APA [2].

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