Phase-Controlled Circular Array Heating Equipment for Deep-Seated Tumors: Preliminary Experiments

GENTEI SATO, FELLOW, IEEE, CHOKICHIRO SHIBATA, SHUICHI SEKIMUKAI, HIROSHI WAKABAYASHI, KAORU MITSUKA, AND KENJIRO GIGA

Abstract —**This paper presents some preliminary results on the development of a circular phased-array equipment for heating deep-seated tumors. It is shown that radiators having sharp directivity are needed to realize excellent focusing of SAR. Moreover, moment method calculations indicate that linearly polarized helical radiators inversely wound with double wires possess the desired directivity and the near field pattern. Field patterns were measured in phantom (plastic cylinders containing saline water) with a circular array formed by four pairs of azimuthally positioned radiators. Excellent focusing of SAR was observed. The ratio of valley to peak value was 0.74. Steering of SAR maximum by phase control was observed and the distance of movement coincided with that estimated from phase variation.**

I. Introduction

HYPERTHERMIA HAS BEEN shown to be effective in the treatment of cancer, especially when combined with chemo- or radio-therapy. Heating instruments consisting of arrays of horn aperture antennas [1], [2], or dipole antennas [3], [4] have been reported. But these heating methods which assume small tumor blood flow are not clinically satisfactory. The blood flow in the peripheral area of tumors is greater than that in the inner area. Formation of SAR maximum is required for the selective heating of tumors including the peripheral area.

The aim of our preliminary experiments is to form SAR maximum in the phantom by circularly arrayed radiators and to steer the SAR maximum electronically by phase control. The following four fundamental approaches were adopted to achieve this aim:

1) Utilization of longer penetration depth in the human body afforded by the UHF band (40.68 MHz).

2) Radiators are immersed in water or equivalent medium to reduce the size of the applicator and to match the impedance to the human body.

3) Use of linearly polarized helical antennas with narrow half power width and small aperture.

4) Use of phase-controlled circular arrays.

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G. Sato is with the Department of Electrical Engineering, Faculty of Science and Technology, Sophia University, Tokyo, Japan.

C. Shibata, S. Sekimukai, H. Wakabayashi, and K. Mitsuka are with the Research and Development Laboratory, New Japan Radio Co. Ltd., Saitama, Japan

K. Giga is with the Research and Development Laboratory, Aloka Co. Ltd , Tokyo, Japan.

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In this paper, the dependency of SAR on the directivity of individual radiators is described first. It is concluded that a sharper focusing of SAR can be achieved using radiators with higher directivity. Secondly, computer simulation of the structure of double-wire helical radiators and the measured radiation characteristics in water are described. On the basis of the above results, SAR in phantom was measured and formation of SAR maximum was demonstrated. Measuring system, method, and measured results are reported. Finally, steering the SAR maximum by phase control is described.

II. Dependency of SAR on the Directivity of Individual Radiators

In this system, circularly arrayed radiators are used to form SAR maximum in the center by a superposition of fields. A simple analysis is applied to describe the dependency of SAR on the directivity of individual radiators. The radiation pattern of an idealized fundamental radiator is assumed as follows:

$$g(\theta,\phi) = K \sin^n\theta \cdot \sin^m\phi \tag{1}$$

where θ and ϕ follow usual definition and K is a constant determined by normalization. Indices n and m are parameters determining the directivity of a radiator. At the point with distance r from the radiator, the electric field is [5]

$$\vec{E} = \sqrt{\frac{P_r}{2\pi\zeta^{-1}}} \cdot \frac{e^{-jkr}}{r} g'(\theta,\phi)\hat{e} \tag{2}$$

where P_r is the radiated power of the radiator, $\hat{e}$ is the unit vector in the direction of polarization, ζ is the intrinsic admittance of free space, and k is a propagation constant. The total electric field superimposed by N radiator is

$$\vec{E} = \sum_{i=1}^{N} \sqrt{\frac{P_r}{2\pi\zeta^{-1}}} \cdot \frac{e^{-jkr_i}}{r_i} g'(\theta_i,\phi_i)\hat{e} \tag{3}$$

where i shows the term concerning the ith radiator.

Assuming linear polarization, four pairs of radiator systems are arranged at equal distance on a circle of 40 cm in diameter. SAR distribution was calculated for various n and m in a muscle equivalent medium (Fig. 1). The frequency is 40.68 MHz. Power to each radiator is constant for each set of n and m.

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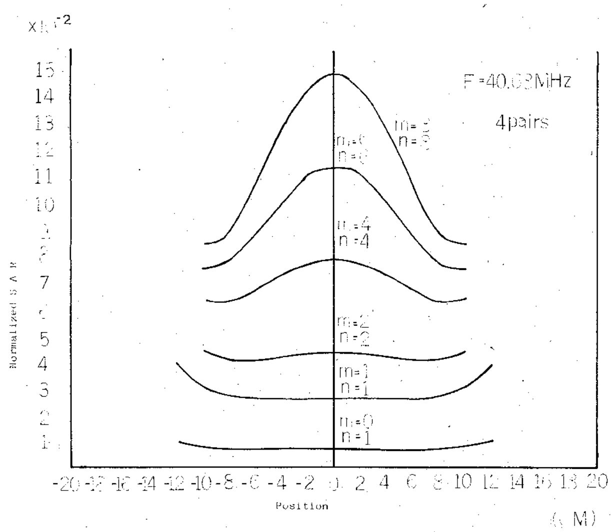

Fig. 1. Normalized SAR characteristics.

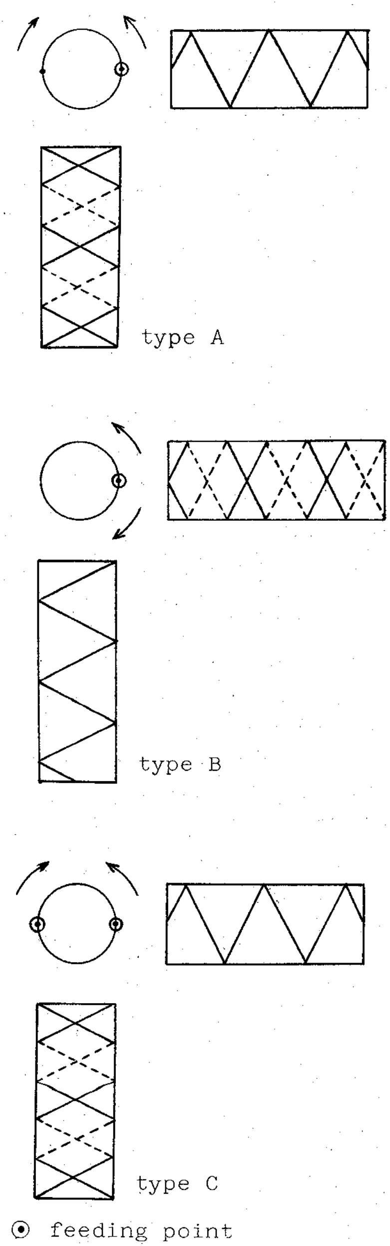

Fig. 2. Structures of helical radiators.

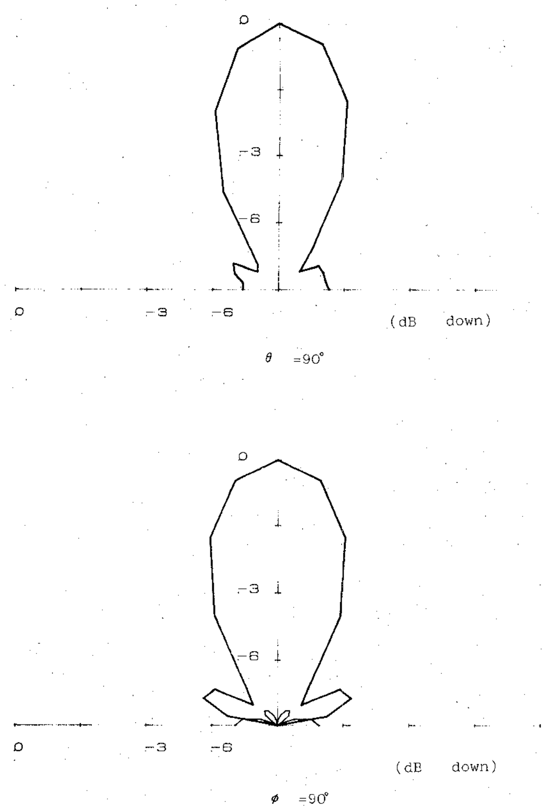

Fig. 3. Radiation characteristics of a B-type helical radiator.

In the case of $n=1$ and $m=0$, which corresponds to an omnidirectional antenna, SAR distribution is flat. Focusing of SAR appears only for cases of n and m larger than four. Clearly, sharp directivity is required for focusing. It should be noted that the above conclusion is applicable only to the far-field condition. We must examine whether the initial assumption is valid in actual cases.

III. Radiation Characteristics of Helical Radiators in Water

We decided to adopt linearly polarized helical antennas as radiators because of their sharp directivity and small aperture. Usually, a helical antenna shows circular polarization, but a linearly polarized helical antenna is obtainable by inverse winding of double wires, such that three types may be classified according to the feeding method:

A-type: single-wire feed;
B-type: double-wire single-point feed;
C-type: double-wire double-points feed.

Structures of each type are shown conceptually in Fig. 2.

Current distribution on the antenna wire and radiating field were calculated by the Moment method [6] for each of the three types. Optimum conditions for the desired radiation pattern and large polarization ratio were determined, assuming a medium of water. The best result was observed for a B-type radiator whose diameter, pitch angle, and turn numbers of helix are 227 mm, 12.5°, and 3.25 turns, respectively. Radiation patterns corresponding to $\phi=90°$ and $\theta=90°$ plane are shown in Fig. 3(a) and (b).

Next, complex field intensities near the helix aperture are calculated by the same method. Field distribution and

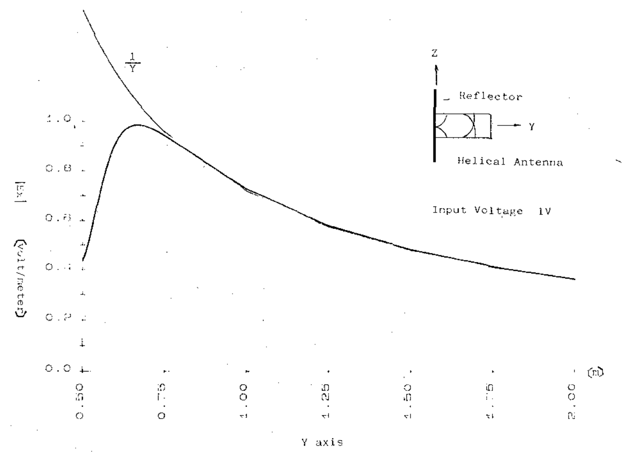

Fig. 4. Field distribution along the axis of a helical radiator.

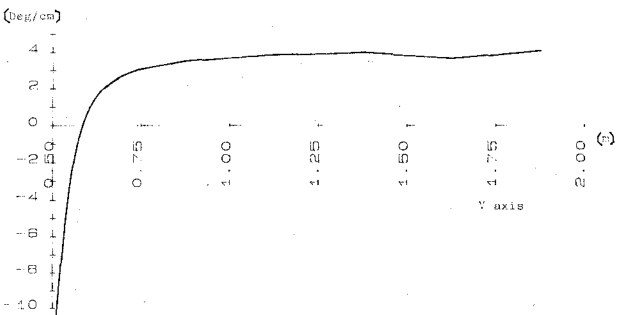

Fig. 5. Relative phase shift along the axis of a helical radiator.

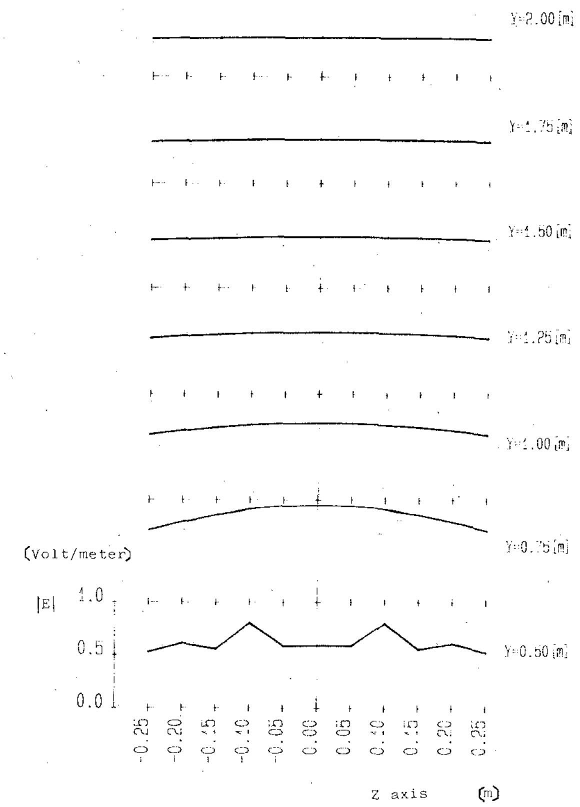

Fig. 6. Field distribution near the aperture of a helical radiator.

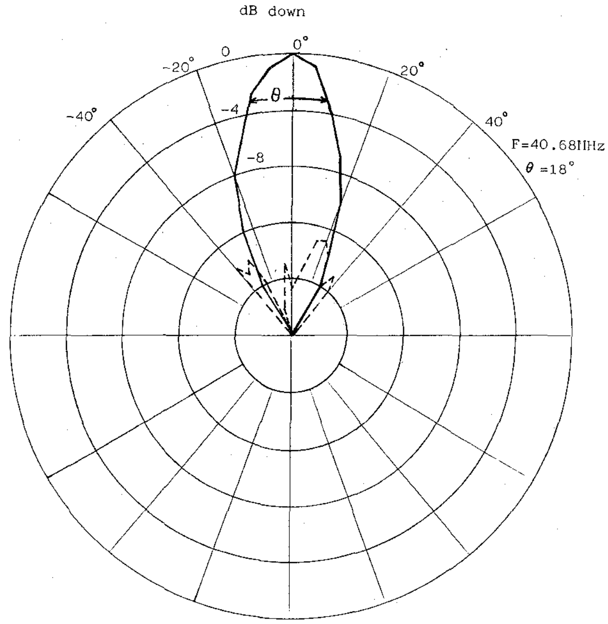

Fig. 7. Radiation characteristics of a 4-pair helical radiator in water.

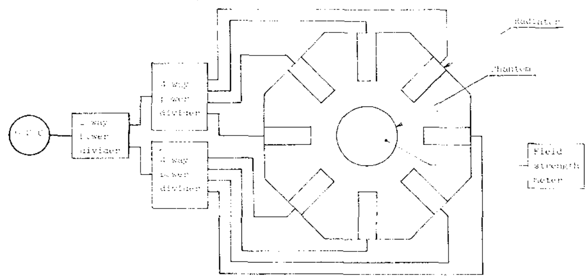

Fig. 8. Field distribution measuring a system block diagram.

phase shift along the helix axis are shown in Figs. 4 and 5. Fig. 6 shows field distribution in the area near helix aperture. From the above results we estimated that the far-field region is at least 25 cm from the helix aperture.

An B-type helical radiator was constructed for trial and its radiation characteristics were measured in a cistern whose dimensions are 2m × 2m × 1m. An example is shown in Fig. 7. Only one radiator was activated; half power width tends to narrow as numbers of radiators increase. A Brown antenna was used for measuring field intensity. The whole antenna system was immersed in pure water for a reduction in dimensions, and all the measurements were also performed in water.

IV. Measurement of SAR Focusing

The preliminary experiment for phase-controlled circular array heating equipment was done using the system shown in Fig. 8. A photograph of the system is shown in Fig. 9. Four pairs of linearly polarized radiators and a plastic cylinder of 40 cm in diameter filled with 0.35-percent weight saline water were immersed in the cistern.

As the penetration depth of the electro-magnetic wave at 40.65 MHz is about 65 m, the wave can reach the center of

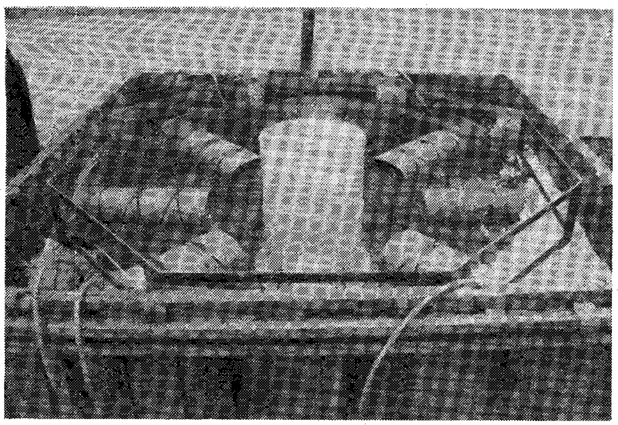

Fig. 9. Photograph of the measuring system.

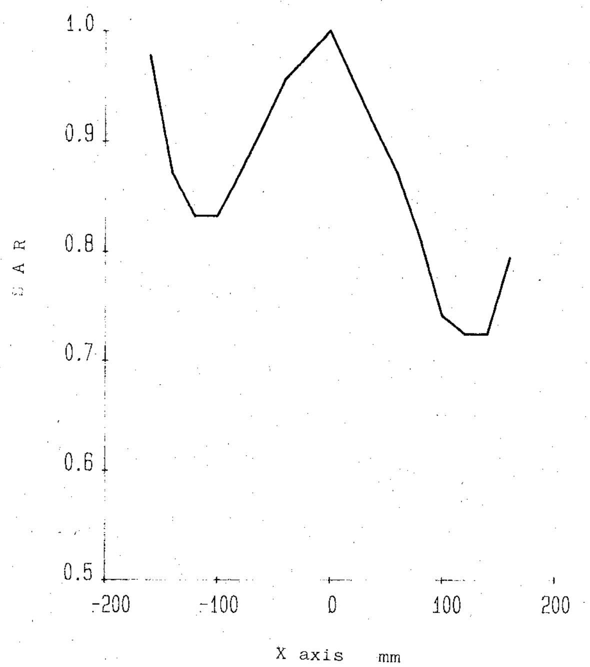

Fig. 10. SAR distribution of a 4-pair helical radiator.

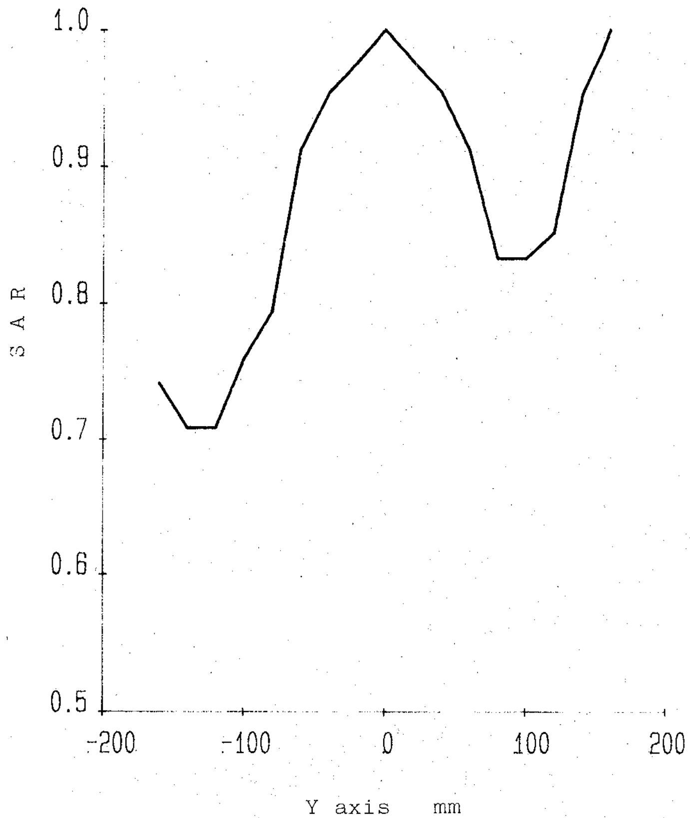

Fig. 11. SAR measured in a direction perpendicular to that of Fig. 9.

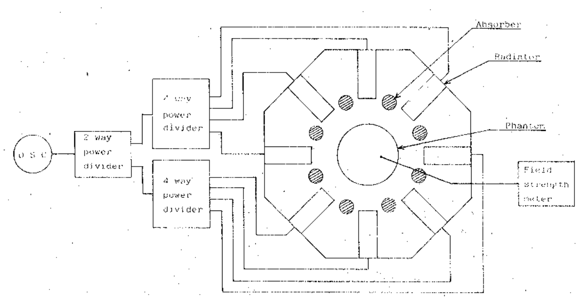

Fig. 12. Field distribution measuring system block diagram with eight absorbers.

the circle (diameter 40 cm) with a very small reduction of power. Radio frequency power was fed to eight radiators after passing through the two-way-divider and dual four-way-dividers. It was previously validated by a network analyzer that each radiator was in phase at the feed point. A Brown antenna was used for measuring field intensity. All measured values are relative. SAR was calculated from the measured field intensity.

Fig. 10 shows SAR distribution along the axis of a pair of radiators facing each other and Fig. 11 shows that in the perpendicular direction. Symmetry is not maintained because of fluctuation in positioning and dispersion of radiator directivity. But the focusing of SAR is clearly demonstrated. Though SAR near the plastic wall was high, cooling by water circulating should solve the problem during actual body heating.

A new system shown Fig. 12 was devised for achieving better focusing of SAR. Eight absorbers comprised of plastic cylinders 7.7 cm in diameter and 1.5-percent weight saline water were placed at appropriate positions between radiators. SAR distribution in this case is shown in Fig. 13. Symmetry of SAR is greatly improved, with accompanying increase in peak-to-valley ratio of SAR.

V. Steering the Focusing of SAR by Phase Control

The possibility of electronic steering does not mean only the positioning of SAR maximum to tumors. Programmable movement of SAR focusing allows a control of temperature distribution in the human body.

In this preliminary experiment, a pair of radiators were arranged for simplicity and phase of each radiator was controlled for steering. One radiator of the pair was set in lead phase and the other was set in lag phase. Movement of

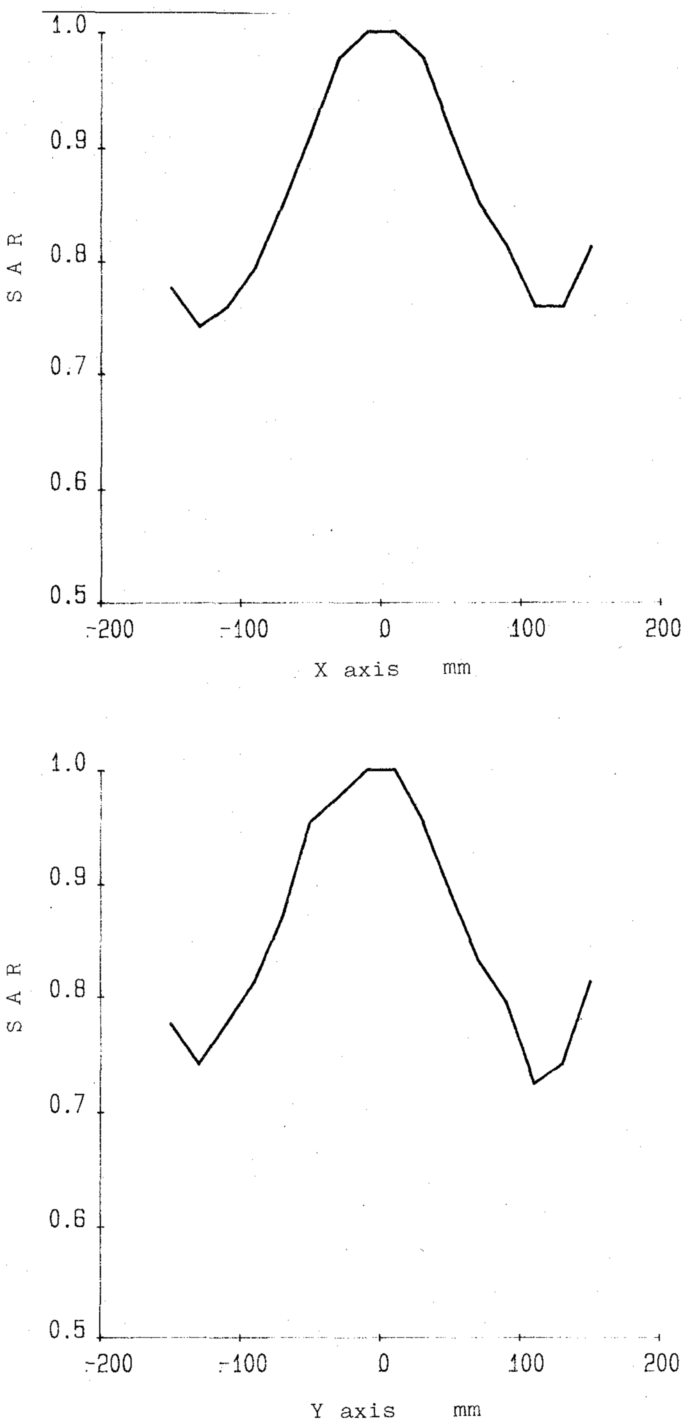

Fig. 13. SAR distribution of 4-pair helical radiators with eight absorbers.

the SAR maximum is observed as shown in Fig. 14. The distance moved coincides with the estimated value from phase variation.

VI. Conclusion

Hyperthermia combined with chemo- or radio-therapy is effective for cancer treatment, but heating technology for deep-seated tumors is not satisfactory clinically. We aimed to overcome the barrier and tried to adopt helical radiators for phase-controlled circular array heating equipment. We have demonstrated the possibility of SAR focusing and the possibility to steer focusing electronically. It is anticipated that heating of deep-seated tumors, including peripheral area, will be possible in the near future applying this system to clinical equipment.

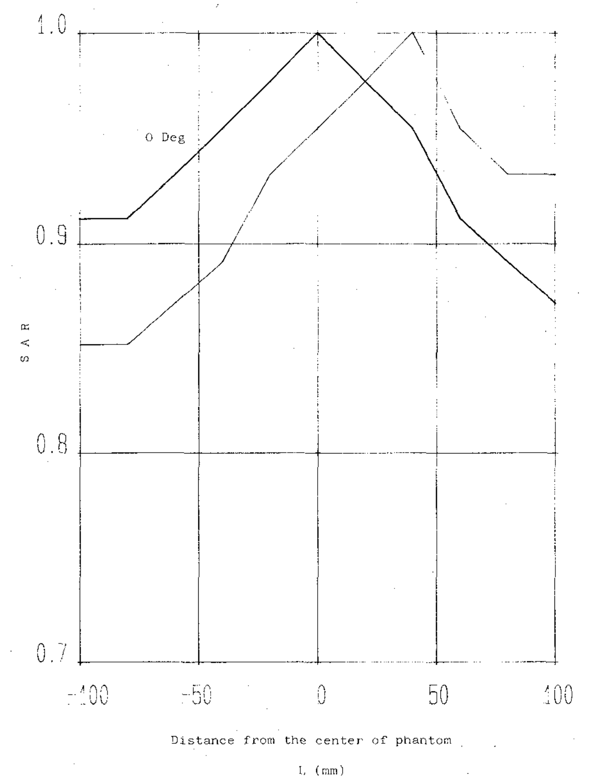

Fig. 14 Steering of SAR characteristics by phase control of one pair of radiators.

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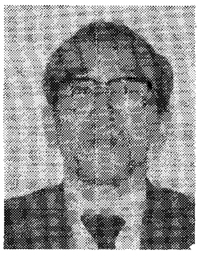
Gentei Sato (M'63–SM'77–F'84) was born in Sendai, on March 15, 1926. He received the B.S. and Ph.D. degrees in electrical engineering from Tohoku University in 1947 and 1961, respectively.

From 1947 to 1955, he was a Research Assistant in the Communication Department of Tohoku University and an Associate Professor at Tohoku University in 1956. In 1961, he joined the research laboratory of Yagi Antenna Co., Ltd. Since 1964, he has been a Professor at Sophia University, Faculty of Science and Technology. At present, his main fields of interest are ultra high-speed electronic scanning phased-array antenna and microwave transmission devices.

Dr. Sato is a member of the Institute of Electrical and Electronics Engineers of Japan, the Institute of Electronics and Communication Engineers of Japan, and the Institute of Television Engineers of Japan.



Chokichiro Shibata was born on January 15, 1923. He received a degree in physics from Tokyo University in 1964 and received the Ph.D. degree from Kyoto University Japan in 1957.

In 1946, he joined Japan Radio Co., Ltd. (JRC), and worked in the field of microwave tubes and solid-state devices development. In 1961, he transferred from JRC to New Japan Radio Co., Ltd., which was founded as a joint venture between JRC and Raytheon Company in 1961. He is now the managing director and general manager of the R&D Laboratory. He has been engaged in the research and development of microwave devices, sensors, microwave applied equipments, infrared devices, and applied equipments.

Dr. Shibata is a member of the Physical Society of Japan, Japan Society of Applied Physics, the Institute of Electrical Engineers of Japan, the Institute of Electronics and Communication Engineers of Japan, the Japanese National Committee for Electro-heat, and the International Microwave Power Institute.

Shuichi Sekimukai was born on January 6, 1936. He received the electrical engineering degree from Tohoku University in 1959.

In 1959, he joined Japan Radio Co., Ltd. (JRC), where he worked in the field of microwave tubes development. In 1961, he transferred to New Japan Radio Co., Ltd. He is presently the section manager of the R&D Laboratory. He has been engaged in the research and development of microwave solid-state devices, microwave applied equipments, and infrared applied equipments.

He is a member of Japanese Society of Hyperthermic Oncology.

Hiroshi Wakabayashi was born on November 15, 1957. He received the degree in electrical engineering from Toyo University in 1980.

In 1980, he joined New Japan Radio Co., Ltd., and has been engaged in the development of microwave devices.

Kaoru Mitsuka was born on May 14, 1960. He received the electrical engineering degree from Toyo University in 1982.

In 1982, he joined New Japan Radio Co., Ltd., where he has been engaged in the development of microwave devices.

He is a member of the Japanese Society of Hyperthermic Oncology.

Kenjiro Giga was born in Tokyo, Japan, on May 27, 1923. He received the B.E. degree in applied physics from Kyoto University, Kyoto, Japan, in 1946.

From 1946–1975, he worked as a designing and production engineer of modern electronic equipment at Japan Radio Co., Ltd., Tokyo, Japan. From 1975–1985, he was a director and worked on researching and engineering at Aloka, Co., Tokyo, a subsidiary of Japan Radio Co., Ltd., where medical and nuclear instrumentations are produced.

He is a member of the Japan Society of Ultrasonics in Medicine.