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A new capacitive heating applicator for the simultaneous radiohyperthermotherapy of superficial and shallow-seated tumors.

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A new capacitive heating applicator for the simultaneous radiohyperthermotherapy of superficial and shallow-seated tumors.*

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Abstract

External capacitive heating is the usual method of electromagnetic wave heating, in which the tumor is caught and heated between two opposite applicators. Using a phantom, the authors developed and evaluated the performance of a new capacitive heating applicator designed for simultaneous radiohyperthermotherapy (SRH) in which the electron beam irradiation is provided from above an external capacitive heating applicator for the treatment of superficial and shallow-seated tumors. The trial applicator was constructed to fulfill the following conditions: 1. use of an electrode plate which does not affect the electron beam depth dose, 2. a uniform thickness to maintain flatness of the electron beam, and 3. a cooling function to prevent damage to normal skin tissue and enhance the therapeutic gain factor. This applicator was comprised of a 0.1-mm-thick copper electrode and a 5-mm-thick cooling chamber. The depth of the 80% dose of the new applicator was 21 mm with a 9-MeV electron beam and 36mm with a 15-MeV electron beam, which was comparable to the effect of a conventional irradiation bolus. The temperature distribution produced by the trial applicator was symmetrical on both sides from the center of the applicator. The 50% specific absorption rate region was 6.4 cm wide at a depth of 1 cm from the phantom surface and 2.8 cm wide at a depth of 3 cm. There have been no previous reports on the development of an external capacitive heating applicator designed for the SRH of superficial and shallow-seated tumors; this is the first such report.(ABSTRACT TRUNCATED AT 250 WORDS)

KEYWORDS: simultaneous radiohyperthermotherapy, applicator, capacitive heating, superficial and shallowseated tumor

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A New Capacitive Heating Applicator for the Simultaneous Radiohyperthermotherapy of Superficial and Shallow-Seated Tumors

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External capacitive heating is the usual method of electromagnetic wave heating, in which the tumor is caught and heated between two opposite applicators. Using a phantom, the authors developed and evaluated the performance of a new capacitive heating applicator designed for simultaneous radiohyperthermotherapy (SRH) in which the electron beam irradiation is provided from above an external capacitive heating applicator for the treatment of superficial and shallow-seated tumors. The trial applicator was constructed to fulfill the following conditions: 1. use of an electrode plate which does not affect the electron beam depth dose, 2. a uniform thickness to maintain flatness of the electron beam, and 3. a cooling function to prevent damage to normal skin tissue and enhance the therapeutic gain factor. This applicator was comprised of a 0.1-mm-thick copper electrode and a 5-mm-thick cooling chamber. The depth of the 80 % dose of the new applicator was 21 mm with a 9-MeV electron beam and 36 mm with a 15-MeV electron beam, which was comparable to the effect of a conventional irradiation bolus. The temperature distribution produced by the trial applicator was symmetrical on both sides from the center of the applicator. The 50 % specific absorption rate region was 6.4 cm wide at a depth of 1 cm from the phantom surface and 2.8 cm wide at a depth of 3 cm. There have been no previous reports on the development of an external capacitive heating applicator designed for the SRH of superficial and shallow-seated tumors; this is the first such report. SRH of these tumors can be performed simply, noninvasively and repeatedly by means of this new applicator.

Key words: simultaneous radiohyperthermotherapy, applicator, capacitive heating, superficial and shallow-seated tumor

The antitumor effect of radiation and heat becomes maximal when applied simultaneously, both *in vitro* (1) and *in vivo* (2, 3). Clinical reports on this phenomenon (4, 5) are extremely rare because technology has not been developed to allow for the simultaneous application of irradiation and capacitive heating in a clinical setting (6). To permit the administration of simultaneous radiohyperthermotherapy (SRH) for the treatment of superficial and shallow-seated tumors, we developed a new capacitive heating applicator and evaluated its performance using a phantom.

Materials and Methods

An external capacitive heating is the usual method of electromagnetic wave heating, in which the tumor is caught and heated between two opposite applicators. For the treatment of superficial and shallow-seated tumors with SRH, electron beam irradiation should be delivered concurrently via an external capacitive heating applicator. Scince irradiation is applied from above the external capacitive heating applicator, the effect of the thickness of the electrode plate on the depth dose of the electron beam was initially studied.

Effect of thickness of the electrode plate on the depth dose of the electron beam. An electron beam of 9 or 15 MeV was applied by MEVATORON-77 (Toshiba Medical, Japan) from above copper plates of 0.1, 0.2, and 0.3 mm thickness using a 5-cmϕ cone at a source surface distance of 100

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cm. The depth dose of the electron beam was measured by placing a 0.03 cm^3 shallow chamber IONEX-2532/3 (NE Technology, England) under acrylics of varying thickness and connecting it to a dosimeter IONEX2500/3 (NE Technology).

Trial production of applicator. An applicator for SRH should satisfy the following conditions: (a) use of an electrode plate which does not affect the electron beam depth dose, (b) a uniform thickness to maintain the flatness of the electron beam, and (c) a cooling function to avoid damage to normal skin tissue and enhance the therapeutic gain factor (TGF) (2, 6). The applicator shown in Fig. 1 was produced on a trial basis to meet these conditions. The applicator is comprised of a 0.1-mm-thick copper electrode and a 5-mm-thick cooling chamber. The 134-cm electrode lead was connected to one end of the electrode to avoid entering the irradiation field. The cooling chamber was filled with distilled water, and connected to a thermoregulated circulatory cooling device via a cooling pipe connected to both ends of the chamber. Next, the effect of this trial applicator on the electron beam depth dose was studied.

Effect of the trial applicator on the depth dose of the electron beam. Instrumentation and methods similar to those described above were used to measure the depth dose below the applicator. As a control, a 4.5-mm-thick conventional Elastomeric bolus (Action Products, USA) for irradiation was used. Then, the heating performance of the trial applicator was evaluated.

Heating performance of the trial applicator. The heat distribution was studied by the method depicted in Fig. 2A and the specific absorption rate (SAR) distribution was studied by the method depicted in Fig. 2B. To prepare a 13.56-MHz standard muscle tissue equivalent phantom, a cylindrical phantom (diameter 13 cm, thickness 6 cm) was prepared using agar powder 4 %, salt 0.24 %, sodium azide 0.1 %, and water 95.66 %. The room temperature was maintained at 20℃. The experiment was initiated after allowing the phantom to stand at room temperature for at least 12 h. The applicator electrode lead and the cooling pipe were connected to a heating device HEH-500C (Omron, Japan) and the internal thermoregulated circulatory cooling device. Heat was applied at 160 W, equivalent to about one-third of the maximum output, via the phantom. For the temperature distribution, a liquid crystal thermosensor (Japan Capsular Products, Japan) was placed between a phantom that

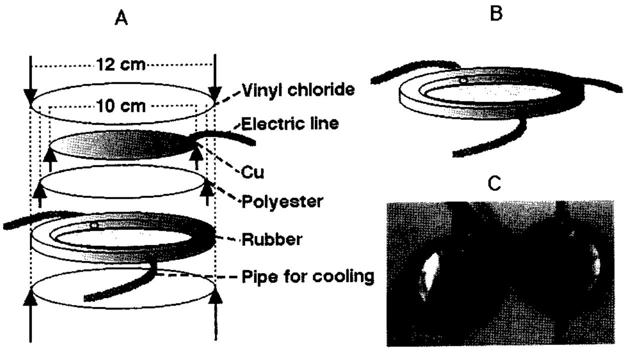

Fig. 1 The new applicator. **A**: Structure of the applicator; **B**: External appearance of the applicator; **C**: The actual applicator. The applicator consists of 0.1-mm-thick copper plate electrode and a 5-mm-thick cooling chamber. Compared with a conventional capacitive heating applicator, the new applicator is characterized by a very thin electrode plate, an attachment site between the electrode and lead wire at the electrode margin, and an applicator of uniform thickness. A cooling function was employed to increase the therapeutic gain factor (TGF) without damaging normal skin tissue.

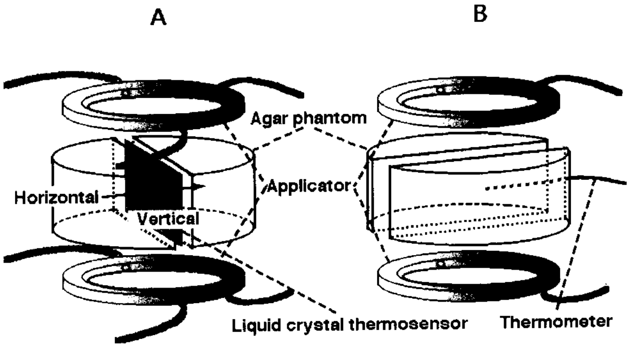

Fig. 2 Method of studying the heating performance of the trial applicator. **A**: Method for measuring temperature distribution. A liquid crystal thermosensor was inserted between the phantom, and the temperature distribution was measured after 8 min (with the thermoregulated circulatory cooling device switched off) and after 9 min (with the thermoregulated circulatory cooling device switched on) of applying an output of 160 W, in a horizontal direction including the electrode lead wire and in a crosswise vertical direction. **B**: Method of measuring the specific absorption rate (SAR). The SAR distribution was calculated by investigating the 3-min temperature elevation at an output of 160 W at each point at 1-cm intervals to a depth of 3 cm from the surface in a horizontal direction.

was split in two parts longitudinally. The temperature distribution was assessed after heating for 8 min with the thermoregulated circulatory cooling device switched off, and for 9 min while applying a cooling temperature of 20 ℃. The temperature distribution was studied in a horizontal direction, including the central part of the phantom and the electrode lead attachment, and in a vertical direction. SAR was determined by the following formula by inserting a 4-point-type thermoluminescent optic fiber thermometer (Luxtron, USA) into the phantom to study the temperature elevation for 3 min at each point lengthwise and crosswise at 1-cm intervals to a depth of 3 cm from the surface in a horizontal direction to the phantom. The specific heat of the phantom was 1.0 Kcal/kg·℃.

$$\mathrm{SAR} = 4.186 \times 10^{3} \cdot C \cdot \Delta T / \Delta t \ (\mathrm{W/Kg})$$

C: specific heat (Kcal/kg·℃)
ΔT: increase of temperature (℃)
Δt: heating time (sec)

The SAR distribution was expressed as the SAR percentage for a given position, taking the maximum SAR at a depth of 1 cm from the surface to be 100%.

Results

Fig. 3 shows the effect of the thickness of the copper plate on the depth dose of the electron beam. For both electron beams of 9 and 15 MeV, the dose immediately below the copper plate increased as the copper plate became thicker, whereas the dose in deep regions was attenuated. However, when the thickness of the copper plate was decreased to 0.1 mm, there was no longer any appreciable effect. The attenuation of the depth of 80% dose was 1 mm with an electron beam of 9 MeV and 1.5 mm with an electron beam of 15 MeV compared with copper-less controls.

The effect of an applicator using a copper plate 0.1 mm in thickness on the depth dose of the electron beam is

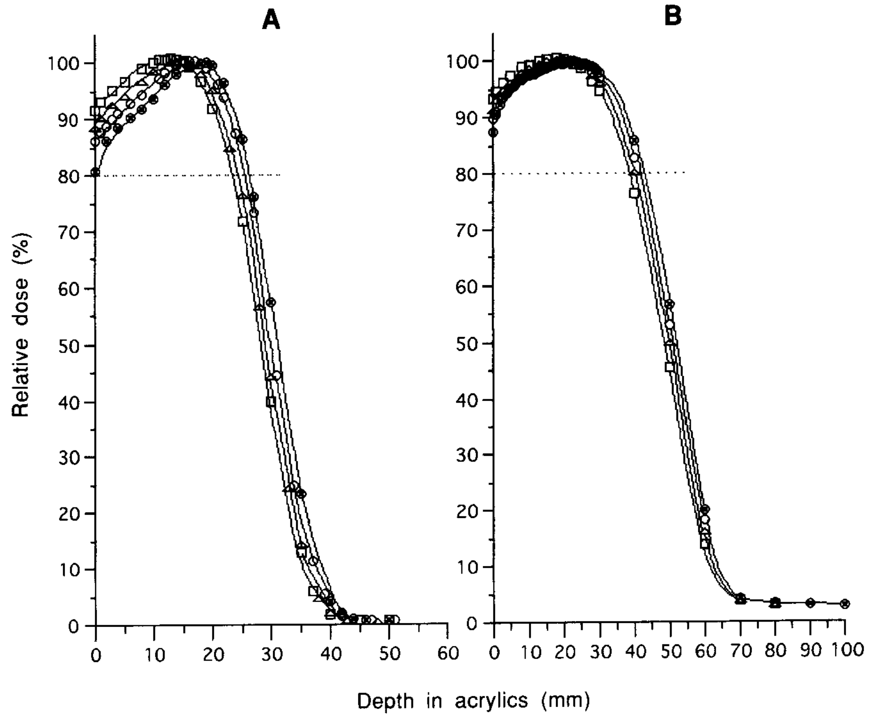

Fig. 3 Effect of copper plate thickness on the electron beam depth dose. ◎, Without Copper; ○, Copper (0.1 mm); △, Copper (0.2 mm); □, Copper (0.3 mm). **A**, Percentage depth dose curve of the 9-MeV electron beam. **B**, Percentage depth dose curve of the 15-MeV electron beam. For both electron beams (9 and 15 MeV), the dose immediately below the copper plate increased as the copper plate became thicker; attenuation occurred in deep regions. When the thickness of the copper plate was decreased to 0.1 mm, there was no longer any appreciable effect. The attenuation of the depth of 80% dose was 1 mm for an electron beam of 9 MeV and 1.5 mm for an electron beam of 15 MeV.

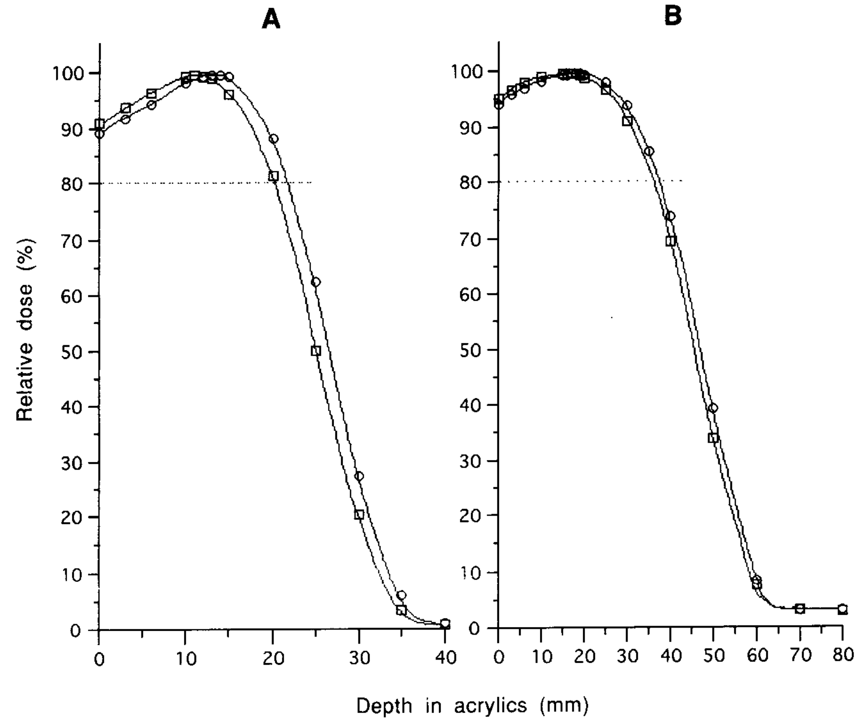

Fig. 4 Effects of the trial applicator on the electron beam depth dose. (○), With a conventional irradiation bolus (4.5 mm in thickness); (□), the trial applicator (5.5 mm in thickness). **A**, Percentage depth dose curve of the 9-MeV electron beam. **B**, Percentage depth dose curve of the 15-MeV electron beam. The depth of 80 % dose of the trial applicator was 21 mm for an electron beam of 9 MeV and 36 mm for an electron beam of 15 MeV. This represented only about a 1-mm decrease compared with a conventional irradiation bolus. For clinical use, this is generally equivalent to a conventional bolus.

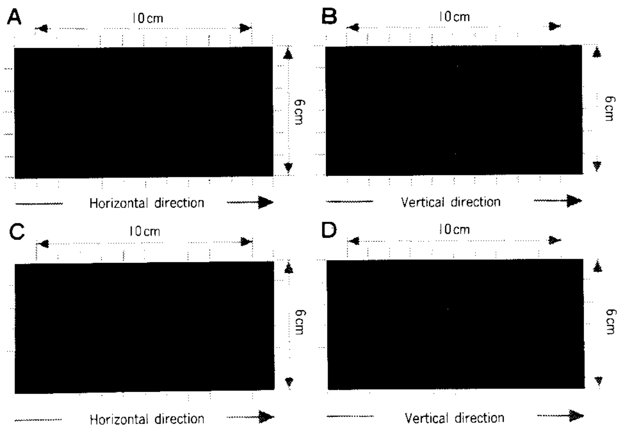

Fig. 5 Temperature distribution after heating by the trial applicator. **A**, **B**, The cooling device switched off. **C**, **D**, The cooling device applied. Heating was symmetrical on both the right and left from the center of the applicator for both the horizontal and vertical directions, irrespective of the attachment site between the electrode and lead wire. The heating distribution was modified by the cooling device.

shown in Fig. 4. The depth of the 80% dose of this 5.5-mm-thick applicator was 21 mm for an electron beam of 9 MeV and 36 mm for an electron beam of 15 MeV. This represented only about a 2-mm decrease compared with a 4.5-mm-thick conventional irradiation bolus. For clinical use, this is generally equivalent to a conventional bolus.

The temperature distribution for the trial applicator (Fig. 5) was symmetrical on both sides from the center of the applicator for both the horizontal and vertical directions irrespective of the attachment site between the electrode and lead wire. The distribution was able to be modified by the cooling device. The 50 % SAR region, an indicator of the range of heating, was 6.4 cm wide at a depth of 1 cm from the phantom surface in the horizontal direction and 2.8 cm wide at a depth of 3 cm (Fig. 6).

Discussion

SRH is a therapeutic technique designed to maximize

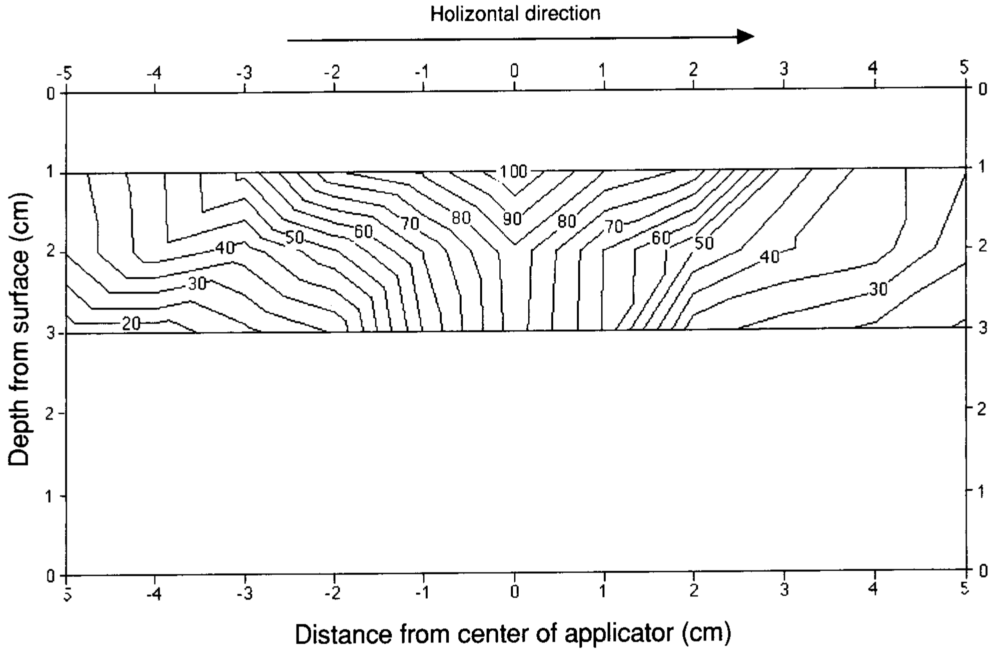

Fig. 6 Specific absorption rate (SAR) distribution after heating with the new applicator. The 50 % SAR region, an indicator of the heating range, was 6.4 cm wide at a depth of 1 cm from the phantom surface in the horizontal direction and 2.8 cm wide at a depth of 3 cm.

the antitumor effect of irradiation and heat. There are very few clinical reports on this subject because technology has not been established (6) for the simultaneous application of electromagnetic wave heating, the main technique used to apply heat in thermotherapy, together with radiotherapy. Previously reported techniques for clinical SRH using electromagnetic wave heating have only employed combinations of external irradiation and external capacitive heating (4) or intraoperative external irradiation and interstitial heating (5). The main part of the *in vitro* and *in vivo* theoretical basis for SRH was obtained by a combination of high dose rate irradiation and relatively high temperature thermotherapy. The dose rate during this experiment was 1.5 (1), 1.9 (2), 2.3 (3) and 3.25 (3) Gy/min, which are close to the desired clinical conditions. Sensitization has been reported *in vitro* (7, 8) by applying a combination of low dose rate irradiation along with long-term simultaneous heat treatment at a temperature of 41℃ or less. Although a combination of brachytherapy and interstitial heating can be expected to produce results as promising as SRH, interstitial heating or brachytherapy require the instrument to be inserted into the tumor invasively, making it difficult to noninvasively treat deep-seated tumors; this also precludes repeated treatment at regular intervals. External capacitive heating apparatuses are widely available throughout Japan, and we developed a technique for SRH using this apparatus. We have previously reported a method for the SRH of deep tumors (4), and this time we report a new applicator for the SRH of superficial and shallow-seated tumors. Compared with conventional capacitive heating applicators, the trial applicator used in this study is characterized by a very thin electrode plate, an attachment site between the electrode and lead wire at the electrode margin, and by having a applicator of uniform thickness. Irradiation is applied via electrodes in SRH. Usually, when radiation is applied via a metal plate, the dose directly beneath the plate is increased due to X-ray contamination (9), whereas the dose in deep regions is attenuated. By using a thin-plate electrode in the new applicator, the effect on the depth dose of the electron beam is generally comparable to that of a conventional irradiation bolus, and the ability to heat was also adequate. With the trial applicator in this study, SRH of superficial and shallow-seated tumors measuring up to a diameter of about 6 cm and a depth of 3 cm would be possible. In the future, SRH of tumors of various sizes and depths will most likely be made possible by preparing applicators of various sizes. With SRH, TGF remains of low clinical value (2, 6), creating the risk of damaging normal skin tissue in the treatment site. When superficial and shallow-seated tumors are present under normal skin tissue, the skin should be cooled by means of the trial applicator and only the tumor heated, thereby maintaining TGF at a high level. In addition, if superficial tumors are located on the skin surface, SRH should be performed without turning on the cooling function.

There have been no previous reports on the development of an external capacitive heating applicator designed for the SRH of superficial and shallow-seated tumors; this is the first such report. SRH of superficial and shallow-seated tumors can be performed simply, noninvasively and repeatedly by means of this new applicator.

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