Unusual Angular Arrangement of Electrodes in Capacitive Heating Device

—Thermal Distribution and Clinical Application—

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In capacitive heating device, which considered efficient for deep heating, parallel arrangement of the electrodes is a serious limiting factor in heating for eccentrically located lesions because it causes overheating of the exposed ipsilateral skin surface, the heating pattern is also frequently inappropriate, and the arrangement tends to be unstable due to the patient's gravity.

Therefore we attempted an angular arrangement of the electordes to achieve more homogenous and efficient heating for such lesions. In phantom study, both the thermal profile and thermogram established the heating pattern in this unusual angular arrangement of the electrodes at 60°, 90° and 120° angles, respectively. An angular arrangement was also clinically applied to 3 patients. The patients' tolerance was good without significant complication and the thermal distribution was satisfactory.

In conclusion, this unusual arrangement of electrodes appears to be promising in the clinical application to the eccentrically located lesions.

Key Words: Capacitive heating, Angular Arrangement, Thermal profile

INTRODUCTION

Improvements in therapeutic gain and tumor response rates achieved when hyperthermia is combined with radiation therapy have been demonstrated by many biological and clinical investigations[1~5]. Demands for the application of hyperthermia to deep seated tumors have accelerated the development of various types of heating equipment, with the goal of producing a tumor temperature between 42~50℃ for 30~60 min per treatment.

One type of heating equipment, the capacitively coupled radiofrequency (RF) system, still remains a potentially useful modality particularly in view of the increasing realization that there are no simple solutions to the problem of non-invasive deep heating, although it causes subcutaneous fat overheating[6~8].

However, this kind of heating system is not suitable for application to the eccentrically located lesions because it is based on a parallel arrangement of paired electrodes, so it frequently causes overheating of the exposed ipsilateral skin surface due to an edge effect. In addition, the heating pattern might not be adequate and the gravity of the patient's body can cause the electrodes, particularly the lower electrode, to be unstable and tilted(Fig. 1-A.B).

Therefore, we changed the arrangement of the electrodes from the conventional parallel one to an angled one with 60°, 90° and 120° angle between the two electrodes in a new attempt to treat eccentrically located lesions, based on electrically ideal current distribution in such an angled arrangement, as seen in Fig. 1-C.

This study reports the pattern of the temperature distribution in this unusual arrangement and the result in cases heated with such an arrangement to evaluate the possibility of clinical application.

MATERIALS AND METHODS

1. Heating Device

Capacitive heating devices operated at 8 MHz RF, i.e., Cancermia (Green Cross Corps, Ltd.) and Thermotron (Yamamoto Vinyter Co.), were used in this study. These consisted of an RF generator, heat exchanger system, a treatment couch, and a rotational gantry with a computerized treatment

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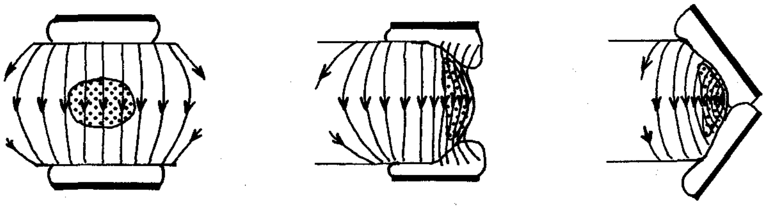

Fig. 1. Patterns of electric field in parallel arrangement of electrodes for the central lesion (A) and the eccentrical lesion (B) and in angular arrangement for the eccentrical lesion (C) in capacitive heating system. Dotted areas are target volumes (tumors).

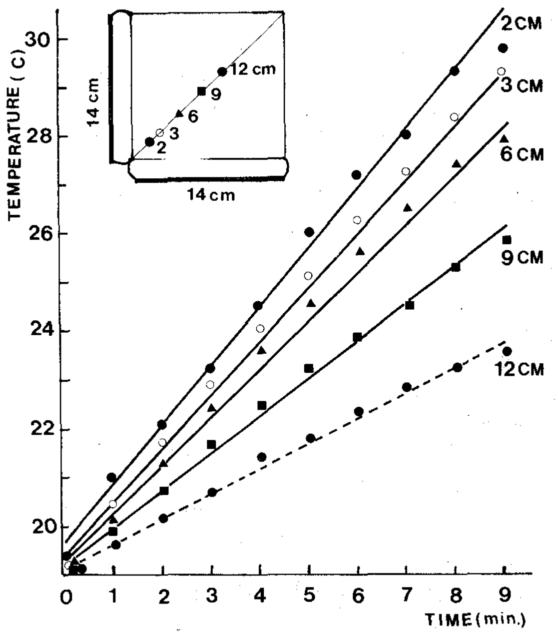

Fig. 2. The changes in temperature along the central axis in 90° arrangement show a linear increase and its rate varies markedly depending on the distance from the vertex.

console. A built-in thermometry system with five Teflon-coated probes of copper-constantan microthermocouples (Sensortek Inc., Type IT-18) were also included. The operating principle of the above heating devices has been described in detail elsewhere[9,10], so will not be discussed here.

2. Phantom Study

Hexahedral phantoms with a thickness of 14 cm and various angles were made of 4% agar gel containing 0.2% NaCl with 0.1% NaN_3 as a preservative. Several 18-gauge catheter tubes were inserted into the phantoms from one vertex which spread at angles of 60°, 90° and 120° to the opposing side in a fanlike shape. Fluoroscopic examination was done to ensure the proper angle of each catheter within the phantoms and then the thermocouples were placed in the tubes. The phantoms were capacitively heated by placing a pair of electrodes of various size on the two neighboring sides of the angles-60°, 90° and 120°-of the phantoms. In placing the electrodes with an angle between them, a fixing device with joints connected to the electrodes, so called universal joint, was used. Each phantom was heated for 20 minutes at 300 watt with surface cooling at 20℃.

The temperature in the phantoms was continuously monitored during the heating with the thermoprobes which were previously inserted into the phantoms. Just before the heating finished, the temperature distributions in the phantoms were determined by moving the thermocouples through the catheter step by step at 1 cm intervals along the track. Thermograms were also taken to obtain a picture of the thermal distribution in an entire heating volume using a thermal video system (TVS -3300 ME, Nippon Avionics Co., Ltd).

3. Human Tumors

As part of the phase I clinical trial, the unusual arrangement of the electrodes at certain angles was attempted in various advanced stage malignancies of different sites. The heatings were usually given twice a week within 30~60 min after irradiation of the tumors. The sizes and angles of the capacitor electrodes used for treatment were determined based on the size, depth, and site of the tumors. After local anesthesia with 1% lidocaine, one or two 18-gauge angiocatheters were inserted into each tumor along the central axis of the tumors. The temperature in the tumors was monitored continuously during heating, and the temperature distribution was observed by pulling the thermocouples toward the skin step by step at 1 cm intervals just before the heating finished. Before the heating started, conductive jelly was applied to the skin surface of the heating volume to improve the coupling of the electrodes, and the temperature of the saline bolus attached to each electrode was maintained at 10~30℃ depending on whether or not the overlying skin was invaded by the tumor.

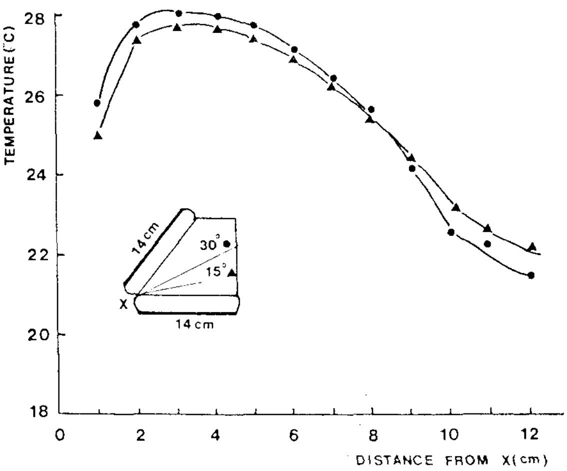

Fig. 3. Thermal profile in 60° arrangement.

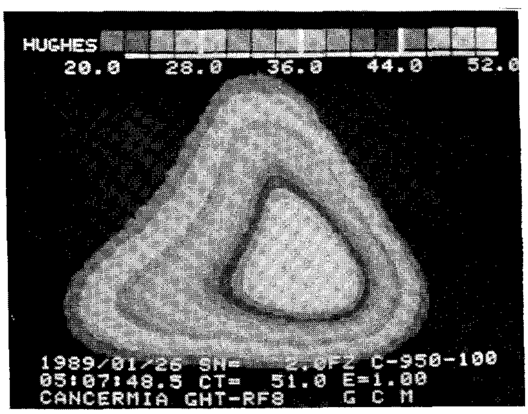

Fig. 4. Thermogram in 60° arrangement taken by thermal video system (The vertex is in right lower end.).

RESULTS

1. Thermal Profile in the Phantom

1) The Rate of the Heating in 90° Arrangement

The temperature rise in a 14 cm thick hexahedral phantom upon heating with 90° arrangement of the electrodes is shown in Fig. 2. Angiocatheters were inserted into the phantom from the vertex of the 90° angle, placing the tip of the catheters at different distances (2, 3, 6, 9, and 12 cm, respectively) along the central axis between the two elecrodes. The rate of increase in temperature varied markedly depending on the distance from the vertex of the 90° angle; at 2 cm distance from the vertex, the heating rate was the fastest and that became less fast as the distance from the vertex increased.

2) Thermal Profiles and Thermograms according to the Change in Angle between Two Electrodes

For further analysis of the thermal profile in the phantom, a transversal thermal distribution was mapped by pulling the thermocouple probes outward at 1 cm intervals after heating for 20 min at 300 watts.

As seen in Fig. 3, the temperature gradient along the axes of the 15° and 30° angles was minimal and the slopes of the temperature change were gentle in the 60° arrangement. On the other hand, the thermal profile in the 120° arrangement showed more distinct temperature gradient along the different axes of the 20°, 40°, and 60° and a sharp rise and fall in temperature change (Fig. 7). The thermal profile in the 90° arrangement fell between that of

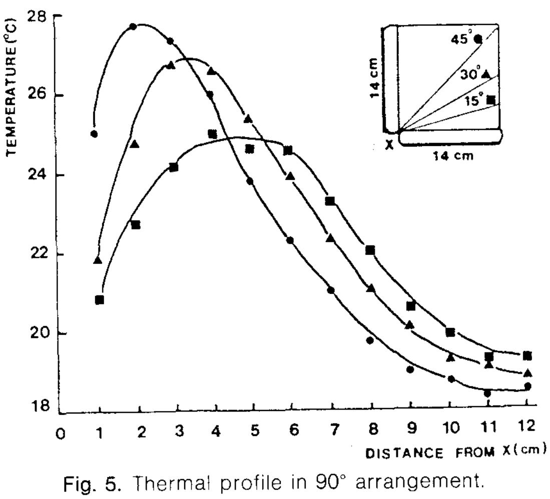

Fig. 5. Thermal profile in 90° arrangement.

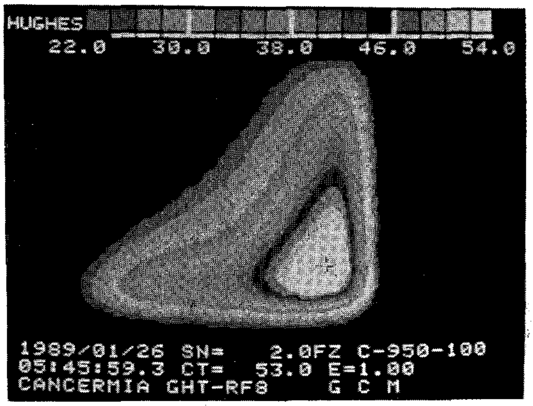

Fig. 6. Thermogram in 90° arrangement taken by thermal video system (The vertex is in right lower end.).

Fig. 8. Thermogram in 120° arrangement taken by thermal video system (The vertex is in right lower end.).

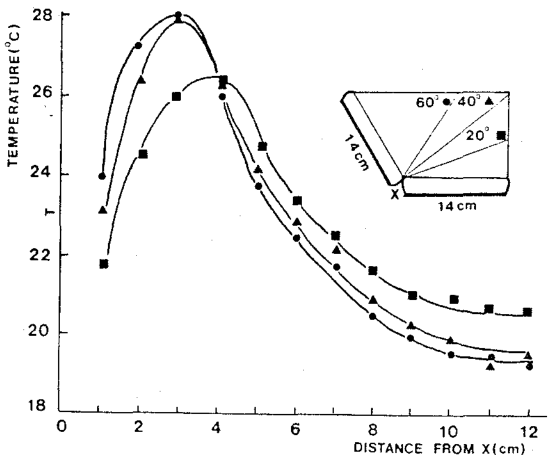

Fig. 7. Thermal profile in 120° arrangement.

the 60° and 120° arrangement (Fig. 5). The hottest area appeared to be between 2 and 4 cm from the vertex in angular arrangement (Fig. 3, 5, 7).

The above findings of the thermal profiles measured by the thermocouples were confirmed by thermograms (Fig. 4, 6, 8).

3) Thermal Profile according to Change in Size of One of the Paired Electrodes in 90° Arrangement

When the size of the one electrode was changed in the 90° arrangement, i.e., from 14 cm×14 cm to 14 cm×21 cm, the configuration of the isothermal region was changed so that it was elongated toward the larger electrode, as shown in Fig. 9.

4) Thermal Profile in Human Tumors

The unusual angular arrangement of the electrodes was attempted in three patients. The following are detailed descriptions of our experiences with 3 tumors, and the therapeutic results will be reported later.

Case 1.

This patient was a 52-year-old male who had an adenoid cystic carcinoma in the base of the tongue with extreme local extension into the supraglottis, submental, and submandibular areas. Estimated tumor size was 6×7×7 cm^3. The tumor was heated with a pair of electrodes 10 cm in diameter in a 60° arrangement, while the patient's neck was fully extended with his head turned down as seen in Fig 10. The applied power was 300 watts without any reflection. The temperature of the bolus of both electrodes was kept at 20℃. Although the heating could not be done over 2 sessions due to difficulty in extending the neck resulting from pain in the tumor, the tumor temperature was over 40℃ and was as high as 44℃ as shown in Fig. 10.

Case 2.

This patient was a 61-year-old male. He had a 6×6×5 cm^3 sized, huge, right side neck mass associated with an adenocarcinoma of the submandibular gland. During the first 3 sessions, the tumor was heated by a parallel arrangement of two electrodes of different diameter sizes; 10 cm in the tumor side and 14 cm in the contralateral normal side. However, difficulty in setting the electrodes due to his short neck and excessive heating of the exposed skin surface of the anterior neck were serious limiting factors in continuation of the heat treatment. After the 90° angle arrangement

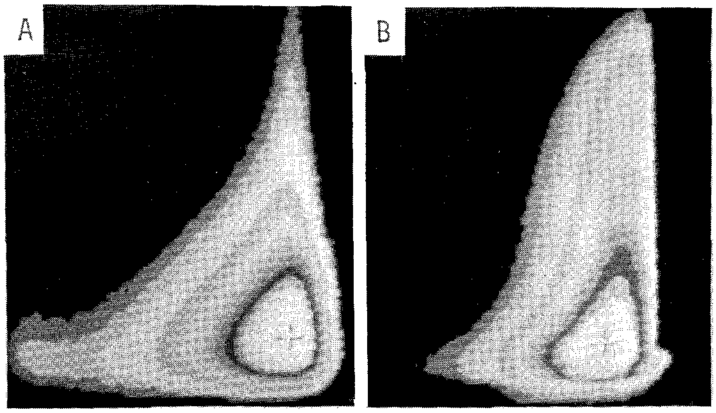

Fig. 9. Thermogram according to change in size of one of paired electrodes (lower electrode x right electrode) from 14 cm×14 cm (A) to 14 cm× 21 cm (B).

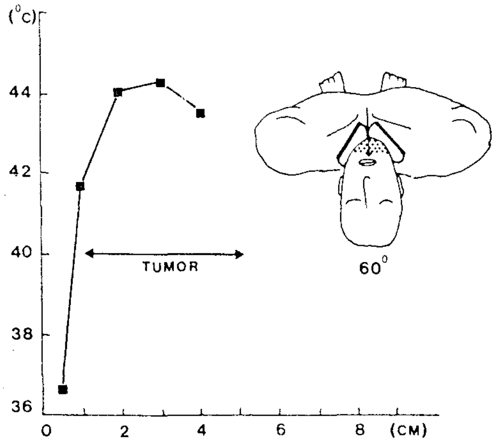

Fig. 10. Temperature distribution along the thermocouple in 60° arrangement.

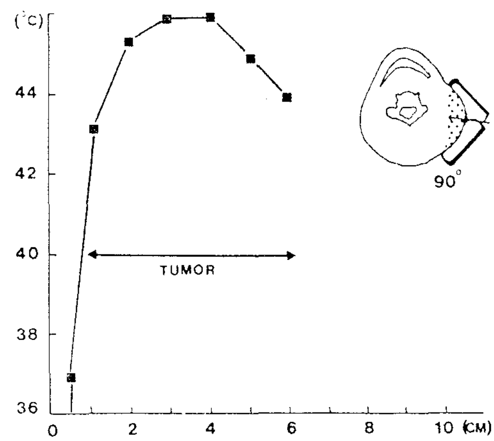

Fig. 11. Temperature distribution along the thermocouple in 90° arrangement.

with a pair of electrodes 10 cm in diameter was attempted from the 4th session, the patient's tolerance improved remarkably and excellent tempreature elevation could be achieved at half the power (250 watts with no reflection) compared to that in parallel arrangement (400~500 watts, reflection 70~90 watts) (Fig. 11).

Case 3.

This patient was a 54-year-old male with a malignant melanoma in the buttock area. The tumor was 6×7×15 cm^3 sized, hard, indurated mass associated with ulceration and bleeding. At the first heating session a parallel arrangement was performed with an electrode 21 cm in diameter on the buttock side and 25 cm in diameter on the opposing lower abdomenpubic side, but that resulted in burning the pubic area without any increase in tumor temperature. Soon the arrangement of the electrodes was changed to the 120° angled position with both the hip and knee joint flexed. Skin surface cooling was not done because the tumor invaded the skin severely. The patient's tolerance was very good and the thermal profile showed a satisfactory tumor temperature between 40℃ and 44℃ and shown in Fig. 12.

DISCUSSION

The interaction of RF electromagnetic radiation and biological tissue involves several mechanisms

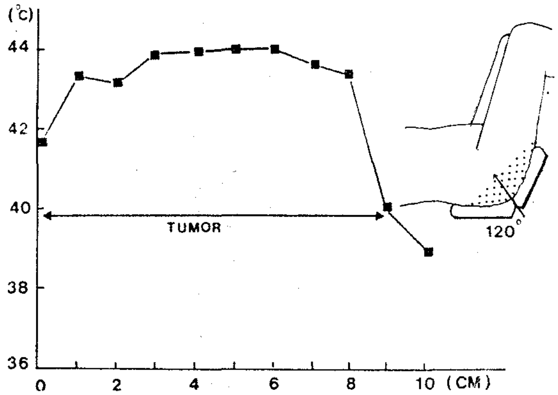

Fig. 12. Temperature distribution along the thermocouple in 120° arrangement.

of varying importance through the RF spectrum (0.1 to 100 MHz).

Radiofrequency fields are coupled to biological material either in a capacitive mode in which RF current passes from one electrode to another through the tissue interposed between the electrodes, or in an inductive mode in which current flow results in tissue placed within an alternating RF magnetic field according to Faraday's law. In this case, the induced electric field can be considered to be the force driving the RF eddy currents[11].

Electromagnetic currents in the frequency range of 0.1 to 10 MHz are used for producing localized hyperthermia in a capacitive mode. Tissue impedances at these frequencies are predominantly resistive, so ohmic heating is the only direct result of RF current flow, while the biological tissue between the electrodes is simply part of an electric circuit and not a propagative medium for EM waves.

In this range, the field penetration depth is not a limiting factor, and the shape of the heated volume can be controlled to some extent by the electrode configuration. Therefore, the capacitive mode is considered efficient for deep heating although it causes subcutaneous fat overheating.

To the eccentrically located lesions, however, such a parallel arrangement of electrodes in a capacitive mode always causes overheating of the exposed ipsilateral skin surface as seen in Fig. 1-B, and is a serious limiting factor. This is because the electric field is closely accumulated in the skin surface and subsurface and the current dose not pass through the air due to the high resistance of the air to the electric field. The heating pattern is also frequently inappropriate so that the normal contralateral side is frequently heated. Furthermore, the arrangement of the electrodes tends to be unstable and tilted due to the patient's gravity.

The newly attempted arrangement of electrodes with some angle between them is thought to be the answer to these problems. Both the thermal profile and the thermogram established a heating pattern in such an unusual arrangement of the electrodes at 60°, 90°, and 120° angles, respectively. As seen in the previous figure, the isothermal region becomes smaller if the angle between two electrodes varies from 60° to 120°. The configuration of the isothermal region can also be controlled by changing the size of the matched electrode. Therefore, we can adjust the target volume to the known heating pattern by changing the angle between the two electrodes and also the size of the electrodes.

Before the clinical application was tried, the possibility of excessive heating of the skin where the edges of the two electrodes abut each other was our major concern. But there was not any skin burn except in case 3 who had a huge tumor involving skin in the buttock area; hence, skin surface cooling could not be done. The patients' compliance was very good and thermal distributions as shown in Fig. 10, 11, and 12, were satisfactory. However, it should be pointed out that the thermometry at the present time has limitations, so we can not obtain further information about the temperature.

Although the attempt at clinical application was achieved satisfactorily, there remains several problems. The most important thing is the development of an accessory device for creating a stable angle. The reproducibility of a certain arrangement of electrodes depends on it and the technical skill of setting the electrodes. Another problem is that detailed and accurate treatment planning should be done before the heat treatment. The isothermal region varies according to the sizes of the electrodes and the angles between them, thus an arrangement of electrodes should be selected considering the target volume, i.e., heating volume.

Although inhomogeneous heat distribution in living tissues may be an inevitable fact in external electromagnetic heating including RF capacitive heating, as mentioned by Song et al[13], this unusual angular arrangement of the electrodes is thought to be promising for eccentrically located tumors in an attempt to achieve more homogeneous and efficient heating.

CONCLUSIONS

The thermal profile in an unusual arrangement of electrodes was investigated in agar phantoms and in human tumors in a capacitive heating device using 8 MHz RF.

Our study demonstrated the following results:

1) The rate of increase in temperature varied depending on the distance from the vertex in 90° arrangement: the fastest at 2 cm and the least fast at 12 cm from the vertex.

2) The hottest area appeared to be between 2 and 4 cm from the vertex in angular arrangement.

3) As the angle between two electrodes increased from 60° to 120°, the temperature gradient along the different axes became more distinct and the temperature change along the distance of a given axis showed a sharper rise and fall.

4) The configuration of the isothermal region changed according to the change in size of the one electrode.

5) Thermal profiles in the clinical application were satisfactory and the patient's tolerance was good without significant complication.

In conclusion, this unusual angular arrangement of electrodes appears to be promising in the clinical application to eccentrically located lesion.

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=국문초록=

유전 가열장치에서 전극의 각도 배열
—온도 분포의 특성 및 임상 적용—

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녹십자의료공업
양 성 화

고주파 유전가열 장치는 심부까지도 효과적인 가온이 가능하여 각종 심부암의 치료에 응용되고 있다. 그러나 한쌍의 전극을 평행으로 대칭 배열하는 현재의 방법은 신체의 일측으로 편재되어 있는 병소에는 배열 자체가 불안정할 뿐만 아니라, 노출된 동측 피부표면이 과열되며 종양의 가온 양상도 만족스럽지 못한 경우가 많아서 임상 적용에 난점으로 지적되고 있는 실정이다.

저자들은 상기와 같은 병소를 보다 안전하고도 효과적으로 가온하기 위하여 두 전극간에 일정한 각도를 이루는 새로운 전극 배열을 시도하였다. 즉, 임상 적용 가능성을 고려한 60°, 90° 및 120°로 전극을 배열하고 모형(phantom)에서 가온 실험을 행하여 이같은 각도 배열에서의 온도 분포의 특성을 평가할 수 있었고, 일측에 편재된 병소를 가진 3예의 환자에게 각도 배열로 온열치료를 시행한 결과 환자의 수용성, 부작용 및 온도 분포에 있어서 만족할 만한 결과를 얻을 수 있었다.

따라서 저자들이 시도한 전극의 각도배열은 일측에 편재된 병소를 유전 가열 장치로 가온할 때 평행배열이라는 한계점을 극복할 수 있는 새로운 방법으로서 매우 고무적으로 생각된다.