ORIGINAL ARTICLE

Relevance of a New Impedance Matching, or Subtrap, Method for the Reduction of Pain During Hyperthermia

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Capacitive heating is widely used in hyperthermic treatment of human malignancies. However, the pain on the body surface or thermoesthesia in the subcutaneous fatty layer may prevent an elevation of temperature in the tumors. Impedance matching is improved by a subtrap method entailing the application of two copper plates (10 × 850 × 0.06 mm) as a subtrap circuit to each of two capacitive electrodes. In a clinical trial the Tmax, Tave, Tmin for the subtrap method were all higher in comparison with those for the conventional technique (42.5 ± 0.7°C, 41.9 ± 1.0°C, 41.3 ± 1.1°C vs. 41.1 ± 1.5°C, 40.6 ± 1.3°C, 40.0 ± 1.3°C). Although the maximal radiofrequency (RF) power applied to patients was higher with the subtrap method (875 ± 189 W vs. 763 ± 200 W), the incidence of surface pain was reduced dramatically. It is concluded that the subtrap method substantially improves the RF capacitive heating of deep-seated tumors.

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Radiofrequency (RF) capacitive heating is widely used for the management of different human malignancies, including deep-seated tumors and its effectiveness has been reported by a number of investigators (1–4). However, since magnetic waves do not entirely penetrate inside the patient's body, but partly circulate on the surface, spots where high voltage is accumulated may appear. As a result, patients often suffer from pain on the body surface, mainly near the edges of the electrodes (i.e. the edge effect) (5, 6). In addition, capacitive heating tends to overheat the subcutaneous fatty layer which may cause thermoesthesia in some patients (7–9). These problems limit the delivery of enough output power to raise the tumor temperature. The quality of RF capacitive heating can be improved in various ways, for example by using an overlay bolus, and by precooling the skin prior to hyperthermia (10, 11).

Impedance matching is an important factor determining the quality of heating (12). In particular, inappropriate matching is one reason for the edge effect and overheating of the subcutaneous fatty layer. In this article we describe our recent observations which suggest that impedance matching can be improved significantly by using a 'subtrap method' (subtrap), by which we could significantly improve the heating of an agar phantom as well as human tumors.

MATERIAL AND METHODS

Phantom study

Phantom. A cylindrical muscle agar-agar phantom (20 × 30 × 28 cm) consisting of 4% agar-agar powder (Nakalai Tesque, Osaka, Japan), 0.22% NaCl and 0.1% NaN_3 as preservative was used.

Heating technique. The Thermotron RF-8 capacitive heating device utilizing 8 MHz (Yamamoto VINITA Co., Osaka, Japan) was used. Cylindrical electrodes 25 cm in diameter were chosen. The output power was 1000 W and the heating time was 15 min.

Matching of impedance. Impedance matching refers to the synchronization between oscillation frequency (fo) and load resonance frequency(fr).

fo = 1/2pvLC, where L = reactance of generator, C = capacity of generator.

fr = 1/2pVLC, where L = reactance of load coil (subtrap), C = capacity of load.

To achieve better matching between the heating object and device, two copper plates (0.1 × 85 × 0.006 cm) were applied as a subtrap circuit (94 mH, 48 Ω) to the lateral sites of the two capacitive electrodes. The plates were then ligated between the upper and lower electrodes (Fig. 1).

Temperature monitoring. The temperature in the central plane of the phantom was measured. The temperature distributions were monitored by moving a copper-constantan thermocouple through a hole in the central axis of the phantom in the direction of the upper to the lower electrode. The interval between registered points was 1 cm.

Clinical trial

Patients. From October 1994 to January 1996, 24 patients (8 males, 16 females, age 3–80 years) were treated in Kansai Medical University with hyperthermia combined with conventional radiotherapy up to a total dose of 46–60 Gy. The tumors of these patients included 11 uterine cervix cancer, 1 lung cancer, 2 rectal cancer, 3 bone metastasis of hepatocellular carcinoma, 2 breast cancer, 2 leiomyoma, 1 cholangiocellular carcinoma, 1 carcinoma of penis, and 1 malignant mesoepithelioma. In accordance with the tumor site, regional hyperthermia was applied to the pelvis area in 17 cases, to the chest in 5 cases, and to the upper extremity in 2 cases.

Heating technique. The regional external hyperthermic treatment was performed once a week by means of a Thermotron RF-8 heating device for a total of 4–8 sessions. The planned heating time was 40–50 min and the target temperature was over 42°C. As a rule, hyperthermia was applied within 30 min after radiation. For each patient, the new subtrap circuit was used at least three times in addition to the conventional heating method, and the effectiveness of the two methods was compared in the same patients. The diameter of the electrodes was 25 or 30 cm depending on the tumor site and patient size. Usually, the cutaneous tissues over the tumor were cooled with circulating water at 5°C for 5 min before and during the treatment.

Temperature monitoring. Thermometry was carried out using a copper-constantan thermocouple. The sensor was put into the 18 G Teflon catheter with a blind end and inserted into the desired position. If needed, the insertion was controlled by US imaging. The temperature at 4 points with an interval of 15 mm was simultaneously monitored.

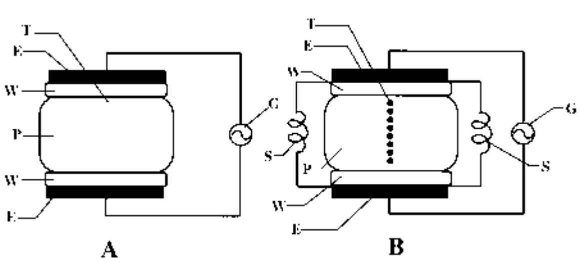

Fig. 1. A simplified diagram of conventional (A) and subtrap (B) radiofrequency (RF) heating device. P = agar phantom (20 × 30 × 28 cm); E = electrode (25 cm in diameter); W = water pad (29 cm in diameter, 2.5 cm thick); G = generator; T = points where temperature has been monitored; S = subtrap coil.

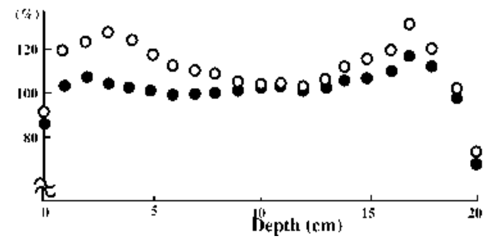

Fig. 2. Temperature distribution in agar phantom during heating by the conventional (open circles) or subtrap (closed circles) method. The center of a 20 cm-thick phantom is marked as a 10 cm point.

We evaluated the maximum temperature, minimum temperature and the average temperature either in tumor tissue (Tmax, Tmin, Tave), when it was technically possible, or in the region adjacent to the tumor (pTmax, pTmin, pTave). Additionally, the maximum values of the power (W) tolerated by the patients were evaluated for both methods.

The degree of surface pain. The patients were instructed to inform the doctor about any painful sensations and the degree of pain was defined in a prospective way as follows: (i) none/mild—the patient feels no pain or only mild pain in the course of the heating. Heating does not cause any damage and does not result in the diminishing of the output power; (ii) moderate—the patient has moderate pain which, however, allows continuance of the treatment. In some cases diminishing of the output power is needed; (iii) severe—the patient experiences severe pain in the course of treatment. The power has to be substantially decreased, or sometimes the treatment even has to be stopped.

Statistical analysis. The numerical data are presented by the mean ± SD. Student's *t*-test, when applicable, was used for the comparison between the two groups. The difference was considered statistically significant if the p value was less than 0.05.

RESULTS

Phantom study

The compiled results of 15 heatings with or without the subtrap method on the pattern of the elevation of the temperature in the agar phantom are presented in Fig. 2. The temperature in the center of the phantom using the subtrap method was taken as 100%. There was no difference in the center of the phantom upon heating with the conventional and subtrap methods, respectively. The heating with the conventional method resulted in hot spots near the edge, where the temperature was about 20% higher than that in the center of the phantom. In contrast, the subtrap method diminished the edge effect resulting in a more uniform temperature distribution.

Table 1

Tmax, Tave, Tmin and pTmax achieved by conventional or subtrap method

	Conventional		Subtrap	
Tmax (°C)	41.1 ± 1.5	p < 0.05	42.5 ± 0.7	
Tave (°C)	40.6 ± 1.3	N.S.	41.9 ± 1.0	
Tmin (°C)	40.0 ± 1.3	p < 0.05	41.3 ± 1.1	
				n = 10
pTmax (°C)	40.5 ± 1.2	p < 0.01	42.0 ± 0.8	
pTave (°C)	40.0 ± 1.2	p < 0.01	41.5 ± 1.0	
pTmin (°C)	39.6 ± 1.1	p < 0.01	40.9 ± 1.0	
				n = 14

Clinical study

Temperature elevation. The temperature in the tumor or in the adjacent area usually reached a maximum within 20–30 min after the start of heating and remained at a relatively stable level until the end of the treatment. The Tmax and pTmax data presented represent the temperature values after about 20 min. For 10 patients we succeeded in measuring the temperature directly in tumor tissue. It was then found that the subtrap method improved the tumor heating (Table 1). In the 14 patients for whom the pTmax, pTave and pTmin data were obtained, the same difference between the two techniques, with better temperature elevation for the subtrap method was observed (Table 1).

We then applied the subtrap method to the tumors which could not be heated above 41°C with the conventional method. It was then possible to raise the tumor temperature by more than 2°C above the temperature obtained with the conventional method (Table 2).

Degree of surface pain. The average power which could be applied with the use of the subtrap method was 875 ± 189 W, as compared with 763 ± 200 W for the conventional method ($p < 0.001$).

Despite the application of a higher power using the subtrap method, more than one-half of the patients did not suffer moderate or severe pain (Table 3). In contrast, very few patients treated with the conventional method were free from pain. Intolerable pain sensation was exceptional with the subtrap method, whereas more than 40% of patients treated with the conventional method complained of severe pain sensation.

Table 2

Tmax, Tave and Tmin as measured by the conventional or subtrap method in the group of patients where Tave under conventional heating was less than 41°C

	Conventional		Subtrap	
Tmax (°C)	40.1 ± 0.7	p < 0.001	42.4 ± 0.7	
Tave (°C)	39.5 ± 0.5	p < 0.01	41.5 ± 1.0	
Tmin (°C)	39.0 ± 0.6	p < 0.01	41.0 ± 0.9	
				n = 5

Table 3

Degree of surface pain and maximum output power for conventional or subtrap method

Degree of surface pain	Conventional		Subtrap
None/mild	5/28		17/28
	18%	p < 0.005	61%
Moderate	11/28		9/28
	39%	N.S.	32%
Severe	12/28		2/28
	43%	p < 0.01	7%
Maximum Output (W)	763 ± 200	p < 0.01	875 ± 189

DISCUSSION

Capacitive heating has been proved to be an effective method for successfully heating both superficial and deep-seated tumors to tumoricidal temperature, i.e. 42–43°C. The use of capacitive heating, however, often causes surface pain or thermoesthesia. Several methods have been proposed and applied to improve heating of deep-seated tumors using the capacitive method. Yanagawa et al. (1985) proposed the use of overlay bolus as a measure of diminishing the edge effect (10). The overlay bolus extends the surface area of the electrodes with consequent diffusion of the electric current at the margins of the electrodes. It has been demonstrated that use of the bolus for patients with thick subcutaneous fat substantially reduces the localized surface pain. Rhee et al. (1991) reported that precooling the surface of the skin decreases the overheating of the subcutaneous fatty layer (11).

Although these methods markedly improved the heating ability of capacitive heating, the pain and thermoesthesia continue to be a problem for some patients, especially those with a thick subcutaneous fatty layer.

It is believed that leakage of current occurs in the process of heating, resulting in the development of stationary waves that cause pain on the surface of body. A method to remove the electrostatic current from the body surface has been proposed by Ueda et al. (1995), who found that massaging the patients' legs can alleviate the pain and thermoesthesia in the patients' skin (13). It is believed that during massage, which is known in Japan as a gripping method, part of the current flowing on the surface of heated patients flows to the body of the person performing the gripping. As a consequence, the surface pain of the patient is diminished allowing application of higher power to the tumor. Hirai et al. (1992) have made an attempt to prevent the leakage of RF waves during hyperthermic treatment of prostate cancer using Endoradiotherm 100A® adopting 13.56 MHz (14). It was shown that leakage of RF waves can be decreased by magnetic material inserted into the coaxial cable between the heating device and the internal applicator. In the present experiments using agar phantom, the use of the subtrap method described above resulted in uniform heating compared with the use of conventional heating. Use of the same subtrap circuit for patients resulted in better elevation of temperature inside the tumors, since the frequency of the pain near the edges of the electrodes was diminished and thus patients could tolerate higher power. Consequently, tumors which were almost unheatable by the usual method could be heated to therapeutic temperatures when the subtrap circuit was used.

The therapeutic basis for the improvement in tumor heating with the subtrap method can be summed up as follows: In capacitive heating a good impedance match helps minimize reflected power. Initially, the oscillation frequency (fo) and load resonance frequency (fr) are not equal, resulting in the accumulation of high voltage on the surface of the human body and causing pain mostly near the margins of the electrodes. The impedance match consists of synchronization between oscillation frequency (fo) and load resonance frequency (fr). The matching between the heated subject and the device can be improved by enlarging either the C or the L factor (see Methods). Technically, it is almost impossible to increase the C factor to the desired values since it requires the use of large electrodes. The results of the present study indicate that one of the ways of increasing the L factor is to use a so-called subtrap circuit. With the employment of subtrap circuit, frequency of apparatus (fo) and patient (fr) can be synchronized. In turn, if frequency is synchronized, the impedance becomes nearly the same for device and load. The appearance of high voltage spots on the surface of the human body declines due to a decrease in the reflected power and, in addition, due to discharge of the current accumulated on the skin surface (earth effect). Clinically, if synchronization is successful, the heat sensation and pain near the edges of the electrodes would decrease.

In conclusion, use of the subtrap circuit (94 mH, 48 Ω) has resulted in good temperature elevation in human tumors. Larger cross-section body segments can be successfully heated as a result of an increased penetration of the current with the use of the subtrap circuit. The subtrap device is also safe.

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