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MAGNETIC FIELD INTENSITY AND ENERGY ABSORPTION DUE TO SHORT-WAVE INDUCTION DIATHERMY

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Abstract. Intensity of magnetic field around the induction diathermy device GS-200 Terapuls decreased to power three with the distance and it was found to be 0.6—0.7 A/m at 5 cm, 0.3 A/m at 30—40 cm, 0.424 μA/m at 3 m, and 0.5 μA/m at 30 m from the electrode. Under highest output parameters with average power output of 60 W and with electrode separated from fluid by 1 cm wall of styrofoam vessel, this device induced specific absorption rate of 18.14 W/kg.

INTRODUCTION

Diathermy denotes the heating of definite tissues for therapeutic purposes. This sort of heating is the result of the transformation of absorbed high frequency or very high frequency electromagnetic (e-m) energy into heat. The International Radio Conference in 1947 (USA) designated definite frequency bands of e-m radiation for industrial, scientific and medical purposes, hoping that every country would exactly establish the application of e-m radiation within these frequency bands. The same year, the Frequency Competence Convention designated for short-wave diathermy three frequency bands increasing harmonically with permissible deviation limits, namely 13.66 MHz and 15 kHz, 27.12 MHz and 320 kHz, and 40.98 MHz and 40 kHz, respectively. It was evident that it would be easier and less costly to make a generator with larger tolerance limits, and this was the reason for the practical application of 27.12 MHz band with 320 kHz tolerance in short-wave diathermy devices (2,3).

At present, three kinds of diathermic treatments are applied and in

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Address reprint requests to M. Kameduła, Department of Physical Hazards, Nofer's Institute of Occupational Medicine, 8 Teresy Street, 90-950 Lodz. P.O.Box 199, Poland each treatment e-m energy penetrates the tissues where it is transformed into heat due to the dielectric losses of the tissues.

1) A short-wave capacitive diathermy device delivers e-m energy to organs or tissues placed between two electrodes which act as condenser plates. The short-wave capacitive diathermy generating energy at 27.12 MHz is an example of such a device. 2) A microwave radiation diathermy device affects tissues with e-m radiation from an antenna. Such a device generates microwaves of 915 MHz or 2450 MHz. 3) A short-wave induction diathermy device is equipped with a single electrode in the form of a coil which is the source of a tissue-penetrating magnetic field. A practical device of this kind generates e-m energy of 27.12 MHz.

In the case of capacitive diathermy, the generated e-m energy is non-modulated and similar to the energy in a condenser. On the other hand, in the case of inductive diathermy, the biological effect is induced by a pulse-modulated magnetic field and this kind of modulation is programmed to achieve high intensity energy per pulse at a relatively low average output power of the device.

Experimental measurements and theoretical calculations made in 1954—1959 (9) indicated that the frequency of 2450 MHz is not the optimum frequency for the purpose of microwave diathermy. This view is supported by: a) the possible formation of a standing wave causing potential overheating of subcutaneous tissue: b) poor penetration of e-m energy into muscles of a relatively thin layer of skin: c) the insufficient ability of patients to sense the absorbed energy due to the varying thickness of subcutaneous tissue. Schwan suggested using 900 MHz or a lower frequency band for the purpose of microwave diathermy as this would make it possible to avoid the inconveniences mentioned above. This proposal was verified and a practical therapeutic device was constructed for the generation of microwaves 915 MHz (2).

Principles of e-m energy absorption in tissues

In an electromagnetic field of homogeneous intensity without dissipation of energy and with a perpendicular incidence of energy on the tissue surface, the reproducible relations between field intensity E_o in space and field intensity E_t in tissue are indicated by the formula:

$$E_o = \Sigma^* t \, E_t$$

where: $\Sigma^* t = (E_t - j\sigma_t \, t/\omega\Sigma_o)$ denotes complex dielectric permittivity of tissue (complex dielectric constant of tissue); σt — specific conductivity of tissue: Σ_o — electric permittivity of free space; Σ_t — electric permittivity of tissue (dielectric constant of tissue); ω — angular frequency

($\omega = 2\pi f$); j — flux (current intensity); E_e — intensity of incident E field; E_t — intensity of E field in tissue.

The absorption of energy in tissue subjected to the action of e-m field is described by the relation (2);

$$P_a = 10^{-3} \frac{\sigma}{\mu} \quad |E|^2$$

where P_a — energy absorption in W; σ — specific conductivity of tissue in S/m; σ — tissue density in kg/dm³; — intensity of E field in V/m (rms) in tissue.

In the case of inductive diathermy, the energy transformed into heat in the tissue depends not only on the current intensity in the coil of the electrode, but also on the current frequency and on the dielectric properties of the tissue (6):

$$P_a = f\mu\sigma$$

where P_a — power in W transformed into heat; f — current frequency in Hz; μ — magnetic permittivity of tissues (really equal to magnetic permittivity of free space, i.e. $\mu = \mu_o = 4\pi\ 10^{-7}$ H/m; σ — specific conductivity of tissues in S/m.

Pulse modulation of high frequency energy generated by an inductive diathermy device causes a reduction of energy loss in superficial tissues. When the power per pulse of high energy and duty factor (pulse duration times frequency of pulse repetition) are known, it becomes possible to calculate the average power of high frequency according to the formula:

$$P_{av} = P_i\, t_i\, f_i$$

where P_{av} — average power output in W; P_i — power per pulse in W: t_i — pulse duration in seconds; f_i — frequency in Hz of pulse repetition.

There are only a few publications dealing with the measurement and hygienic evaluation of e-m field from short-wave inductive diathermy devices (5,10,11). This paper presents the results of e-m field measurement around the coil electrode and feeding cables, and the results of the calculation of power absorption in fluid phantom.

MATERIAL AND METHOD

The subject of the hygienic assessment was the e-m field around the short-wave inductive diathermy GS-200 "Terapuls", a device manufactured in the Electromedical Equipment Factory in Lodz, Poland. The diathermy GS-200 Terapuls is equipped with an active head containing a coil, which is the sourse of a magnetic field, and with a condenser for the adjustment of the circuit to resonance with the object of treatment (a patient). GS-200 Terapuls generates a magnetic field with parameters as follows: basic frequency 27.12 MHz; energy modulation in pulses of duration 60 μs or 100 μs and repetition frequency 80, 160, 300, 400, 500 or 600 Hz; penetration grades "1, 2, 3, 4 or 5" denoting peak power output 300, 500, 700, 850 or 1000 W, respectively, per pulse. In the case of maximum parameters, i.e. penetration grade "5", $P_i = 1000$ W, $t_i = 100$ μs and $f_i = 600$ Hz, the average power (P_{av}) delivered to the object amounts to 60 W.

There is no standard procedure for measuring e-m field around the inductive electrode. Polish standards of permissible intensities for e-m fields including band 27.12 MHz (7) do not define the permissible intensity of an H field. The intensity of an H field was measured around the inductive electrode of GS-200 Terapuls during conventional treatment procedures and under standardized laboratory conditions. Such measurements were carried out in the vicinity of the electrode and in the function of distance from it. Energy absorption (specific absorption rate — SAR) was calculated from the temperature rise in fluid phantom loading the electrode. The phantom was in the form of a styrofoam vessel 10×10×10 cm (1 cm wall thickness) lined inside with a layer (about 2 mm) of nonlossy water-proof material (gumlike adhesive material manufactured by STOMIL, Cracow).

The instruments used for measurements included: 1) Electric and magnetic field meter type NFM-1 with frame antenna which has linear transmission within 100 kHz to over 30 MHz (VEB Funkmechanik, GDR); 2) Interference meter type LMZ-3 with frame antenna AMZ-3A (product of INCO, Wroclaw) indicating the intensity of an H field but calibrated in units of E field intensities (dB re, y uV/m); H field, intensity is calculated from relation $E/H = 120\ \pi\Omega$ valid for a plane wave in free space; 3) Thermistor thermometer (Elektrolaboratoriet, ELLAB Instruments, Copenhagen) make possible temperature read outs within 16—50°C with accuracy to 0.1°C.

The specific absorption rate (SAR) was calculated from the temperature rise in 0.9% NaCl in phantom vessels according to formula:

$$P_{w/kg} = \frac{4186\ c\ \Delta T}{\Delta t}$$

where $P_{w/kg}$ — energy absorption; c — specific heat in kcal/kg×°C of tested material; ΔT — temperature rise in °C in irradiated material; Δt — exposure time in seconds. Styrofoam which is used for phantom, is a nonlossy material for electromagnetic energy and owing to its characteristic the e-m energy enters into 0.9% NaCl without any losses. In every test measurement, the saline was exposed for 10 minutes without taking into consideration some dissipation of heat from the phantom by convection and radiation. This means that the conditions of SAR assessment were comparable to those in tissues of patients where some heat from e-m energy is dissipated by blood circulation, convection and radiation. Phantom with stationary fluid makes possible a reasonably accurate determination of SAR in a patient's body.

RESULTS

Measurements carried out in the physiotherapeutic unit at a distance of 5 cm around the coil electrode loaded with maximum working parameters showed H field intensity of 0.6—0.7 A/m. This intensity decreased rapidly with the distance, amounting to 0.3 A/m at a distance of 30—40 cm, 0.424 µA/m at a distance of 3 m, and only 0.5 µA/m at a distance of 30 m from the coil electrode. At applied loading of coil electrode situated 5 cm above the saline in the phantom, the estimated SAR was somewhat above 1 W/kg (Table 1).

TABLE 1. Results of H field measurement around the inductive diathermy GS-200 Terapuls in the therapeutic unit. Working parameters of the diathermy were: pulse duration 100 µs, pulse repetition — 600 Hz, penetration index "5". The fluid phantom was in the form of styrofoam vessel 10×10×10 cm with 1 cm wall and filled with 750 cc of 0.9% NaCl. Active coil electrode touched the upper surface of phantom, being 5 cm above the saline surface. Exposure duration: 10 minutes

I. *Measurements of H field in A/m with NFM-1 meter and frame antenna:

1) 5 cm from the electrode on the front	0.6 A/m
2) 5 cm from the electrode on the left side	0.65 A/m
3) 5 cm from the electrode on the back	0.75 A/m
4) 5 cm from the electrode on the right side	0.7 A/m
5) 5 cm from the electrode on the left side parallel to bed	0.5 A/m
6) 10 cm from the electrode at the left side	0.3 A/m
7) 40 cm from the electrode under the table	0.3 A/m

II. *Measurements with interference meter LMZ-3 and frame antenna AMZ-3A:

	E mV/m	equivalent	H µA/m
1) 3 m from the electrode	160	"	424
2) 7 m from the electrode	3.2	"	8.5
3) 10 m from the electrode	1.0	"	2.7
4) 15 m from the electrode	1.0	"	2.7
5) 30 m from the electrode	0.18	"	0.5

III. *Calculation of absorbed energy (SAR) based on temperature increase in saline.
The average rise in temperature from three readings at 10 minute intervals was 0.15 °C. Hence, calculated SAR was 1.05 W/kg.

* Characteristics of meters and principles of SAR calculation were described in section "Material and Method".

During measurements carried out under laboratory conditions, the device GS-200 was placed at one end of 50 m long hall and the surface of the coil electrode contacted the phantom perpendicularly to the long axis of the hall. The intensity of the H field was close to 1.5 μA/m at 6 m, and 0.45 μA/m at 45 m from the coil electrode (Table 2). The results presented in this table indicate that the intensity of the H field decreases in relation of 1^{-4} to 1^{-6} in respect to distance (l) from the source. In the case of close contact of the electrode with the phantom (distance 1 cm from fluid), SAR amounted from 8.37 W/kg to 18.14 W/kg, depending on the

TABLE 2. Measurements of e-m energy dissipated from the electrode of inductive diathermy GS-200 Terapuls under standard laboratory conditions. The inductive electrode was loaded with phantom in the form of styrofoam vessel 10×10×10 cm (walls thickness — 1 cm) filled with 750 cc of 0.9% NaCl. The inductive diathermy was located at one end of 50 m long hall and the plane of the electrode touched the phantom perpendicular to one axis of the hall, 1.2 m above the floor. Working parameters of the diathermy were: frequency of e-m field — 27.12 MHz, pulse repetition — 600 Hz, pulse duration — 100 μs, penetration grade "5", exposure time — 10 minutes. The measurements of e-m field were performed with the interference meter LMZ-3 and frame antenna AMZ-3A (as described in section "Material and Method")

	Distance from electrode	E mV/m	equivalent to	HμA/m
1.	6 m	531—562	„	1408—1491
2.	18 m	0.9—1.1	„	2.4—3.0
3.	29 m	0.3—0.32	„	0.67—0.75
4.	45 m	0.14—0.17	„	0.38—0.45

TABLE 3. Calculation of energy absorption P in W/kg due to inductive diathermy GS-200 Terapuls operation. The test was carried out in the shielded chamber EK-2. The active coil electrode was loaded with phantom in the form of styrofoam vessel 10×10×10 cm (with 1 cm wall) containing 500 cc of 0.9% NaCl. This vessel was placed on the electrode at 1 cm distance from the fluid. SAR was calculated from the average rise in temperature after three 10 min. exposures. *The measurements were repeated three times on successive days'.

Working parameters of diathermy:				
pulse repetiton (Hz)	pulse duration (μs)	penetration grade	Average rise in temperature (T. °C)	SAR (W/kg)
300	100	"3"	1.2	8.37
300	100	"5"	1.5	10.47
600	100	"5"	2.6	18.14
**600	100	"5"	0.1	0.7

* Measurement of rise in temperature and principles of SAR calculation are specified in section "Material and Method".

** Electrode fixed above the phantom vessel at 10 cm from the surface of fluid.

parameters of H field applied. When the gap between the electrode and the phantom saline was 10 cm, the SAR was only 0.7 W/kg at loading of the electrode with maximum parameters (Table 3). These calculations prove that the magnitude of energy absorption in the irradiated object depends on the parameters of the applied current and on the distance of the electrode surface from this object, lowering as this distance increases.

DISCUSSION

The assessment of power output from diathermy devices usually has two aspects, irrespective of the kind of device, i.e.: 1) quantity of energy transferred to tissue for therapeutic purposes; 2) quantity of energy dissipated to surrounding environment by active electrodes and feeding cables. The main application of diathermy depends on the delivery of an appropriate quantity of e-m energy to tissues for expected heating, which can be calculated by the amount of absorbed energy in W/kg. The transformation into heat of e-m energy absorbed in tissue is a general principle of diathermic treatment. On the other hand, the dissipation of e-m energy into the surrounding environment is highly undesirable from both the economic and hygienic points of view, with regard to persons operating diathermic equipment. The quantity of dissipated energy is evaluated by the measurement of e-m field intensity. In the case of capacitive diathermy (condenser field between two electrodes), the intensity of E field is measured most often, but in the case of inductive diathermy (inductive field of coil electrode), the intensity of H field is measured.

Measurements with the use of fluid phantom revealed that in the case of maximum working parameters of inductive diathermy (average power 60 W, pulse repetition 600 Hz, pulse duration 100 μs, and penetration grade "5"), the energy absorption was 18.14 W/kg. In the case of capacitive diathermy with comparable average power 65 W, the energy absorption was 35.6 W/kg. These results indicate that efficiency of e-m energy transmission to tissues is significantly higher in the case of capacitive diathermy than in the case of inductive diathermy.

There are also some striking differences in the quality of e-m energy dissipated by diathermic devices of these two kinds. In the vicinity of a capacitive diathermy device, the intensity of E field ranges from above 1000 V/m at 0.1 m to 20 V/m at 2 m from electrodes and feeding cables (8). Measurements in fluid phantom (equivalent to muscle tissue) showed that in the case of energy absorption of 22 ±2 W the intensity of H field was 0.52 A/m at 0.5 m from feeding cables and capacitive electrodes. Around the inductive electrode causing energy absorption of

139 ±5 W in fluid phantom, the intensity of H field was 0.52 A/m at about 0.2 m from the electrode and feeding cable (5). The results obtained in the measurements presented above showed an intensity of 0.7 A/m of H field in the case of maximum technical parameters of inductive diathermy GS-200 Terapuls. These results indicate that in the vicinity of an inductive diathermy device, the e-m field is of significantly lower intensity than in the vicinity of a capacitive diathermy device. It should be stressed that the main sources of energy dissipation (in the case of short-wave diathermy devices) are non-shielded cables carrying high-frequency energy to electrodes. However, for technical reasons the use of shielded cables (coaxial) for the purpose of energy transmission in these kind of diathermy devices is not recommended.

The measurements of H field intensity in the vicinity of the inductive diathermy GS-200 Terapuls and the calculation of energy absorption in fluid phantom imply that there is no need to carry out measurements of H field intensities for hygienic control of exposure. It has been recommended that persons operating inductive diathermy devices should keep a distance of over 0.8 m from the active electrode and from feeding cables. At such a distance, the intensity of H field is usually below 0.2 A/m and it does not create any health risk from the hygienic point of view (according to Standard ANSI c.95.1-1982) (1).

CONCLUSION

Magnetic field intensity was 0.6—0.7 A/m at 5 cm, 0.3 A/m at 30—40 cm, 0.424 µA/m at 3 m, and 0.5 µA/m at 30 m from the electrode of inductive diathermy device GS-200 Terapuls working with maximum technical parameters and loaded with fluid phantom under normal conditions of treatment. Comparable intensities of magnetic field were measured under standardized conditions using this device. Under conditions of maximum technical parameters with an average power output 60 W, this device induced the specific absorption rate (SAR) 18.14 W/kg in fluid phantom with the electrode separated from the fluid by 1 cm wall of the styrofoam vessel. The efficiency of e-m energy transmission to tissues was significantly lower in the case of inductive than capacitive diathermy devices. It was found that at distances exceeding 0.8 m from the inductive diathermy device, there is no health risk due to magnetic field intensity from the hygienic point of view.

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