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An evaluation of radiofrequency exposure from therapeutic diathermy equipment in the light of current recommendations

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Abstract. Shortwave and microwave diathermy equipment use by physiotherapy departments in Grampian Region has been studied. Stray electric and magnetic fields close to equipment have been measured and compared with exposure levels recommended by the INIRC and the NRPB. Fields above the recommended whole body levels extend to 0.5-1.0 m from the electrodes and cables for continuous wave (CW) shortwave equipment, and up to 0.5 m for microwave units and pulsed shortwave models. Operators were exposed to local fields above these values for 2 - 3 min during CW shortwave treatments, but rarely exceeded the recommended exposure. However, short localised exposures to high fields, which can occur if the operator moves close to the electrodes or cables, could exceed these limits. Physiotherapists are advised to remain at a distance of at least 1 m during CW treatments, and not to approach within 0.5 m of the electrodes and cables even for a short period.

1. Introduction

Shortwave and microwave diathermy are used to treat many acute and chronic conditions of joints, muscles, ligaments and tendons. The main mechanism of therapeutic action is heating, which stimulates blood circulation and enhances metabolism in treated tissues (Guy *et al* 1974). Heating promotes relaxation and pain reduction in muscles, and reduces tension in collagenous tissues such as tendons and joint capsules. Athermal effects of electromagnetic fields may also contribute to the healing process.

Stray electric and magnetic fields close to diathermy equipment can be substantial. During the 1980s, UNEP/WHO/IRPA (1981, 1987) and NCRP (1986) reviewed the biological effects of electric and magnetic fields. There have also been advances in non-ionising radiation dosimetry (IRPA/INIRC 1985, Guy 1987). In the light of these data consideration has been given to the levels to which people might be exposed (ANSI 1982, NRPB 1986). Limits have been recommended (IRPA/INIRC 1988, NRPB 1989), designed primarily to protect against thermal effects, radiofrequency burns and electric shocks. In order to assess current working practices in the light of these recommendations, a survey of therapeutic diathermy use has been carried out. Electric and magnetic fields associated with such equipment have been measured and personnel exposure assessed.

Although a few manufacturers use 434 MHz, most shortwave equipment operates at 27 MHz with two types of treatment arrangement. In the first, known as the capacitive method, the part of the body to be treated is placed between two electrodes so that it forms the dielectric material between the plates of a capacitor. In the second, known as the inductive method, a coil is positioned close to the body so that the changing magnetic flux induces eddy currents in the tissue. Coils are commonly of helical form within a single applicator, or may consist of a cable wound round a limb. The idea that electrical currents

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flowing in tissue are an important factor in stimulating healing has lead to the development of pulsed shortwave equipment. The pulses are thought to be short enough to allow blood flow to cool the tissue to body temperature after each pulse at low pulse repetition frequencies, so that prolonged heating does not occur.

Microwave diathermy heats tissue through absorption of 2.45 GHz radiation. However, standing waves can produce excessive heating of subcutaneous fat and penetration in muscle tissue is often limited. A frequency of 915 MHz has been found to produce more uniform heating (DeLateur *et al* 1970, Guy 1971).

The main hazards resulting from exposure to stray electromagnetic fields from diathermy equipment are overheating and radiofrequency burn. One cause of overheating at frequencies below 30 MHz is the flow of induced charge to ground through the limbs (Ghandhi and Chatterjee 1982). Induced currents from coupling of the body to electric fields are greater than those from equivalent plane wave magnetic fields, so electric and magnetic fields must be considered separately in hazard assessments at 27 MHz.

2. Methods

A survey of diathermy equipment and treatments was carried out in Grampian Health Board Physiotherapy Departments. A form was completed by each department, giving information on equipment, treatment rooms and numbers of patients. Data were obtained from 15 hospitals and 5 health clinics. In 17 of these centres, forms were completed for every patient treated within a period of one week. This included equipment settings, part of the body treated, treatment time, and details of the time spent by the physiotherapist in the field from the electrodes. Physiotherapists were asked to record the time and position for any period over 30 s spent within one metre of the electrodes and also the total time they were between one and two metres from the equipment.

The physiotherapist is working mostly in the far field of equipment operating at both 27 MHz (wavelength 11 m) and 2.45 GHz (wavelength 0.12 m). The power density (S), which is related to the cross product of the electric and magnetic field vectors, can be derived from the squares of the electric and magnetic field strengths in the far field from the equations:

$$S = \frac{1}{2} H_{\mathrm{RMS}}^2 Z = \frac{1}{2Z} E_{\mathrm{RMS}}^2 \tag{1}$$

where H_{RMS} and E_{RMS} are the RMS values of the electric and magnetic field strengths and Z is the impedance of the medium. A Raham Model 4 meter (General Microwave Corporation, USA) was used for measuring electric field strengths. Magnetic field strengths were measured using a 20 mm diameter coil constructed from a strip of 15 mm wide, 0.25 mm thick brass foil, and shielded from electrical interference by a copper alloy wire cage wound around a polystyrene insulator. The output waveform was monitored by a Leader LBO-518 oscilloscope. Three orthogonal components of the field were recorded at each position, and the magnitude of the field strength calculated from the sum of their squares. Time averaged values of the electric and magnetic field strengths (E_{av} and H_{av}) and their squares ($(E^2)_{\mathrm{av}}$ and $(H^2)_{\mathrm{av}}$) were calculated. For pulsed equipment, the averaged values depend on the pulse repetition rate (f) and pulse length (p), which were measured from the oscilloscope trace,

$$(E^2)_{\mathrm{av}} = pf\, E_{\mathrm{RMS}}^2 \quad \text{and} \quad (H^2)_{\mathrm{av}} = pf\, H_{\mathrm{RMS}}^2 \tag{2}$$

$$E_{\mathrm{av}} = pf\, E_{\mathrm{RMS}} \quad \text{and} \quad H_{\mathrm{av}} = pf\, H_{\mathrm{RMS}} \tag{3}$$

where E_{RMS} and H_{RMS} are the RMS field strengths during the pulses. Field measurements were made during patient treatments in the Physiotherapy Department at Woolmanhill Hospital, Aberdeen. A grid of squares, side length 200 mm, was marked around three diathermy units and a variety of patient treatments with many electrode configurations were studied.

Measurements were made at the grid intersections in a horizontal plane at the same height as the electrodes to give two dimensional plots of electric field strengths for each treatment. One dimensional plots of magnetic and electric field strengths were made in different directions from the electrodes of each unit. Additional data plots were made in seven other departments using phantoms and standard machine settings. The phantoms were constructed from plastic modules filled with saline of conductivity 600 mS m^{-1}, which is similar to that of muscle tissue at 27 MHz (Guy *et al* 1974). The modules were: eight five litre containers, a 65 mm diameter tube and a glove. These were placed side by side or taped together to represent different treatment arrangements.

To assess the exposure of physiotherapists, the decrease in electric and magnetic fields with distance from the electrodes was evaluated for each configuration from all the patient and phantom data. Average field strengths at standard settings were calculated along the axes through the centres of the electrodes, perpendicular to them, and at 45° on either side. Values of electric $E_{RMS}(u,e,d,\Theta)$ and magnetic $H_{RMS}(u,e,d,\Theta)$ field strengths were recorded in a look-up table for distances (d) of 0.1 to 1.0 m from the electrodes. These represented values for standard treatment configurations e, either a capacitive contraplanar arrangment or one of the range of inductive electrodes, with unit u, in direction Θ. Multiplication factors $T_E(d,\Theta)$ and $T_H(d,\Theta)$ were derived to convert from the contraplanar arrangement on Ultratherm 708S and Curapuls 419 units to other capacitive configurations on these, and other 27 MHz units. Of capacitive shortwave treatments 93% were carried out on these two models. Factors were derived for each machine to correct for differences due to the power ($P(u)$) settings used. For a given treatment, the electric and magnetic field strengths $F_E(u,e,d,\Theta)$ and $F_H(u,e,d,\Theta)$, at distance d and in direction Θ, could be calculated from equations of the form:

$$F_E(u,e,d,\Theta) = E_{RMS}(u,d,e,\Theta)\ T_E(d,\Theta)\ P(u) \tag{4}$$

The data on machine settings, physiotherapist positions during treatment and field strengths were used to calculate typical electric and magnetic field exposures for each treatment.

3. Results

The twenty physiotherapy departments studied operate 36 diathermy units, details of which are given in table 1. Most continuous wave (CW) units were purchased in the 1970s and early 1980s. In 1981 departments began to acquire pulsed shortwave units and all new equipment purchased in the past five years has been of this type. Thirteen departments have single units, which are used in rooms large enough to enable the physiotherapist to stand 1 - 2 m from the electrodes. In the other departments, several units are operated in a single room with cubicles 2 - 2.2 m across, partitioned by curtains. Physiotherapists treating patients in one cubicle could sometimes be within 1 m of the electrodes in an adjacent one. In 1988, about 33,500 treatments were carried out in Grampian Region using this equipment. Of these treatments 27% were shoulders, 26% spine and back, 19% knee and 11% neck. Of the treatments 76% used pulsed 27 MHz fields, 22% used CW 27 MHz, 1% CW 434 MHz, and 0.4% used 2.45 GHz. Treatment times were between 5 and 25 min, with an average of 14 min.

Table 1. Therapeutic diathermy equipment operated by Grampian Health Board.

Model	Make	Frequ. (MHz)	Pulsed or cw	Electrodes	No. of units	Date of purchase	Pulse length (μs)	Pulses pers (s^{-1})
Megatherm Jnr Mk 5	EMS	27.12	cw	C / I	5	1970s		
Ultratherm 608	Siemens	27.12	cw	C / I	4	1970s		
Ultratherm 708S	Siemens	27.12	cw	C / I	5	1976-82		
Sieretherm 609S	Siemens	434.92	cw	C / I	1	1981		
Erbotherm 1100P	Erbe	27.12	Pulsed	C / I	1			10-100
Curapuls 419	Enraf-Nonius	27.12	Pulsed	C / I	17	1981-88	32	15-200
Megapulse	EMS	27.12	Pulsed	I	3	1980s	20-400	100-800
Microtron 200	EMS	2456	cw	R	3	1979		

C - capacitive, I - inductive, R - radiative

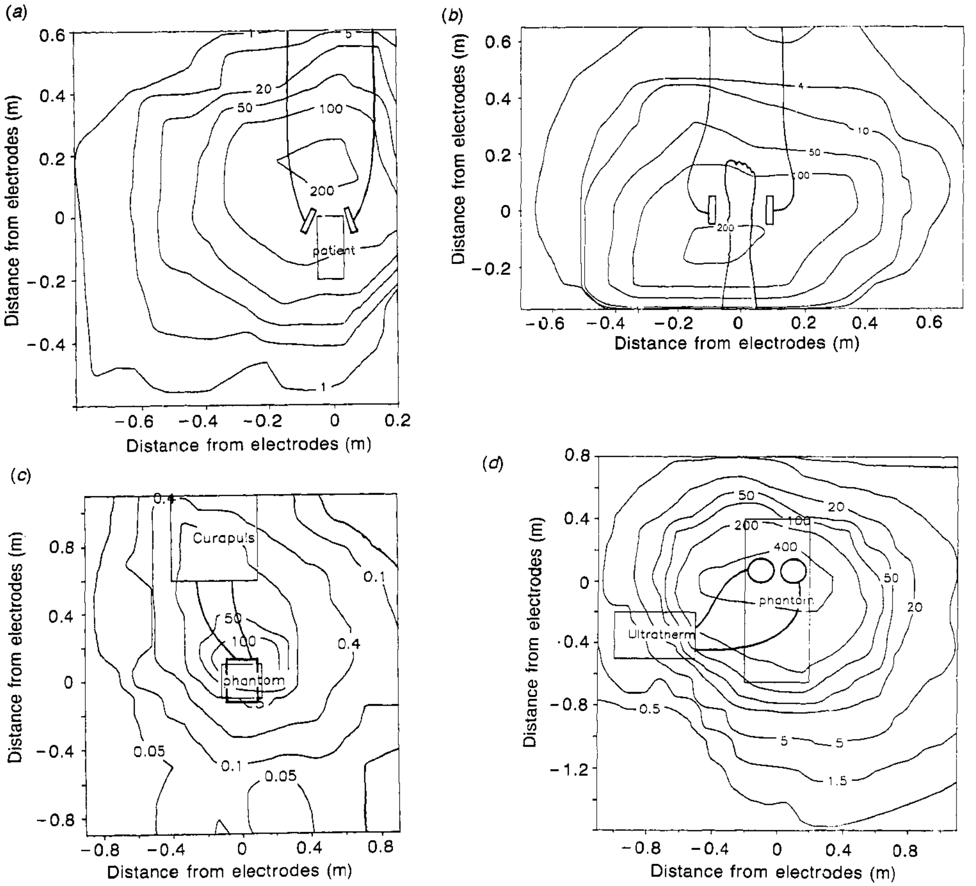

Figure 1. Time averaged stray electric fields $\sqrt{[(E^2)_{av}]}$ in V m^{-1} during two patient treatments using a Curapuls 419 with contraplanar electrode arrangements, (*a*) a shoulder treatment (power 6, pulse 26), (*b*) an ankle treatment (power 3, pulse 26); and two phantom treatments, (*c*) a shoulder treatment with a Curapuls 419, using a hinged double inductive electrode called a Flexiplode (power 4, pulse 26), and (*d*) a coplanar treatment of a back with an Ultratherm 608 (power 3),

Contour maps were made showing the strengths of stray fields around different electrode configurations (figures 1 and 2), and plots of the fall in field strengths with distance were prepared from these data (figures 3 and 4). The plots show data for commonly used machine power settings, but possible values with other settings of CW units ranged from 0.5 to 1.5 times these levels. The fields from most CW shortwave equipment had a small 50 Hz ripple, but the CW output from Curapuls 419 units was modulated at 50 Hz. The pulse field strengths from pulsed 27 MHz equipment were similar to those from CW 27 MHz units (figures 3 and 4), but time-averaged values were much lower because the fields were only on for between a hundredth and a thousandth of the time (table 1).

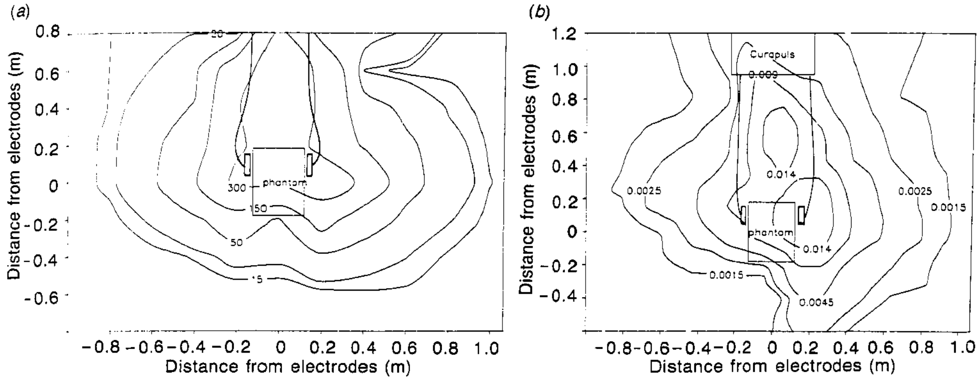

Figure 2. Time averaged electric (*a*) and magnetic (*b*) field strengths in V m^{-1} and A m^{-1} respectively, during a contraplanar treatment of a phantom with a Curapuls 419 (power 4, pulse 26).

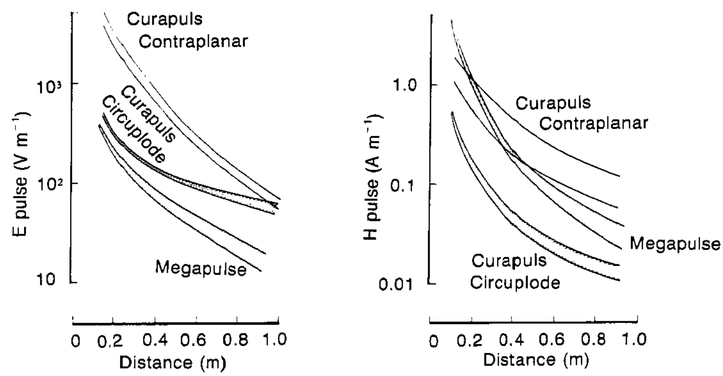

Figure 3. Electric E and magnetic H field strengths around pulsed diathermy units, derived from patient and phantom measurements. The data show RMS field strengths during pulses; for capacitive treatments with (light shading) a Curapuls 419 unit (power setting 4), and for single electrode inductive treatments with a Megapulse (medium shading) and a Curapuls Circuplode (power setting 4) (dark shading).

At distances of 0.15 - 0.2 m from the electrodes, the electric field strength for CW shortwave equipment was generally over 500 V m^{-1} and sometimes as high as 5000 V m^{-1} for capacitive treatments, but usually less than 200 V m^{-1} when inductive applicators were used. The electric field strengths varied by factors of 2 - 3 in different directions from the electrodes, and could be reduced by a factor of 10 or more in regions shielded by a patient's body (figure 1(*a*)). However, fields from different units of the same type with similar electrode configurations, were usually within a factor of 2 for both patients and phantoms, except in regions shielded by the body. In capacitive configurations, magnetic field

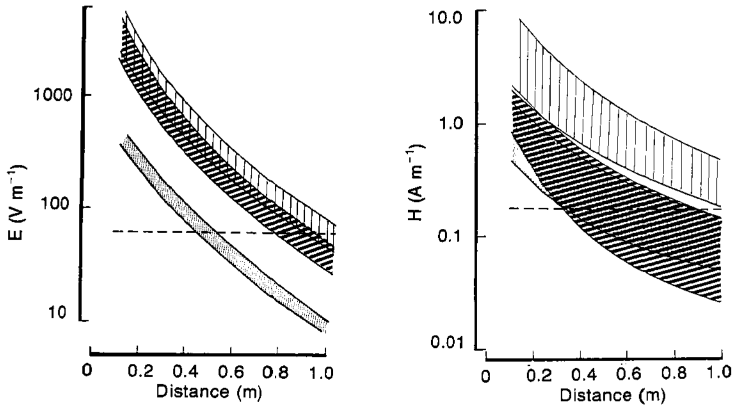

Figure 4. Variation in electric E and magnetic H field strengths with distance from the electrodes derived from patient and phantom measurements; for a Megatherm Jnr Mk 5 used for shoulder treatments (power 4) (vertical shading), and an Ultratherm 708S (power setting 3) used for shoulder treatments (diagonal shading), and wrist treatments (dotted shading). The horizontal dashed lines indicate the NRPB whole body reference levels.

strengths were 0.5 - 2.0 A m^{-1} at 0.15 - 0.2 m from the electrodes. Variations in magnetic field strength with direction from the electrodes were often as large as 20 (figure 5), because of the high magnetic fields associated with the cables (Stuchly *et al* 1982, Lau and Dunscombe 1984). An experiment in which fields were measured perpendicular to the cables of a Curapuls Unit (figure 6) showed that the magnetic field near the centre of the

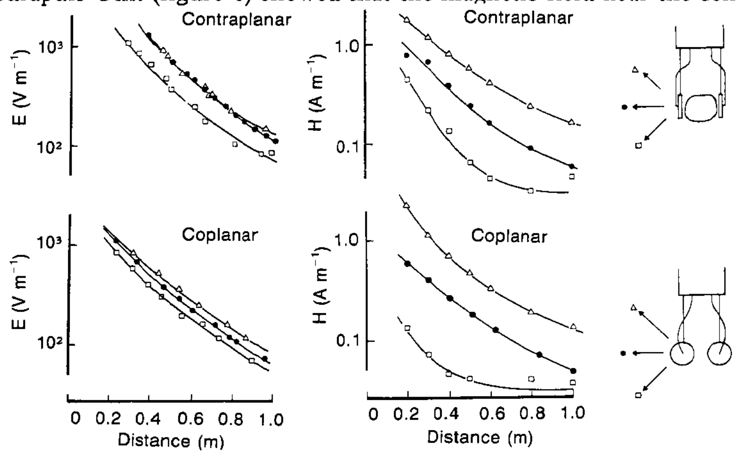

Figure 5. Variation in electric and magnetic field strengths with distance from the electrodes of an Ultratherm 708S shortwave diathermy unit in three directions, for contraplanar and coplanar configurations (power setting 3).

cable was four times greater than that near the electrode. Many other factors also affect the magnitudes of stray fields of which a few examples are given for capacitive treatments. The separation between the electrodes and the body surface was typically about 20 mm, but increasing the distance from 10 to 30 mm raised both the electric and magnetic field strengths close to the electrodes by 10 - 30%. Replacing 140 mm diameter electrodes with 64 mm diameter ones during a capacitive treatment of a large phantom, almost doubled the magnitude of stray fields at the rear of the electrodes. When the electrodes are close together, as in a contraplanar treatment of a flat wrist, the stray electric fields are smaller than for a shoulder treatment (figure 4), but when the electrodes are moved further apart but used to treat a smaller tissue volume such as the knee, the stray electric fields are larger.

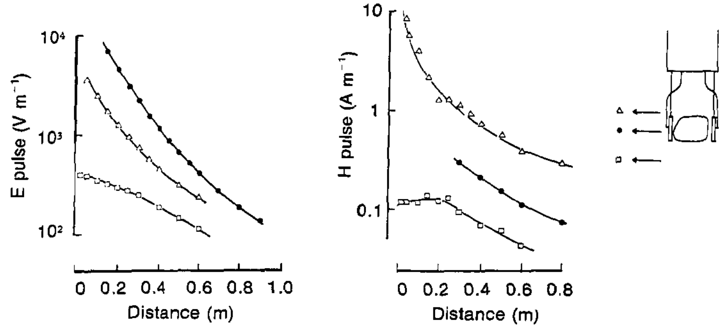

Figure 6. Plots of pulse electric and magnetic field strengths perpendicular to the cables of a Curapuls 419 during a contraplanar treatment of a phantom, with the cables extended in the horizontal plane (power setting 4).

Variations in power density with distance from microwave applicators are shown in figure 7. The range of power densities resulted from the directional variation shown in a three dimensional plot of power density (figure 8). The plot also shows a standing wave pattern typical of those detected around these units.

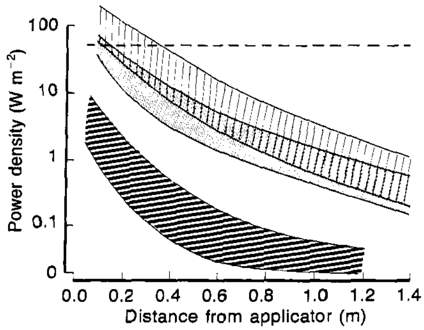

Figure 7. Variation of the power density in stray fields from a Microtron 200 (2.45 GHz) with distance from the applicator; for a 210 × 120 mm rectangular applicator at 50 W (vertical shading), an 80 mm diameter cylindrical applicator at 10 W (dotted shading), and a hand-held 35 mm diameter applicator for localised superficial treatments (diagonal shading). The horizontal dashed line represents the NRPB reference level for whole body exposures.

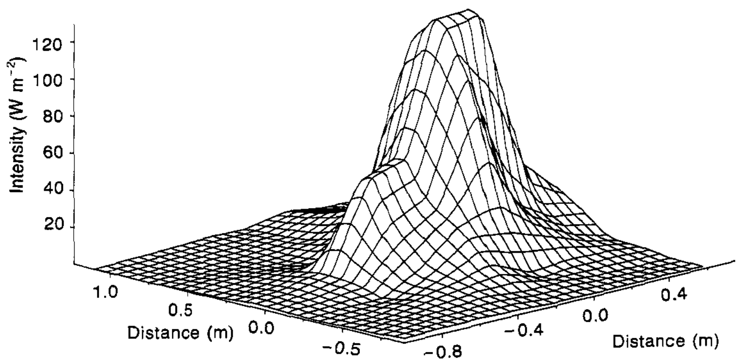

Figure 8. Three dimensional plot of the power density distribution in the horizontal plane around a whole body phantom irradiated with 2.45 GHz radiation from a Microtron 200 (power 50W) with a 210 × 120 mm rectangular applicator.

Data on machine settings and physiotherapist positions during 27 MHz treatments were combined with field data to calculate electric and magnetic field exposures. Physiotherapists often moved to about 0.5 m from the electrodes for periods of 30 s - 2 min to reassure a patient and occasionally moved as close as 0.2 m, but most of their time was spent at distances over one metre from the units. The results were divided into three groups; cw capacitive, pulsed capacitive and pulsed inductive treatments, and drawn in the form of histograms which represent the average time an operator was exposed to different field strengths during a typical treatment (figure 9). The values given are those at the height of

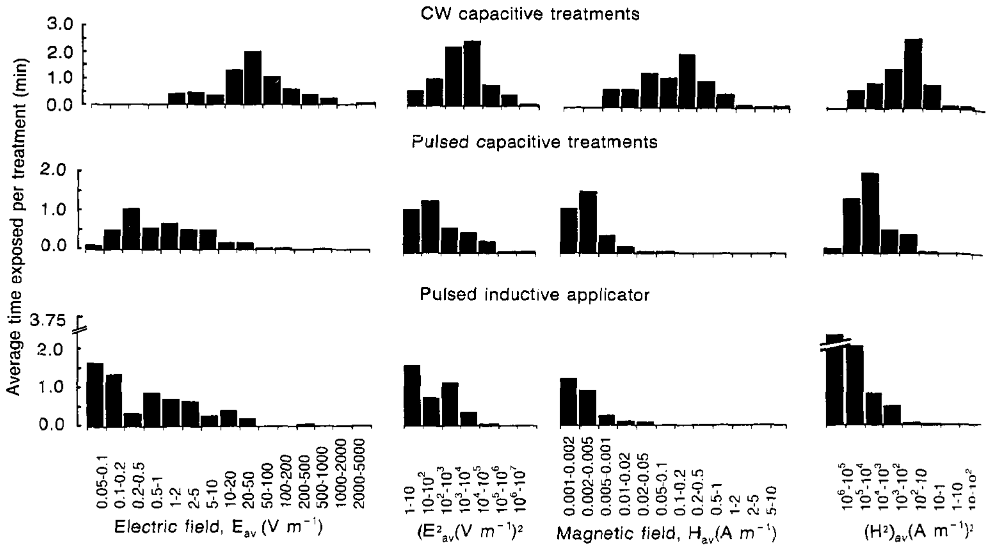

Figure 9. Histograms showing the average exposure of the operator to different electric and magnetic fields during 27 MHz diathermy treatments. Data is given for electric and magnetic field strengths (E_{av} and H_{av}), and the squares of each ($(E^2)_{av}$ and $(H^2)_{av}$). The three treatment categories are cw capacitive (Ultratherm 708S and 608, Megatherm Jnr Mk 5 and cw Curapuls 419), pulsed capacitive (Curapuls 419) and pulsed single electrode inductive (Megapulse and Curapuls Circuplode). The results were derived from analysis of 119, 201 and 101 treatments respectively.

the electrode. They do not take account of factors which affect the specific absorption rate (SAR) for energy in an electromagnetic field, such as absorption and distortion of the field by the operator or the orientation of the operator (Guy 1987), nor do they give a whole body exposure. They do, however, provide a picture of typical field strengths in which a physiotherapist might work. The electrodes are usually between knee and waist height. The squares of the field strengths at eye level were less than 1% of the values at the height of the electrodes at distances of 0.2 - 0.3 m, 2 - 4% at 0.5 m, and 30 - 40% at 1 m. Thus the exposure of physiotherapist's eyes is not usually large, but that of the patient's eyes may be more significant.

4. Discussion

Recent publications by the IRPA/INIRC and NRPB recommend exposure levels for occupationally exposed workers and members of the general public. They do not apply to patients undergoing treatment using the techniques. The IRPA/INIRC (1988) recommend occupational exposure limits for 27 MHz radiation based on an SAR of 0.4 W kg^{-1}, which for a plane wave, corresponds to electric and magnetic field strengths of 61 V m^{-1} and 0.16 A m^{-1} respectively. This is a whole body exposure averaged over any six minute period. NRPB (1989) have recommended reference levels for exposure, based on the IRPA/INIRC findings, of 61.4 V m^{-1} for electric fields of 27 MHz and 0.18 A m^{-1} for magnetic fields. They also recommend that peak SARs in any 0.1 kg of an internal organ or tissue averaged over a period of six minutes should not exceed 10 W kg^{-1}. These recommendations could be implemented in a similar manner to the ionising radiations limits (Bandle 1989), although the levels differ in that they are set to avoid physical effects, rather than reduce long-term risks to health. Field strengths above the whole body levels extend 0.5 - 1.0 m from CW shortwave equipment (figure 4), and 0.3 - 0.5 m from electrodes of Curapuls and Erbotherm units operated in contraplanar modes at low or medium pulse settings. While field strengths above the recommended levels rarely extended for more than 0.2 m from the electrodes and cables of Curapuls and Megapulse inductive applicators even with the highest settings. IRPA/INIRC (1988) suggest that the average power density in a pulse should not exceed 10,000 W m^{-2} at 27 MHz, which would correspond to electric and magnetic field strengths of 1950 V m^{-1} and 5 A m^{-1} respectively in the far field. Fields of this magnitude only extend for 0.1 - 0.2 m from the electrodes of Curapuls units (figure 3) on typical treatment settings, and even with the highest power settings only extended to 0.3 m from the electrodes.

Operators were exposed to fields above the recommended levels for an average of 2 - 3 min during a CW treatment (figure 9). Occasional exposures to fields 10 - 50 times the recommended whole body levels occurred when physiotherapists moved close to the electrodes or cables of CW equipment. These exposures were localised and never exceeded one minute, so the whole-body exposures would be substantially lower. However, such exposures could approach both the whole-body limits and the local exposure levels recommended by the NRPB (1989). Physiotherapists should, therefore, be advised to remain at least 1 m from the electrodes and cables of CW equipment during a treatment, and emphasis placed on the need to avoid approaching within 0.5 m even for short periods when the field is switched on. Positioning of the equipment so that the operator does not have to walk past the electrodes in order to reach the control panel can assist in reducing this exposure. Electric fields could be reduced by screening the cables, but magnetic fields from capacitive arrangements are more difficult to limit with the current design of equipment. Operator exposure from pulsed shortwave diathermy was much less than from CW, and on low and medium pulse settings sufficient protection was offered by not approaching within 0.5 m of the electrodes and cables. However, all the pulsed units could be operated in CW mode and under these circumstances, precautions similar to those in CW shortwave equipment are advisable.

The IRPA/INIRC (1988) recommend further exposure limits for the general public for 27 MHz electric fields of 27.5 V m^{-1} and magnetic fields of 0.073 A m^{-1}. However, the occupational exposure limits are designed to take account of all effects, and so the NRPB do not recommend that lower levels be applied to exposure of members of the public except in areas of uncontrolled access, or where there is a danger of electric shock or burn (NRPB 1989). It is often the practice in physiotherapy departments to treat patients in adjacent cubicles, and under these circumstances compliance with the NRPB recommendations can be achieved by ensuring that other patients and physiotherapists are 1 m from the electrodes and cables of CW diathermy equipment.

The reference level for exposure to 2.45 GHz radiation is a power density of 50 W m^{-2} (NRPB 1989). Fields of this magnitude extend for 0.1 - 0.5 m from the applicators of the Microtron 200 in agreement with results reported by Moseley and Davison (1981).

However, because of standing waves, localised hot spots could occur at distances up to 1 m. In the treatments monitored, the average time for which an operator was exposed to fields above this level was less than 10 s per treatment, substantially less than for CW shortwave units.

Conducting material concentrates electromagnetic fields and can cause local heating of nearby tissue. Metallic objects on patients' clothing should be removed, and parts of the body containing metallic implants should where possible be excluded from the region to be treated. Patients should also not be able to come into contact with earthed conducting objects such as metal couches or tables which may provide alternative pathways to earth for the diathermy current, as well as modifying the field distribution.

Links have been suggested between a variety of bio-effects and electric and magnetic fields, and in recent years evidence has been found for an association between leukaemia clusters and exposure to low frequency magnetic fields (Wertheimer and Leeper 1979, 1982, Coleman and Beral 1988): however, there is insufficient data for an assessment of health risk. These studies together with investigations into effects on cells (Byus *et al* 1987, Phillips *et al* 1986) suggest that lower frequency EM fields, or fields modulated at these frequencies, may be more biologically active. The cases investigated in the leukaemia studies were for prolonged exposure to fields of the order of 0.1 - 1.0 A m^{-1}. These field strengths are similar to those in pulses from Curapuls and Megapulse units at distances of 1 m. The largest low frequency fields result from the Curapuls 419 used in CW mode, where the 27 MHz signal is modulated at 50 Hz. However, the exposure times for all these fields are many orders of magnitude less than those in the leukaemia studies, and so are unlikely to pose a long term health risk on the basis of current evidence.

5. Conclusions

The study has shown that during diathermy treatments physiotherapists are only exposed to RF fields for relatively short periods of time, and the exposure levels are below those recommended by the IRPA/INIRC (1988) and NRPB (1989). Short exposures to high fields can occur when physiotherapists move close to an electrode and are more significant than exposures received by operators standing 1 - 2 m from the equipment. Emphasis should be placed on the need to avoid moving to within 0.5 m of the electrodes or cables, and maintaining a distance of at least 1 m when talking to a patient during CW treatments. Fields from pulsed diathermy equipment are much lower than from CW units and significant hazard only results from exposure within 0.5 m of the electrodes and cables.

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