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2004 Phys. Med. Biol. 49 2999

(http://iopscience.iop.org/0031-9155/49/13/016)

INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **49** (2004) 2999–3015 PII: S0031-9155(04)74787-9

An evaluation of safety guidelines to restrict exposure to stray radiofrequency radiation from short-wave diathermy units

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Received 15 January 2004
Published 17 June 2004
Online at stacks.iop.org/PMB/49/2999
doi:10.1088/0031-9155/49/13/016

Abstract

Short-wave diathermy (SWD), a form of radiofrequency radiation used therapeutically by physiotherapists, may be applied in continuous (CSWD) or pulsed (PSWD) mode using either capacitive or inductive methods. Stray radiation emitted by these units may exceed exposure guidelines close to the equipment. Discrepant guidelines exist on a safe distance from an operating unit for operators and other personnel. Stray electric (*E*-field) and magnetic (*H*-field) field strengths from 10 SWD units in six departments were examined using a PMM 8053 meter and two isotropic probes (EP-330, HP-032). A 5 l saline phantom completed the patient circuit. Measurements were recorded in eight directions between 0.5 m and 2 m at hip and eye levels while the units operated at maximum output and data compared to current guidelines. Results found stray fields from capacitive CSWD fell below operator limits at 2 m (*E*-field 4.8–39.8 V/m; *H*-field 0.015–0.072 A/m) and at 1 m for inductive CSWD (*E*-field 0–36 V/m; *H*-field 0.01–0.065 A/m). Capacitive PSWD fields fell below the limits at 1.5 m (*E*-field 1.2–19.9 V/m; *H*-field 0.002–0.045 A/m) and at 1m for inductive PSWD (*E*-field 0.7–4.0 V/m; *H*-field 0.009–0.03 A/m). An extra 0.5 m was required before fields fell below the guidelines for other personnel. These results demonstrate, under a worst case scenario, emissions from SWD exceed the guidelines for operators at distances currently recommended as safe. Future guidelines should include recommendations for personnel other than physiotherapists.

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1. Introduction

Short-wave diathermy (SWD) is an electrotherapeutic agent applied therapeutically by physiotherapists. It is a form of radiofrequency (RF) radiation that operates at 27.12 MHz and can be applied as either continuous short-wave diathermy (CSWD) or pulsed short-wave diathermy (PSWD). Treatment may be applied using either the electric field (capacitive method) or magnetic field (inductive method) component of the radiation, the method of application being dependent on the type of electrode chosen.

A relatively high level of SWD equipment ownership exists in Ireland (Shields *et al* 2001), the UK (Pope *et al* 1995), Australia (Lindsay *et al* 1990, Robertson and Spurritt 1998) and Canada (Lindsay *et al* 1995). The use of SWD has, however, declined among clinicians for several reasons including concern regarding its safety and, in particular, the possibility of adverse effects to equipment operators (Shields *et al* 2001). Research has suggested potential adverse health effects from excessive exposure to RF radiation, to the cardiovascular system, the nervous system, the eyes and the reproductive organs (Bernhardt 1992). For physiotherapists, the greatest concern is a potential adverse effect on pregnancy outcome. Case-control studies have investigated in physiotherapists the possible association between SWD exposure and both spontaneous abortion and congenital malformations (Taskinen *et al* 1990, Larsen 1991, Larsen *et al* 1991, Kallen *et al* 1992, Ouellet-Hellstrom and Stewart 1993, Lerman *et al* 2001). While these studies do not provide strong evidence of adverse delivery outcomes, two studies (Taskinen *et al* 1990, Lerman *et al* 2001) reported a statistically significant increase in the odds ratio of congenital malformation in pregnancies where the mother operated SWD equipment during the pregnancy.

The International Commission on Non-ionizing Radiation Protection (ICNIRP) has established limits to reduce RF exposure in workers and the general public. Since the absorption of RF radiation in the range 1–100 MHz leads to the generation of heat, exposure limits within this band are limited by heat tolerance and are accordingly based on the rate of energy absorption as measured by the specific absorption rate (SAR). Human-based research established that a 1 °C increase in body temperature was produced when humans were exposed to a SAR of 4 W kg^{-1} for 20 min. While human physiology can tolerate such a change, it was unclear whether a long-term elevation of body temperature of 1 °C would cause adverse effects. Therefore, the basic safety limit for RF radiation exposure at 27.12 MHz was established by reducing this exposure level by a factor of 10 to a SAR of 0.4 W kg^{-1}. The exposure is averaged over a 6 min period. Practically, SAR is difficult to determine so the more readily measurable quantities of unperturbed electric (E-field) and magnetic (H-field) field strength measurements are used. The derived E- and H-field strengths for a SAR of 0.4 W kg^{-1} are 61 V/m and 0.16 A/m respectively (ICNIRP 1998).

These limits apply to occupationally exposed individuals but were not considered appropriate for the general public. This was because the working population was considered homogeneous, comprising individuals of similar age and health status, while the general population was heterogeneous for these variables and were, therefore, deemed more susceptible to adverse health effects. Furthermore, workers were considered to be exposed to a maximum of the duration of their working day for their working life and were in a position where they could take precautions against exposure. In comparison, the general public were exposed 24 h a day for their lifetime and could not reasonably be expected to take precautions against exposure. The RF exposure limit was therefore further reduced for the general public by a factor of 5 equating to a SAR of 0.08 W kg^{-1} over any 6 min period. The derived limits were accordingly reduced by a factor of $\sqrt{5}$, equating to an E-field of 28 V/m or a H-field of 0.07 A/m. The latter limits would apply, for example, to administrative staff, physiotherapy assistants and patients who are not receiving SWD treatment.

The levels of stray RF fields close to SWD units have been shown to exceed exposure guidelines (Stuchly *et al* 1982, Lau and Dunscombe 1984, Tofani and Agnesod 1984, Skotte 1986, Coppell 1988, Martin *et al* 1990, McDowell and Lunt 1991, Tzima and Martin 1994, Lerman *et al* 1996, Li and Feng 1999). However, operator exposure can be significantly reduced through basic safety measures and broad recommendations on working practice have been made by four international associations: the British Chartered Society of Physiotherapy, the Australian Physiotherapy Association, the Australian National Health and Medical Research Council and the Department of Health and Welfare, Canada (DHW 1983, ANHMRC 1985, CSP 1992, 1994, Robertson *et al* 2001). Studies have shown that the level of stray radiation decreases sharply with distance from the operating equipment (Stuchly *et al* 1982, Martin *et al* 1990, Tzima and Martin 1994) so that occupational exposure is significantly reduced when physiotherapists remain at a discreet distance for the duration of treatment. Seven of the ten studies completed have advised on a safe distance that physiotherapists should remain from an operating SWD units (Stuchly *et al* 1982, Lau and Dunscombe 1984, Tofani and Agnesod 1984, Skotte 1986, Coppell 1988, Martin *et al* 1990, McDowell and Lunt 1991, Tzima and Martin 1994, Lerman *et al* 1996, Li and Feng 1999). However the recommendations made are disparate and vary between 0.2 m and 1.1 m, making it very unclear to physiotherapists which advice they should follow.

The recommendations of some of these studies are restricted by methodological limitations. For example, Li and Feng (1999) reported that overexposure only occurred at distances of less than 20 cm, however, this recommendation was based on measurements from only one unit and no details of the output intensities of the equipment during testing were given. In another study, McDowell and Lunt (1991) concluded that a distance of 0.5 m was adequate having examined two PSWD units operating at maximum output. However, their measurements were undertaken without a patient or phantom completing the equipment circuit. Furthermore, measurements were taken at 0.3 m and 0.6 m, with no actual measurements taken at 0.5 m.

The extent of stray radiation from SWD units is influenced by output intensity; the higher the output intensity, the greater the magnitude of stray fields emitted (Lau and Dunscombe 1984). Current guidelines are based on studies that measured the levels of stray RF fields operating at doses advised by physiotherapists working in the department where the study was completed. Since the doses selected were less than the maximum output, the results are only valid in the context of the doses tested. In addition, research by Shields *et al* (2003) found that the output intensity from SWD units was not constant between units of similar make and model or for different SWD models meaning that measurements taken from one SWD unit may not accurately reflect the output of other units. The possible levels of stray radiation from SWD units would, therefore, be better determined by data collected from a broad range of units in a variety of settings operating at the highest possible intensity.

Caution is warranted when translating research findings into guidelines for clinical practice to ensure that measurement error has been considered. Only one previous study (Skotte 1986), however, has allowed for measurement error in its calculations. The measurement error in the study was estimated to be of the order of 20%. This study, however, did not make a recommendation on a safe distance for operators to remain from SWD units. In contrast, the studies which have shaped the physiotherapy professional guidelines to date have not allowed a margin of error and therefore may not actually represent best practice for physiotherapists.

Research has consistently reported the highest levels of stray RF fields are found beside the electrodes and cables of SWD units (Stuchly *et al* 1982, Lau and Dunscombe 1984,

Table 1. Type and model of SWD units used for experimental tests.

Model	Manufacturers	Continuous (C) or pulsed (P) SWD	Electrodes	No. of units
Curapuls 970	Enraf-Nonius	C + P	Air-space or drum	3
Curapuls 419	Enraf-Nonius	C + P	Air-space or drum	2
Thermatur 200	Elecktromedizin	C + P	Air-space	1
Phyaction performa	Uniphy	P	Drum	1
Ultratherm 808	Siemens	C + P	Air-space or drum	1
Megapulse	EMS	P	Drum	1
Ultratherm 808i	Siemens	C + P	Air-space or drum	1

Coppell 1988, Tzima and Martin 1994). In spite of this, both the Department of Health and Welfare, Canada (DHW 1983) and the Australian Physiotherapy Association (Robertson *et al* 2001) guidelines advise physiotherapists to remain at least 1 m from the console and 0.5 m from the cables of operating SWD units, thereby allowing operators to position themselves closer to a functioning unit at the points where the highest stray field intensities are found. Thus, current guidelines are not necessarily based on best practice and their future development needs to be informed by up-to-date research in the area.

Unnecessary exposure from SWD units should be avoided among all persons in the physiotherapy department. Current guidelines do not include information on safe distances for workers employed in an area who are not physiotherapists (including administration staff and physiotherapy assistants) or patients who are receiving treatment other than SWD. An environmental survey of physiotherapy departments (Shields *et al* 2003) highlighted that situations can arise whereby these individuals could be working or be receiving treatment in an area next to an operating SWD unit. Guidelines (ANHMRC 1985) suggest it is the responsibility of the equipment operator to ensure these people are not exposed, but no data exist to aid physiotherapists determine what a safe distance from an operating unit is in this situation.

In light of the widespread availability of SWD treatment and the potential for overexposure of all personnel within a department, it was decided to undertake a study to determine the extent of stray RF fields around SWD units. The results would determine the safety advice that best serves both physiotherapists and other personnel within a physiotherapy department and whether amendments to current professional guidelines are needed. The output generated by these investigations would provide the basis for a revised code of practice and may also alleviate the fears associated with SWD.

2. Methods

2.1. Equipment tested

Ten SWD units in clinical use at six hospital-based physiotherapy departments were tested. All units operated at 27.12 MHz and the specific type of equipment and applicators tested are summarized in table 1. Each device was tested prior to the study using a quality control protocol developed for SWD units (Shields *et al* 2003) and all were found to be operating within the parameters proposed.

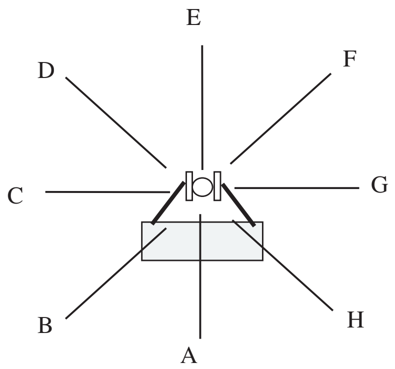

Figure 1. Points in the horizontal plane where field-strength measurements were taken.

2.2. Instrumentation

Field strength measurements were made using a PMM 8053 electromagnetic field meter with two isotropic probes (EP-330 and HP-032) to measure the *E*-field and the *H*-field respectively. Both probes were calibrated prior to data collection. The uncertainty of the meter was ±10%.

The international guidelines for occupational exposure to RF radiation are based on an averaging time of 6 min. Measuring field strengths averaged over a 6 min period would have greatly increased the time required for data collection. Therefore, a series of tests were completed that compared measurements taken over a 6 min period with shorter duration intervals of data collection between 30 s and 6 min. The *E*- and *H*-field emissions from a SWD unit (Enraf Nonius Curapuls 970) operating under four treatment set-ups (CSWD and PSWD using capacitive and inductive methods of application) were measured at 1 m from the unit. In all cases, the 30 s sample differed from the 6 min average value by no more than the sensitivity of the RF field meter, and therefore a 30 s sample was deemed sufficient for data collection (data not shown—available from the authors).

2.3. Positions of measurement

Measurements were taken in eight directions around the SWD unit (see figure 1). In each direction readings were taken at hip height and eye level to reflect the levels of exposure at the reproductive organs and head respectively at distances of 0.5 m, 1 m, 1.5 m and 2 m. Normative anthropometric measurements for women between 19 years and 65 years were used to determine the position for the vertical plane measurements which were 815 mm (hip height) and 1490 mm (eye level) respectively (Pheasant 1984). Female anthropometric data were chosen, as physiotherapy is currently a female dominated profession. The RF meter was positioned at each height using an adjustable wooden stand that was completely metal free.

2.4. Patient phantom

SWD units require a suitable load to tune, otherwise the RF radiation is emitted at a lower level (about 20% of normal capacity). It was considered inappropriate to undertake measurements during patient treatments for several reasons. A normal treatment session would be too short to complete all the 128, 30 s measurements that were taken. It would require the interruption of treatment every 30 s to enable the tester to change the position of the meter as doing so during treatment would expose them to excessive stray radiation. In addition, interrupting treatment could compromise treatment effectiveness. Other problems anticipated included ethical difficulties such as patient informed consent and the co-ordination of testing with appointment times. Finally, testing at maximum intensity levels would not have been possible and therefore it was decided the most appropriate method was to use a patient phantom.

The phantom needed to reflect as closely as possible a patient treatment set-up used. The ideal phantom would be a life-size mannequin equipped to replicate the physical and physiological characteristics of a human but such a phantom would be both difficult and costly to construct. The phantom had to be portable for transport between the participating physiotherapy departments and therefore a phantom replicating a human thigh was chosen. The volume of the phantom was 5 l as this was found to reflect normative data for human thigh volume (Martin *et al* 2000).

Chou *et al* (1984) described a phantom that simulated the conductivity and dielectric constant properties of muscle tissue at 27.12 MHz, which was initially considered for use in this study. However, despite rigorously following the procedures described in the published literature and supplemented with information from the original authors, the phantom developed did not display the conductivity properties of human muscle when tested by the National Physical Laboratory in London, UK. As a result, an alternate phantom needed to be chosen. Previous studies in this area used a saline phantom for testing, therefore it was decided to use a phantom that consisted of a 5 l plastic cylindrical container (height 32 cm, diameter 16.5 cm) containing 0.365% NaCl solution (saline). The conductivity of this solution (measured using a Metrohm 660 conductometer) was 6.08 mS cm^{-1} which reflected the conductivity of human muscle tissue (Lehmann 1990). The phantom was positioned at hip height beside the SWD unit using a wooden stand (figure 2).

2.5. Procedure

All measurements were recorded on-site in the physiotherapy department where the SWD units were located. The area around each unit was cleared and included only the equipment required to take the required readings. All machines operated at maximum power output for all set-ups thereby testing the 'worst-case' scenario. The four treatment set-ups tested were capacitive CSWD, inductive CSWD, capacitive PSWD and inductive PSWD. Each set-up was repeated four times to obtain data for both the *E*-field and *H*-field at the two vertical heights selected. The number of tests completed on each SWD unit was limited by the availability of electrodes. Two units were tested for only one set-up, four units were tested for two set-ups, one unit was tested for three set-ups and three units were tested for all four set-ups.

2.6. Reproducibility

The reproducibility of the field measurements was investigated prior to the main study. Three potential sources of error were anticipated (a) the test–retest reliability, (b) the reproducibility of positioning the RF field meter and (c) the reproducibility of repositioning the SWD unit. Each of the conditions was examined within the four treatment set-ups for both *E*- and *H*-field, when the RF meter was positioned at either 0.5 m or 1 m from the phantom, in seven directions (position A in figure 1 was not tested). Test–retest reproducibility was examined by three consecutive measurements and the co-efficient of variation ranged between 0.0% and 1.7%. The reproducibility of positioning (a) the RF meter and (b) the SWD unit were also examined and the co-efficient of variation ranged between 0.4–3.7% and 1.4–10.0% respectively. Therefore, variation in measurement was taken to be ±10% giving an overall measurement error of ±20% including the uncertainty of the RF field meter.

Figure 2. Phantom electrode configuration for testing the capacitive method (for the inductive method, the electrode was positioned at one side of the phantom).
(This figure is in colour only in the electronic version)

2.7. Guideline limits of exposure

The recorded measurements were compared with the guidelines proposed by ICNIRP (1998) for adult workers exposed to RF radiation and also for the general public.

3. Results

The extent and distribution of the stray RF fields were found to be related to the treatment set-up, therefore, the results are described relative to these.

3.1. Capacitive CSWD

Capacitive CSWD emitted the highest levels of stray radiation. *E*-field measurements were not taken at 0.5 m as at this distance the readings triggered the meter's in-built alarm, indicating the fields were high and would damage the probe. Therefore, data collection began at 1 m. Four units with large capacitive electrodes and four units with medium-sized electrodes were tested under these conditions.

As the distance from the unit increased, the *E*-field and *H*-field strengths decreased. At 1m the field strengths for units tested with large electrodes ranged 43.8–219.7 V/m and 0.03–0.27 A/m respectively. The corresponding data for units with medium-sized electrodes were

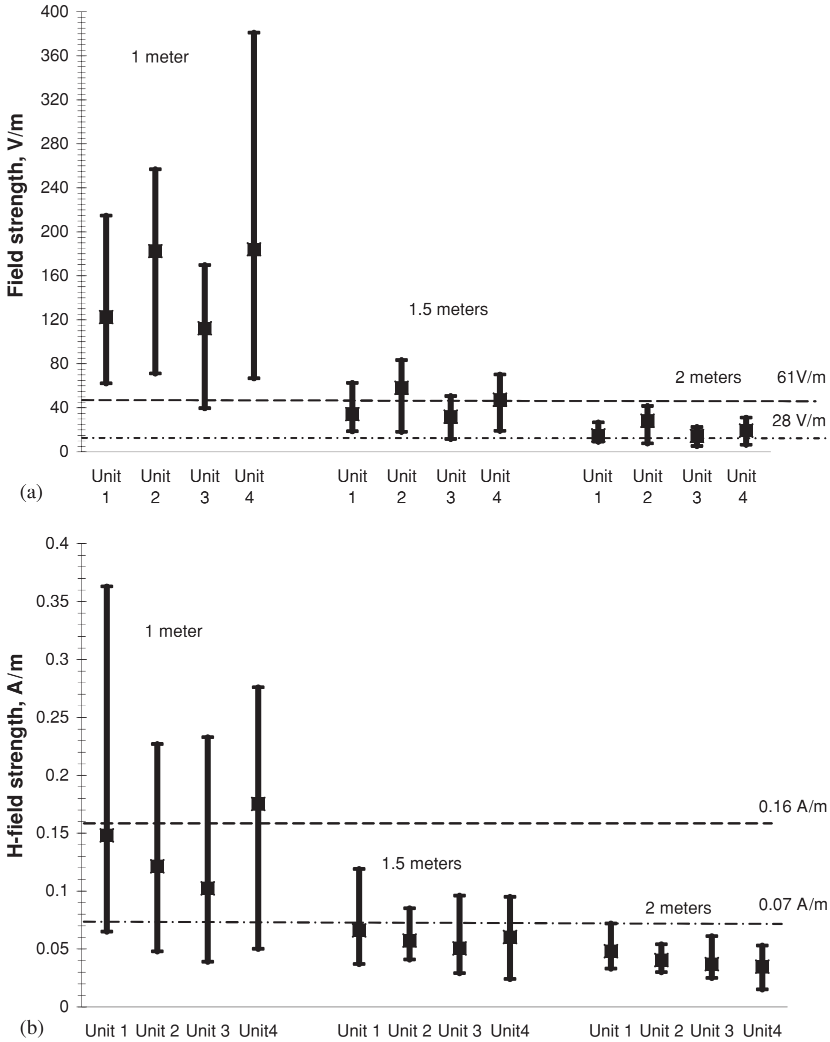

Figure 3. (a) The maximum, minimum and mean *E*-fields emitted by four capacitive CSWD units with medium-sized electrodes relative to the distance from the unit. (b) The maximum, minimum and mean *H*-fields emitted by four capacitive CSWD units with medium-sized electrodes relative to distance from the unit.

39.7–380 V/m and 0.04–0.36 A/m (figures 3(a) and (b)). Nearly all the *E*-field measurements taken at 1 m exceeded the guidance levels (61 V/m) (figure 4(a)). The highest *E*-fields were measured beside the electrodes (points C and G) and the highest *H*-fields were found close to the cables (points B and H) (figures 4(a) and (b)).

At 1.5 m, the *E*-field levels recorded were lower for units with large electrodes (12.1–62.5 V/m) than medium-sized electrodes (4.6–83.2 V/m). At this distance, while most of the *E*-fields measured were below the limits, the levels beside the electrodes (points C and G) still exceeded 61 V/m. All the *H*-fields measured at 1.5 m were less than 0.16 A/m (units with large electrodes 0.02–0.11 A/m; medium electrodes 0.02–0.12 A/m).

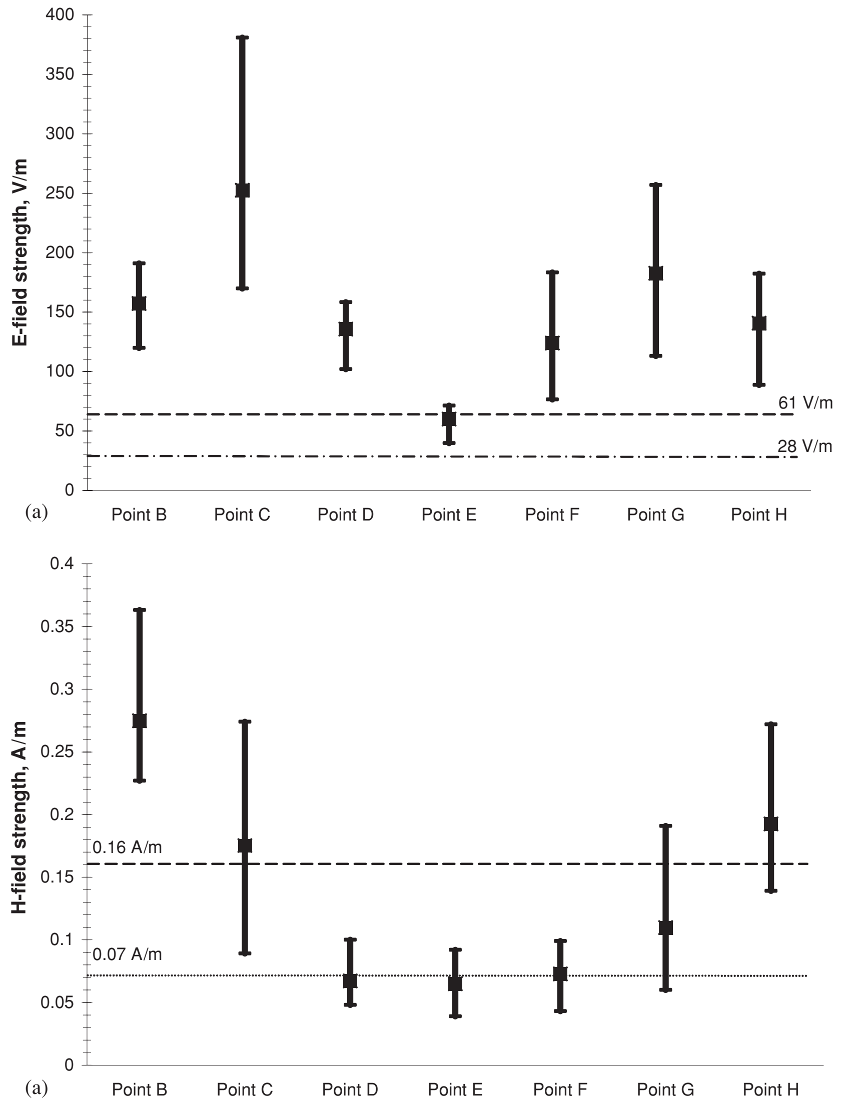

Figure 4. (a) The maximum, minimum and mean *E*-fields levels at points B–H, 1 m from capacitive CSWD units with medium-sized electrodes (measurements at point A were not taken due to the length of the units). (b) The maximum, minimum and mean *H*-field levels at points B–H, 1 m from capacitive CSWD units with medium-sized electrodes (measurements at point A were not taken due to the length of the units).

All field strengths were below the operator exposure limits at 2m (figures 3(a) and (b)). However, neither the *E*-field measurements (units with large electrodes 5.6–23.9 V/m; medium electrodes 4.8–39.8 V/m) nor the *H*-field measurements (units with large electrodes 0.02–0.06 A/m; medium electrodes 0.02–0.07 A/m) for capacitive CSWD were within the guidance values for the general public at 2 m when a measurement error of 20% was considered.

Since the horizontal distance between the field probe and the phantom was kept constant when testing hip height and eye level, the field strengths measured at eye level were lower

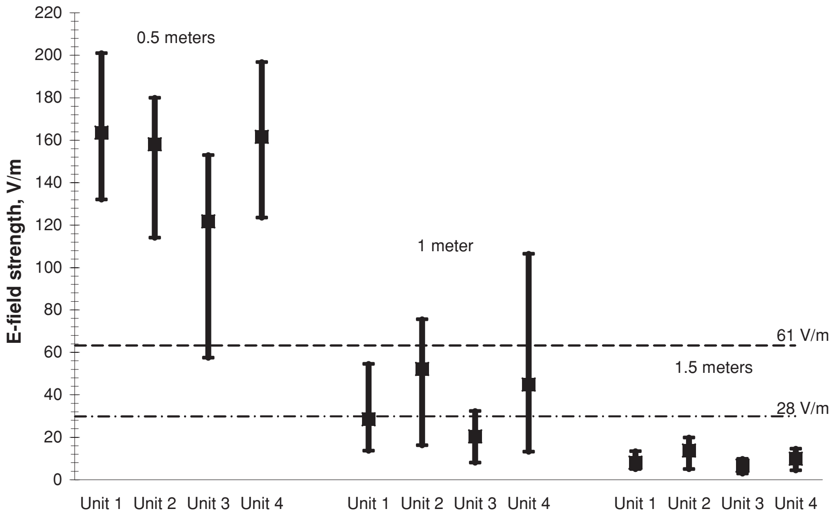

Figure 5. *E*-fields emitted by capacitive PSWD with medium-sized electrodes relative to distance from the unit.

than at hip height. The magnitude of this difference decreased with increasing distance from the unit and at 2 m the fields at hip and eye levels were similar.

3.2. *Capacitive PSWD*

The stray RF fields emitted by capacitive PSWD were measured using the same number and type of units tested for capacitive CSWD. All field levels decreased with increasing distance and the field strengths recorded at eye level were lower than those measured at hip level. Peak values were recorded at the same points as capacitive CSWD.

E-field measurements at 0.5 m were above the operator exposure limits for units using both large (81.4–318.8 V/m) and medium-sized electrodes (57.5–201 V/m) (see figure 5). The maximum *H*-field level from a unit with large electrodes at 0.5 m was 0.87 A/m and 1.729 A/m for medium electrodes.

The *E*-field guidelines were also exceeded at 1 m for units with large electrodes (9.4–83.1 V/m) and medium electrodes (8.1–106.5 V/m) but the *H*-field levels at 1 m were $<$0.16 A/m for units with large electrodes (0.02–0.1 A/m) and medium electrodes (0.01–0.11 A/m). All RF fields recorded at 1.5 m were below the limits of exposure for the general public.

3.3. *Inductive CSWD*

The inductive method produced significantly less stray radiation than the capacitive method. Analysis also found that inductive CSWD emitted less stray radiation than capacitive PSWD. Three of the four inductive CSWD units tested emitted stray fields below the occupational exposure guidelines at 0.5 m (*E*-field 0.6–27.8 V/m; *H*-field 0.035–0.1 A/m). The stray RF fields from a fourth unit, however, produced significantly higher fields throughout testing (see figure 6). At 1 m the field levels recorded for this unit were below the operator exposure guidance limits (*E*-field 0–36 V/m, *H*-field 0.01–0.065 A/m) but they continued to exceed the guidelines for the general public up to 1.5 m (*E*-field 0–7.4 V/m, *H*-field

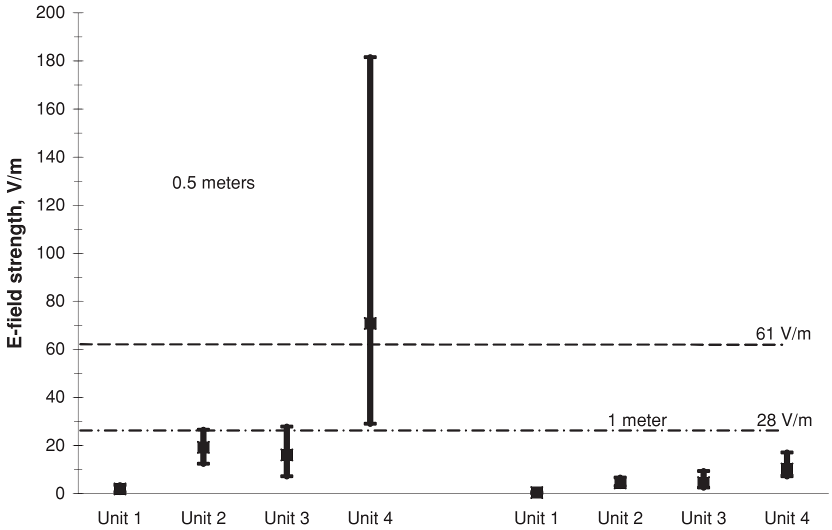

Figure 6. *E*-fields emitted by inductive CSWD at 0.5 and 1 m from the unit.

0.012–0.033 A/m). All field values recorded at eye level were significantly lower than those at hip level. The highest fields were measured beside the inductive electrode.

3.4. Inductive PSWD

Five units were tested for this set-up. Inductive PSWD produced the lowest stray fields of the treatment set-ups tested. The *E*-fields measured from four and the *H*-fields measured from three of the five units tested were below the occupational exposure guidelines at 0.5 m (figure 7). However, the *E*-fields and *H*-fields from two older inductive PSWD units were significantly higher and only fell below the guidelines for operators and members of the general public at 1 m (*E*-field 0–11.1 V/m, *H*-field 0.009–0.038 A/m). As with inductive CSWD, the peak field values were found beside the inductive electrode. All field values measured at eye level were significantly less than at hip level.

3.5. Comparison of the stray fields emitted with the unit power output

Three of the four categories included data from units identical in make and model. The fields emitted from these units were compared and differences were found. The stray radiation levels were therefore compared with the power output of the unit (as measured during the quality control testing prior to testing—data presented in Shields *et al* (2003)). This analysis revealed when two units similar in make and model were compared the levels of stray RF fields were generally higher in units with higher power output. When data were normalized, the stray output remained higher for some of the units with high output power although this was not the case for all pairs of units.

The levels of stray fields from units of different make and model operating under similar conditions also appeared to be very different. However, when the power outputs of these units were compared, the units with a higher output power did not necessarily emit the highest levels of stray radiation.

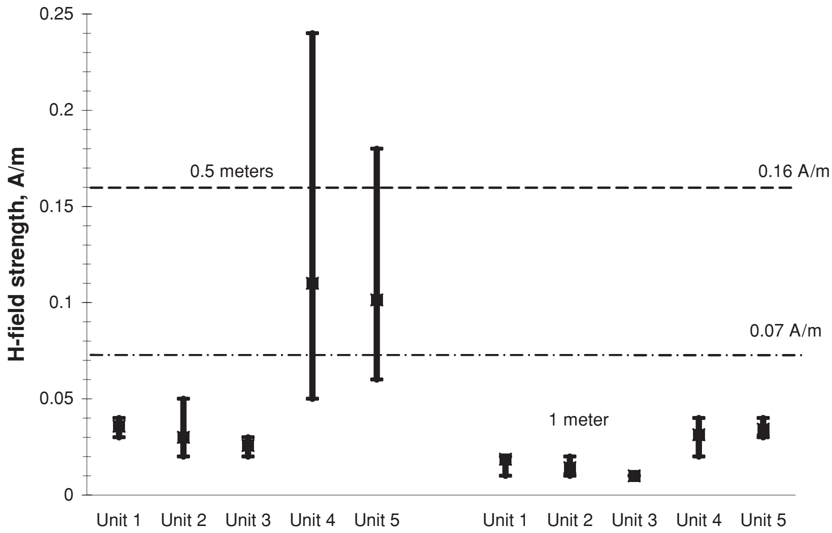

Figure 7. A comparison of the range of *H*-field values recorded for all inductive PSWD units at 0.5 m and 1.0 m from the unit.

3.6. Compatibility of SWD with other electrical equipment

The stray radiation from SWD units may also affect the functioning of electrical equipment, including other electrotherapy modalities. Current guidelines recommend that a level of immunity of 3 V/m would provide a reasonable margin of safety for equipment from sources of RF radiation. Since SWD units emit fields in excess of this level, it is important that other equipment in the vicinity is placed at such a distance as would prevent it failing or malfunctioning. The current results reveal that the levels of stray radiation from all modes and methods of SWD application are in excess of 3 V/m at 2 m. The predicted trend in the emitted fields, based on the worst-case data collected, suggests that field levels >3 V/m may extend up to 7 m from SWD equipment operating at maximum intensity (figure 8). Further research is required to determine whether this is in fact the case or whether the rate of decrease in field strength is greater than that predicted.

4. Discussion

The total number of units tested was greater than in previous studies (Stuchly *et al* 1982, Lau and Dunscombe 1984, Skotte 1986, McDowell and Lunt 1991, Tzima and Martin 1994, Li and Feng 1999), although Lerman *et al* (1996) examined 15 units and three other studies (Tofani and Agnesod 1984, Coppell 1988, Martin *et al* 1990) did not state clearly the number of units tested. Previous research concluded that CSWD produced higher stray fields compared to PSWD (Tzima and Martin 1994) and that capacitive treatments produced higher stray fields than inductive treatments (Lau and Dunscombe 1984, Tzima and Martin 1994). The current results concur with these findings. Tzima and Martin (1994) ranked the treatment set-ups of SWD in order of the levels of stray RF fields they emit. Capacitive CSWD was ranked highest followed by capacitive PSWD and inductive PSWD. The case of inductive CSWD was not examined. Results from the current study, however, rank inductive CSWD below capacitive PSWD.

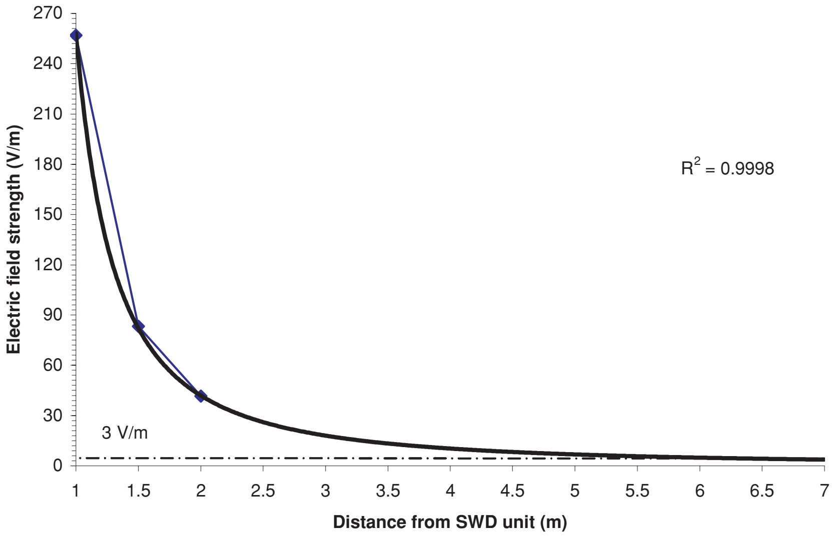

Figure 8. Predicted trend in stray fields emitted compared with electromagnetic compatibility levels.

This study was conducted using a patient phantom the rationale for which was outlined earlier. Only one study (Stuchly *et al* 1982) has compared clinical and laboratory measurements and concluded that they were well correlated, although no statistical results of this comparison were presented. As many clinical factors as possible were included in the current study by undertaking measurements on-site in physiotherapy departments where the units were normally used and by ensuring the phantom used to represent the patient had a conductivity as close as possible to human muscle conductivity.

The primary aim of this study was to determine the most appropriate distance for physiotherapists and the general public to remain when in the vicinity of an operating SWD unit. The results concluded that physiotherapists should remain at least 2 m from capacitive CSWD, 1.5 m from capacitive PSWD and 1 m from inductive CSWD and PSWD. For the general public greater distances were required. When capacitive PSWD and inductive CSWD are in use, other personnel should remain at 1.5 m and at 1 m from inductive PSWD. At 2 m stray fields from capacitive CSWD were still in excess of the guidance limits for the general public. Although no measurements were taken at 3 m, it may be inferred from the trend of decreasing field strength measurements between 1 m and 2 m that the levels of stray radiation would have dropped below guidance levels at 3 m (figure 9). Further research would be required for this to be determined absolutely.

These guidelines are conservative and are based on a 'worse-case' scenario. The ICNIRP guidelines (1998) permit time averaging of both electric and magnetic field strengths at frequencies >100 kHz over a 6 min period. While SWD units can give rise to exposures that exceed the ICNIRP reference levels, such exposure may not be continuous over a 6 min period (Allen *et al* 1994). Furthermore, the spatial distribution of electric and magnetic fields is highly non-uniform so that field strengths averaged over the whole body or parts of the body may be lower than those that would be expected to occur under uniform exposure to the local maximum field strength. The position of the SWD unit in the physiotherapy department is therefore critical. If this equipment is to be operated in a general departmental area due consideration needs to be given to its placement to account for stray radiation exposure,

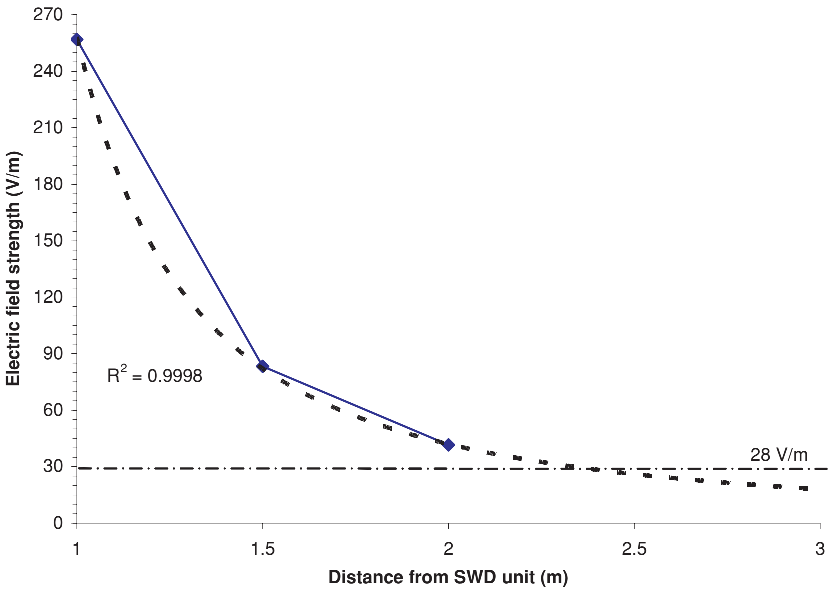

Figure 9. Predicted trend in electric field strength levels for capacitive CSWD.

particularly if it is to operate beside another cubicle where a patient not undergoing SWD treatment would be treated or beside a therapist's administration station.

The proposed changes to the guidelines are purposely conservative to allow for an error margin of 20% reflecting the uncertainty of the meter and reproducibility of the study set-up. This error margin is also important as although the magnetic field probe used (PMM HP-032) is specified for usage between 0.1 and 30 MHz, the manufacturer's data show significant drop off at 27 MHz. The probe has an absolute error of ±1 dB and a flatness between 1 and 25 MHz of ±1 dB. The drop off at 27 MHz is approximately −1 dB from the average value for the flat portion of the curve. Therefore, the probe may have underestimated the *H*-field measurements by about 25%. However, given that the *E*-field data were greater in magnitude than the *H*-field data and subsequently that the proposed guidelines are based on the *E*-field data rather than the *H*-field data, it is likely that the end result would have been similar had the accuracy of the probe been greater.

The distances recommended as safe for operators of SWD equipment to remain at are greater than those suggested by current standards and based on this study's findings, it is recommended that professional organisations consider amending their guidelines. The results also provide a good indication of what constitutes a safe distance for the general public including measures for those patients receiving treatment near an operating SWD unit but who are not receiving SWD treatment. A distance of 1.5 m from both methods of PSWD application and inductive CSWD would ensure exposure is below the guideline levels. Although definite evidence cannot be provided that a safe distance from capacitive CSWD is 3 m, based on the measurements taken and the trends in field strength measurements, this distance is probably adequate and should be confirmed by future research in the area.

Advice on the distance required to prevent malfunction of equipment due to electromagnetic incompatibility is beyond the scope of this study. Results show that a distance of 2 m is inadequate to ensure the safe operation of electrical equipment in the vicinity of operating capacitive CSWD. The predicted trend from the available data suggests that a distance up to 7 m may be required for the stray emissions to reach standard levels of immunity (3 V/m) but this requires further investigation.

Analysis of the points at which the peak fields were located found the highest *E*-fields beside the electrodes when the capacitive method was used. The peak *H*-fields for this method were found beside the cables. These results concur with previous authors who noted the cables attaching the electrodes to the SWD units were a source of high fields (Stuchly *et al* 1982, Lau and Dunscombe 1984, Coppell 1988, Tzima and Martin 1994). The Department of Health and Welfare, Canada (DHW 1983), the Australian National Health and Medical Research Council (1985) and the Australian Physiotherapy Association (Robertson *et al* 2001) guidelines all recommend that physiotherapists remain at least 1 m from SWD electrodes and 0.5 m from the cables. This advice would position physiotherapists closer to where the peak RF fields are found and therefore should be revised. Furthermore, despite studies repeatedly having noted the SWD cables as a source of significant stray radiation no changes have been made to the design of SWD units by the manufacturers. Future research should aim to reduce the field levels emitted from the cables through better shielding and equipment design. This is particularly important in light of earlier findings that the capacitive method is the most commonly used application method (Shields *et al* 2002).

RF measurements recorded for units with different sized capacitive electrodes differ from previous results. Lau and Dunscombe (1984) concluded that the level of stray *H*-fields emitted from SWD units increased with increasing electrode size. The current study compared the stray RF fields emitted by eight SWD units, four with medium-sized capacitive electrodes attached and four with large electrodes. The results found the units with large electrodes did not always emit the higher field levels. Therefore, electrode size is important when comparing the stray fields emitted by a single unit but when comparing multiple units, other variables including the type of units will influence the stray field levels to a greater degree.

When the RF fields emitted by similar SWD models were compared, the results found different levels of stray radiation. Further analysis revealed the stray fields emitted were related to the power output of the individual unit and since units of similar make do not emit the same levels of power output (Shields *et al* 2003), the levels of stray fields they emit will also differ. Accordingly, results from testing one unit of a particular brand for the level of stray radiation it emits cannot be extrapolated to other units of that type. Furthermore, when dissimilar models were compared for output power and stray fields emitted, results found the units with a higher power output do not always produce large amounts of stray radiation. Therefore, the only way of ensuring the exact amount of stray radiation emitted by an individual unit is to undertake measurements specifically on that unit. In these cases, the safety procedures used could then be adapted for that particular department. If such testing is unavailable then it is recommended that departments base their safety measures on the ‘worst-case’ scenarios presented herein.

5. Conclusion

The results from this study demonstrate the high levels of stray RF radiation that SWD units are capable of emitting under maximum output. The results conclude that physiotherapists should remain 2 m from capacitive CSWD, 1.5 m from capacitive PSWD and 1 m from inductive CSWD and PSWD. For members of the general public the recommended distance from capacitive PSWD and inductive CSWD is 1.5 m and 1m from inductive PSWD. For capacitive CSWD the guidelines for this group were still exceeded at 2 m but the trend in the measurements suggests that at 3 m the field strengths would have fallen below 28 V/m and 0.07 A/m respectively. None of the professional guidelines currently available, recommends distances of this order. No guidelines suggest limits for the general public and it is recommended that the distances reported herein are adopted and included in revised guidelines. This is important as previous work (Shields *et al* 2003) has demonstrated that SWD equipment is often operated in an open area of the physiotherapy department and therefore it is possible for another patient who is not being treated with SWD to be within the 2–3 m area of an operating SWD unit.

Two important findings regarding the influence of power output on stray electromagnetic radiation have been noted. The first is that similar units do not necessarily emit the same levels of stray radiation. The electric and magnetic fields emitted are related to the power output of the unit and since the power output varies between units so will the stray RF fields emitted. In some cases a discrepancy remained even when data were normalized. Secondly, the stray RF fields emitted by different SWD models with a similar treatment set-up are related to the type of model tested and not the power output of that model. In view of these findings it is recommended that on-site RF field testing is conducted in order that recommendations can be individualized to a department. If individual testing is unavailable, then the recommendations suggested herein could be adopted as an interim measure.

Acknowledgments

The following organisations are acknowledged for their financial support: Enterprise Ireland, Trinity Trust Foundation and Coyle Hamilton Bursary. The support of the physiotherapy departments that participated in the study is acknowledged.

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