Exposure of Non-Target Tissues in Medical Diathermy

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With different prevalence in different regions, radio frequency (RF) electromagnetic fields (EMF) are widely used for therapeutic tissue heating. Although short-wave diathermy (27.12 MHz) is the most popular treatment modality, quantitative data on patient's exposure have been lacking. By numerical simulation with the numerical anatomical model NORMAN, intracorporal distributions of specific absorption rates (SAR) were investigated for different treatment scenarios and applicators. Quantitative data are provided for exposures of target treatment areas as well as for vulnerable regions such as the eye lenses, central nervous system, and testes. Different applicators and distances were investigated. Capacitive and inductive applicators exhibit quite a different heating efficiency. It could be shown that for the same output power therapeutic heat deposition can vary by almost one order of magnitude. By mimicking therapist's practice to use patient's heat perception as an indicator for output power setting, numerical data were elaborated demonstrating that muscle tissue exposures may be several times higher for inductive than for capacitive applicators. Presented quantitative data serve as a guide for power adjustment preventing relevant overexposures without compromising therapy; they also provide a basis for estimating target tissue heat load and developing therapeutic guidelines. Bioelectromagnetics 31:12–19, 2010. © 2009 Wiley-Liss, Inc.

Key words: electromagnetic fields; specific absorption rate; short-wave; heat load

INTRODUCTION

Although with different prevalence in different regions, radio frequency (RF) electromagnetic fields (EMF) are one of the major modalities for therapeutic tissue heating in particular in treating muscle tissues and joints [DeLisa et al., 2004; Lin, 2006; Knight and Draper, 2008]. For medical applications, European EMF spectral management allocated certain frequencies such as 27.12 MHz (short-wave), 433.92 MHz (decimeter-wave) and 2.45 GHz (microwave). Among them short-wave diathermy (SWD) is most popular. It allows in-depth heating while microwave applications concentrate on superficial areas. SWD may be applied in continuous or pulsed mode using either capacitive or inductive electrodes. Its prevalence varies from region to region depending on the tradeoff between its benefits and disadvantages, compared to other modalities such as ultrasonic heating. It is widely preferred over ultrasound in Europe [Schlemmer et al., 2004]. The benefits of SWD are delivering in-depth heat into larger tissue regions without the need of manual application, while ultrasonic heating requires continuous movement of the applicator to avoid pain due to excess heating at bone/tissue interfaces which could potentially damage cellular membranes by cavitation. On the other hand, there are several contraindications using diathermy, in particular because of electromagnetic interference and excess heating of implanted metal parts such as pacemakers or leads of deep brain stimulators [FDA, 2002]. In spite of its frequent use, quantitative data on SWD-induced exposures are sparse and mainly restricted to invasive in vivo temperature measurements at a few selected spots [Draper et al., 1999; Garrett et al., 2000].

To prevent general population and workers from adverse health effects of RF-EMF, basic limits were set [ICNIRP, 1998; European Council, 1999] restricting the health-relevant intracorporal quantity of interference which in the RF range is considered the absorbed power per tissue mass (the specific absorption rate SAR) averaged over the whole body (whole-body SAR_{WB}) as well as over any 10 g tissue (local SAR_{10g}). In addition,

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reference levels of measurable field quantities have been derived from numerical calculations that allow conformity checking by external field measurements. SAR limit values were derived from exposures causing first health-relevant thermal effects such as the onset of thermoregulatory response. For occupational exposure, threshold values were lowered by a reduction factor 10 accounting for uncertainties such as interpersonal variability and dosimetry. This resulted in basic limits of $SAR_{WB} = 0.4$ W/kg for whole-body exposure and $SAR_{10g} = 10$ W/kg for local exposure. To account for different vulnerable groups such as children, the frail or elderly, these limits for workers were lowered by another fivefold leading to basic limits $SAR_{WB} = 0.08$ W/kg and $SAR_{10g} = 2$ W/kg for the general population.

Similar to other irradiation methods, heat delivered by SWD is not only restricted to the target region. However, so far investigations of unintended side-effects have concentrated on potential overexposures of nearby persons such as medical staff, or electromagnetic interference with medical devices, including implanted cardiac pacemakers, due to RF-EMF fields leaking from cables and electrodes [Moseley and Davison, 1981; Pinski and Trohman, 2002]. Field monitoring during diathermy practice and procedures [Pinski and Trohman, 2002] and measurement programs in the working environment [Stuchly et al., 1982; Martin et al., 1990; Li and Feng, 1999; Tuschl et al., 1999; Shields et al., 2004; Shah and Farrow, 2007] have demonstrated that RF-EMF stray fields may expose people near SWD devices to higher reference levels. Considerable excess of recommended exposure reference levels has been reported at distances up to 2 m for those occupationally exposed and 2.5 m for the general public [ICNIRP, 1998], depending on the type of applicator used. However, except for epidemiologic studies on potential adverse pregnancy outcome of medical staff applying, or pregnant women subjected to diathermy [Taskinen et al., 1990; Quellet-Hellstrom and Stewart, 1993; Lerman et al., 2001], to date, little attention has been given to unintended exposures of patients' regions outside the treatment area in particular to vulnerable regions such as eye lenses, gonads or the fetus.

Treated patients are exempted from general radiation protection regulations. Therefore, thermal overexposures outside target regions could be accepted if patient's benefits outweigh risks. However, this does not constitute a general carte blanche. The European Medical Devices Directive [European Council, 1993, 2007] requests minimizing patient's risks including those of unintended side effects by adequate device design and/or application rules. Although the risk of potential unintended overexposure outside the target region of diathermy-treated patients is known, except for vague recommendations to cautiously apply diathermy, specific rules of application are missing, not least because quantitative data are lacking. This article is intended to provide quantitative information on therapeutic heating efficiency and potential overexposure of vulnerable tissues outside the target region by mimicking conventional approaches of setting the power at maximum tolerable output.

METHODS

Within the patient, the thermal load induced by short-wave diathermy with capacitive and inductive electrodes was investigated using the numerical anatomical human model NORMAN [Dimbylow, 1997] which has been widely used for radiation protection dosimetry. It represents a 2 mm-voxelized 73 kg/176 cm man, segmented into 35 different tissues. Dielectric properties of tissues were based on in vitro investigations [Gabriel et al., 1996]. Numerical simulations were performed with the software package CST Microwave Studio® (Computer Simulation Technology GmbH, Darmstadt, Germany) which has been frequently used for EMF health risk assessment. It allows calculating intracorporal SAR distributions by solving Maxwell's equations with the finite integral method [Weiland, 1977]. Intracorporal SAR distributions and local SAR_{10g} values averaged over 10 g mass of contiguous tissues as recommended [ICNIRP, 1998; European Council, 1999] were calculated, the latter with a self-written algorithm.

Therapeutic applications such as treatment of head, shoulder, spine, hip, and knee that are used frequently and associated with exposures close to vulnerable regions were investigated. Simulated applicator positions were based on advice by physicians and the literature [Rentsch, 1985; Wenk, 2004; Omerspahic, 2007; Knight and Draper, 2008]. The antenna-skin distance rather than the enclosure-skin distance was used to characterize the applicator position. This was done to account for two facts. First, for different SWD devices the radiating antennas of commercial applicators might have different distances to their enclosures. Second, applicators might be placed at different distances to the skin so as to have space to put a folded towel in between skin and applicator housing [Wenk, 2004; Knight and Draper, 2008]. Since the antenna distance might vary, its influence on exposure was investigated. Numerical models of applicators (Fig. 1) were derived from commercial devices (SIEMENS, Erlangen, Germany), in particular capacitive electrodes (circular plates, 6.5 cm diameter) and inductive appli-

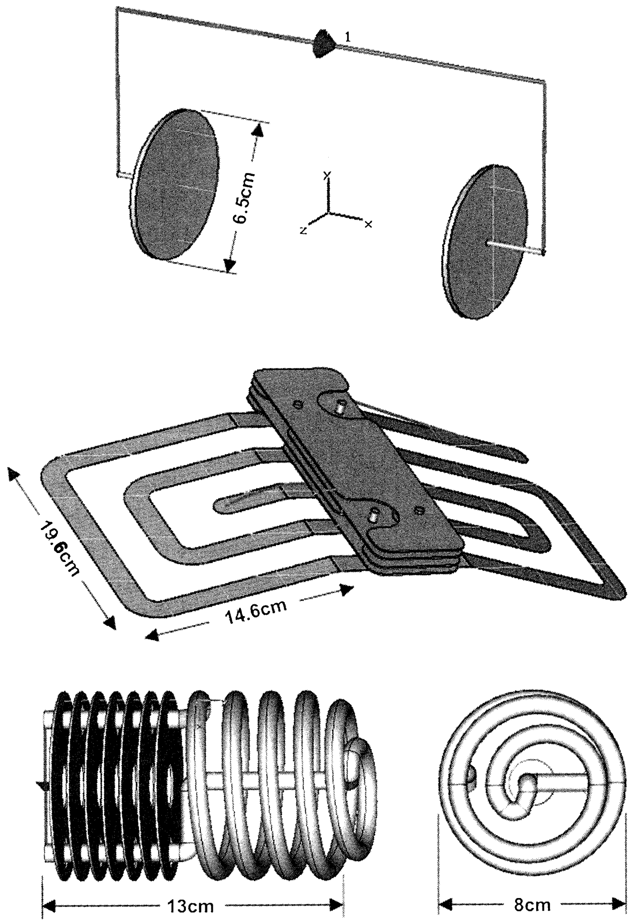

Fig. 1. Numerical applicator models for short-wave diathermy: capacitive electrodes (**top**), large inductive (Diplode, **middle**) and small inductive applicator (Minode, **bottom**).

cators (Minode, 8 cm diameter, 5 windings, and Diplode, 20 cm × 40 cm with 2.5 spiral windings and adjustable wings).

The impedance of the numerical electric source feeding the applicators was selected to fit the calculated RF-EMF distributions to real field measurements. The achieved agreement was better than 5%. Calculations were made for 500 W which is the maximum output power of diathermy devices permitted by the international standard of short-wave diathermy equipment [IEC, 1998; CENELEC, 1999].

RESULTS

It is self-evident that in practice, output power needs to be adjusted considering treatment site and individual characteristics of the patient. However, results can be easily downscaled from the maximum output power to other output settings because SAR values are linearly proportional to output power. Similar to practical application, radiating parts of applicators were positioned at a distance of 1.5 cm from the skin (head treatment) which corresponds to applicators contacting the skin, and 4 cm (hip, knee, and spine) which corresponds to applicator enclosures separated from skin by a folded towel (which is frequently attached to absorb perspiration). Calculated SAR distributions are shown in planes across the intracorporal SAR maximum for treatment of head, knee and spine (Fig. 2).

Head exposure, such as for paranasal sinus treatment, was performed by using small inductive applicators with the enclosure contacting the skin (with RF-EMF radiating inductive coils in some distance to the enclosure and, hence, to the skin). This treatment can be associated with relevant exposures of eyes and

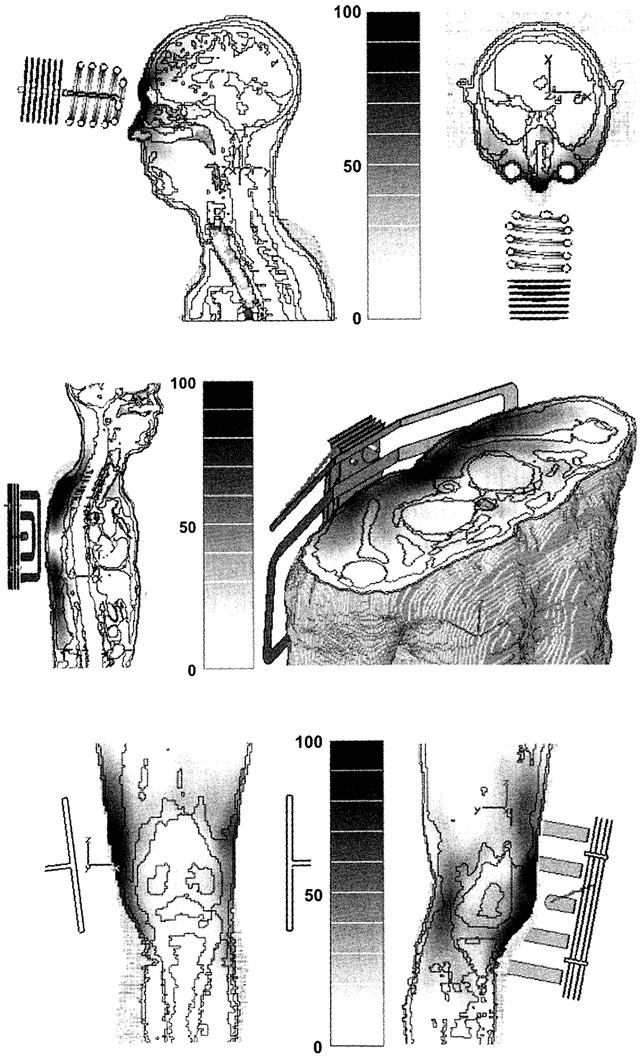

Fig. 2. Intracorporal SAR distributions during head, shoulder, and knee treatment of the adult man model NORMAN; linear gray scale normalized to the maximum SAR value.

brain (Fig. 2). Because of its higher water content [Duck, 1990] brain tissue is more highly exposed than the eye lens. Depending on the localization of the inductive applicator, local SAR_{10g} values of the eye lenses range from 3.5 W/kg (frontal position) to 6.1 W/kg (root of the nose position). The exposure of the brain does not critically depend on applicator positioning since the distance to the brain does not vary much. This is demonstrated by comparison of results of local brain SAR_{10g} values associated with frontal position (7.8 W/kg) and the root of the nose position (8.7 W/kg).

Treatment of the back may also lead to relevant exposures of the central nervous system (CNS), in particular the spinal cord, with higher exposures from capacitive electrodes than from inductive applicators. The maximum SAR values at 4 cm antenna distance are $SAR_{10g} = 6.5$ W/kg for capacitive and 1.5 W/kg for inductive applicators, respectively. However, it may increase by more than 2.5-fold in contact application.

Knee treatment is not associated with relevant overexposures of testes. Depending on the applicator used, local SAR_{10g} values are 0.36 W/kg for capacitive electrodes and 0.63 W/kg for inductive applicators, respectively.

Hip treatment in men (Fig. 3) may result in exposures of the testes of local $SAR_{10g} = 0.44$ W/kg for capacitive electrodes to 3.4 W/kg for inductive applicators, respectively, when antennas are positioned 4 cm from skin. However, results with the antenna close (5 mm distance) to the skin (corresponding to contact application) can result in local testicular SAR_{10g} values up to 5.8 W/kg.

Variation of applicator-skin distance was investigated for inductive and capacitive applicators. Results are presented in Figure 4. The dependence of tissue

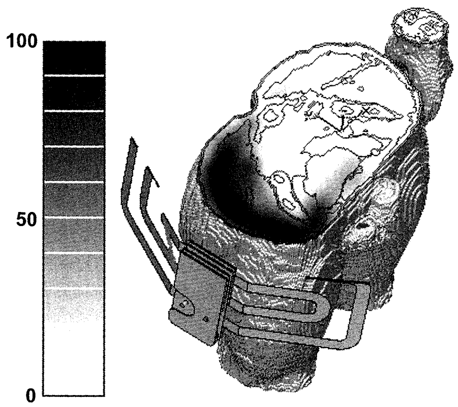

Fig. 3. Cross-sectional SAR distributions during hip treatment with an inductive applicator (Diplode) at the adult man model NORMAN (right), linear gray scale normalized to the maximum.

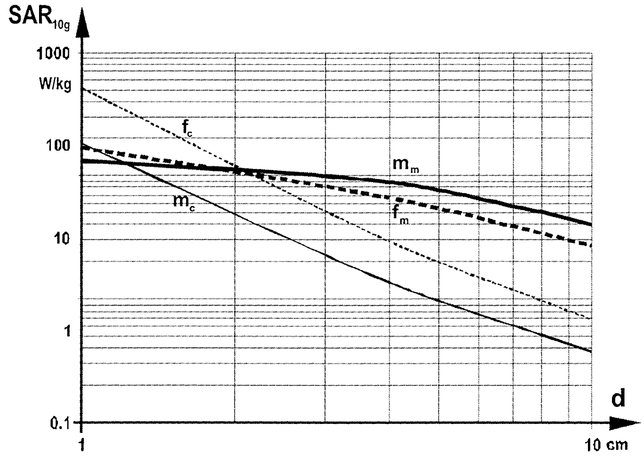

Fig. 4. Local SAR_{10g} maxima in muscle (*m*) and fat (*f*) tissue in dependence on distance (*d*) of active elements during hip treatment with inductive (index *m*) and capacitive applicators (index *c*).

heating on antenna-skin distance is more pronounced for capacitive electrodes. With increasing distance SAR values in both muscle and fat tissue decrease more rapidly (proportional to about $1/d^2$) for capacitive electrodes compared to inductive applicators, where SAR_{10g} decreases proportional $1/d$.

Figure 4 also shows the different efficiency of fat and muscle heating. Fat tissue exposure is about twofold higher compared to muscle tissue. Differences in tissue heating are less pronounced for inductive applicators, and the relationship changes with distance. At contact application (with distances of active elements less than 1 cm) fat is more highly exposed than muscle. However, with increasing distance inductive applicators cause up to 68% higher exposures of muscle tissue compared to fat.

DISCUSSION

Regulations limiting exposures of the general population are not directly applicable to medical treatment. Patients are explicitly exempted. As an example, in radiology it is common practice that X-ray imaging may be associated with doses well above exposure limits of the general population, and even higher exposures are applied in X-ray therapy. Likewise, diathermy exposures beyond general population's exposure limits must not be considered as violating radiation protection limits. However, they may need to apply the justification principle which demands that benefits should outweigh risks. In this article, recommended basic restrictions of local exposures of the general population ($SAR_{10g} = 2$ W/kg) were used as guidance to quantitatively identify the onset of unintended relevant exposures rather than as compliance criterion. In fact, it was found that regions of high local SAR_{10g} values may extend well beyond the target treatment area.

For this investigation, the anatomical model NORMAN ("normalized man") of a slim adult has been chosen because it represents an average European adult. This model is not an unusual choice; it is widely used for health risk assessment of exposures to electromagnetic fields in daily life and occupational environments. In regard to medical diathermy interpersonal differences in terms of anatomical variability, body size and fat thickness play a minor role, compared to the variability caused by the kind of applicator, its size, positioning and distance to the body. In short-wave diathermy cables feeding the applicators are unshielded and, therefore, cause additional leaking fields contributing to exposure both of patients and staff. Simulations did not account for contributions of such leaking fields because instructions for use require keeping cables away from the patient.

Similar to the approach of radiation protection bodies, vulnerable targets of unintended exposures were considered to be the lens of the eye (because of the impaired heat exchange and, hence, the increased thermal risk), the central nervous system (brain and spinal cord), and reproductive organs [ICNIRP, 1998]. Results show that if relevant exposures were encountered they were mainly associated with inductive applicators. Head treatment could cause overexposures of the eye lenses up to 3.8-fold and the CNS up to 4.4-fold of the exposure limit. During hip treatment with inductive applicators next to skin men's testes can be exposed up to 2.9-fold (Table 1). Limit values refer to 6 min averages. Since typical treatment times are 15–20 min [Knight and Draper, 2008] these limits can be applied. Results demonstrate that exposure reduction is possible without compromising treatment, in particular since different heating efficiency, depending on applicator type and distance, would allow achieving similar heating in the target region at reduced output power.

Quantitative results are summarized in Table 1. It can be seen that for the same output power (500 W) muscle heating at hip treatment with capacitive electrodes is lowest causing $SAR_{10g} = 17.5$ W/kg while the same power leads to 6.5-fold higher values when using an inductive applicator. Overall, muscle heating varies by 6.4-fold with local SAR_{10g} values ranging from 17.5 to 112.4 W/kg. This demonstrates that therapeutic heating efficiency varies considerably. For quantitative comparison, heating of muscle tissue at hip treatment (SAR_{10g} value) was chosen as reference. Consequently, to achieve the same SAR_{10g} values in treated muscle output power could be reduced when using capacitive electrodes. Potential power reduction factors are listed in Table 1, together with output power levels P_{po} associated with the onset of unintended exposures on vulnerable regions potentially exceeding reference levels.

Considerable EMF energy is also delivered to bone. It could amount up to 93% compared to muscle (back treatment with the inductive diplode applicator). Local bone SAR_{10g} values ranged from 4 to 21 W/kg (Table 1).

Overall, results demonstrate the systematic differences between capacitive and inductive electrodes: This can be explained by the different underlying physical principles.

Capacitive applicators cause intracorporal dielectric current densities S_i that are forced to flow across tissue layers from one electrode to the other, on their way heating tissues depending on their specific

TABLE 1. Maximum Local SAR_{10g} Values in Various Tissues of the Anatomical Adult Man Model NORMAN Associated With Different Diathermy Treatment Scenarios Using Maximum Permitted Output Power (500 W) and 4 cm Distance From Skin to Inductive Antenna or Capacitive Plates (at Head Treatment Antenna Distance = 1.5 cm Corresponding to Skin-Contact of the Applied Part)

Treatment	Appl.	SAR_{10g} muscle	SAR_{10g} fat	SAR_{10g} bone	SAR_{10g} skin	SAR_{10g} testes	SAR_{10g} lens	SAR_{10g} CNS	f_{muscle}	P_{po} W
Head	M	23.4	48.5	20.8	36.7	—	7.60	10.8	0.75	93
Back	D	32.0	19.0	17.6	7.0	0.015	0.041	1.8	0.55	500
Hip	D	112.3	83.6	11.2	29.9	4.19	—	1.19	0.16	239
Knee	D	43.6	52.7	16.1	49.8	0.79	—	0.02	0.40	500
Shoulder	C	28.0	81.4	7.8	43.3	0.001	0.008	0.19	0.63	500
Back	C	87.1	176.4	13.9	65.0	0.18	—	8.1	0.20	123
Hip	C	17.5	36.4	3.8	12.6	0.55	—	0.17	1.00	500
Knee	C	50.9	106.7	17.0	123.2	0.45	—	0.01	0.34	500

f_{muscle}, power reduction factor for same muscle heating; P_{po}, output power with potential overexposures; *M*, Minode; *D*, Diplode; *C*, Capacitive applicator.

resistances ρ. With the specific mass m, SAR can be written as

$$\mathrm{SAR} = \frac{\rho S_i^2}{m} \tag{1}$$

Consequently, SARs of fat tissue (with higher specific resistance ρ) were found to be higher compared to muscle (up to threefold at shoulder treatment with capacitive electrodes). Capacitive applicators allow better localized heating areas if positioned close enough to the body surface.

Inductive applicators primarily induce intracorporal electric field strengths E_i causing (eddy) currents flowing along pathways governed by electric conductivities $\sigma = 1/\rho$, hence depositing more power in tissues of higher conductivity. In this case SAR becomes

$$\mathrm{SAR} = \frac{E_i^2}{\rho m} \tag{2}$$

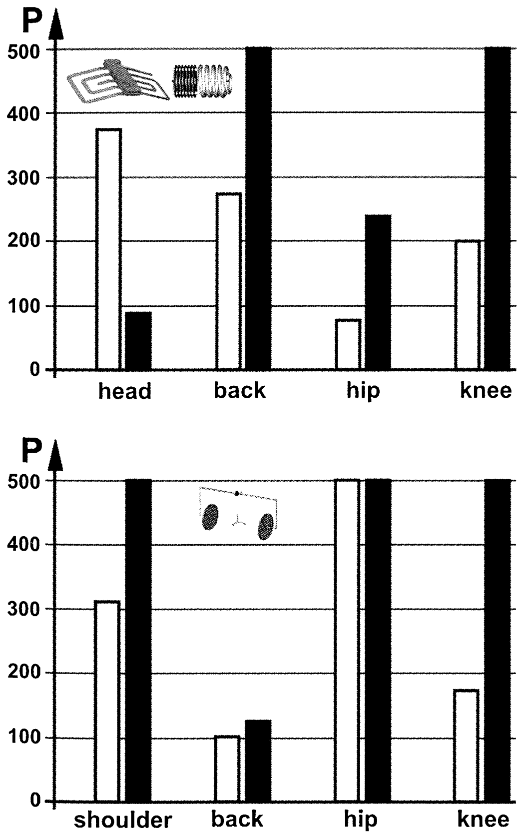

Fig. 5. Short-wave diathermy output power P (white bars) to achieve the same muscle heating relative to hip treatment with capacitive electrodes, and maximal output power P (black bars) still preventing vulnerable regions (eye lenses, CNS, gonads) from exposures above the local SAR_{10g} limit. **Top**: treatment with inductive applicators. **Bottom**: treatment with capacitive applicators.

Consequently, SARs were found to be higher in muscle tissue (with higher conductivity) than in fat (up to 1.7-fold at hip treatment with inductive electrodes). It is not surprising that relevant exposures distant from treated regions were found mainly with inductive field applicators. The reason is that eddy currents induced by the magnetic field of such applicators involve a larger body region thus involving vulnerable regions more frequently.

Figure 5 presents the required output power to achieve the same muscle heating (same SAR_{10g} values within muscle tissue) relative to the least efficient scenario (hip treatment with capacitive applicators) together with the maximum protective output power P_P which would still prevent vulnerable regions (eye lenses, CNS, gonads) from exposures above the local SAR_{10g} limit. It can be seen that in most cases P_P is higher or equal to the power necessary for sufficient muscle heating. This means that adjusting for equivalent muscle heating considered sufficient at hip treatment would also protect from unintended overexposures of vulnerable regions. The only exception is head treatment; however, in this case muscle is rarely the target tissue.

An attempt was made to derive quantitative guidance for diathermy by mimicking the common medical practice and relating SAR values in target regions to local skin SAR. The presented data demonstrate the existing difficulty to estimate delivered heat in the target region. The common medical practice is to increase SWD output power until the patient perceives thermal pain or discomfort. This conventional approach makes target heat load dependent on patient's heat perception. Since human heat sensors are located within the skin, this conventional approach can be mimicked by relating SAR values to local skin SAR_{10g}. This approach could be used to compare the use of inductive and capacitive applicators. Depending on the site of application it was found that if power setting is based on same skin SAR_{10g} (patient's sensations) target heat exposure (patient's muscle) is 2.1- to 3.4-fold higher for inductive electrodes compared to capacitive applicators (Table 2). In addition, apart from physical reasons, thermal sensitivity differs with body region and varies considerably among individuals [Adair et al.,

TABLE 2. Power Reduction Factor f_R for Inductive Applicators to Generate Same Local SAR_{10g} Within Muscle Tissue Compared to Capacitive Applicators

Treatment	f_R
Back	3.4
Hip	2.7
Knee	2.1

2003; Foster and Adair, 2004]. Although quantitative data on interpersonal thermal perception variability are lacking, investigations of other modalities such as electric current densities have demonstrated that variability could extend to even two orders of magnitude [Leitgeb et al., 2007]. The SAR comparisons and interpersonal variability demonstrated that the common approach of power setting in medical practice is only weakly correlated with heat deposited in target regions.

As far as unintended overexposures outside the target regions are concerned, the results do not indicate that they are an unavoidable accompaniment of SWD nor do they demonstrate that overexposures need to be expected at any SWD treatment. Table 1 demonstrated that risk/benefit considerations and/or conscious adjustment of output power levels or the choice of applicator type are recommended if the head is treated with more than 93 W, the back with more than 120 W and the hip with more than 240 W, while knee treatment can be considered uncritical for vulnerable regions. At the same time it is demonstrated that even the available maximum output power can be chosen provided the applicator is selected properly. The conclusions might need adjustment if pregnant women are investigated.

It needs to be emphasized that presented data are intended to assist quantitative risk assessment, which has become an indispensable part of medical device risk management, and give quantitative guidance to apply short-wave diathermy. They do not constitute new output power limits and still leave room for individual judgment. However, physicians should be aware of these quantitative relationships and make their decisions appropriately.

CONCLUSION

The investigation of SWD-induced intracorporal SAR distributions showed that therapeutic heating efficiency and target heat load vary considerably. Capacitive and inductive applicators exhibit quite different heating efficiency. Short-wave diathermy can cause relevant unintended exposures in vulnerable regions well outside the treated area such as the eye lenses, CNS and gonads. Properly adjusting output power and/or choosing applicator type and distance would allow reducing or avoiding unintended overexposures of vulnerable regions without compromising muscle heating.

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REFERENCES

Adair ER, Mylacraine KS, Allen SJ. 2003. Thermophysiological consequences of whole body resonant RF exposure (100 MHz) in human volunteers. Bioelectromagnetics 24:489–501.

CENELEC. 1999. Medical electrical equipment. Part 2: Particular requirements for short-wave therapy equipment. European Standard EN 60601-2-3 + A1.

DeLisa JA, Gans BM, Walsh NE, editors. 2004. Physical medicine and rehabilitation: Principles and practice. Baltimore: Lippincott & Wilkins.

Dimbylow PJ. 1997. FDTD calculations of the whole-body averaged SAR in an anatomically realistic voxel model of the human body from 1 MHz to 1 GHz. Phys Med Biol 42:479–490.

Draper DO, Knight KL, Fujiwara T, Castle JC. 1999. Temperature change in human muscle during and after pulsed short-wave diathermy. J Orthopaed Sports Phys Ther 29(1):13–22.

Duck FA. 1990. Physical properties of tissue. Academic Press, Inc. San Diego.

EU Council. 1993. Directive concerning medical devices. Directive 93/42 EEC Official EU Journal L169: 1–42.

EU Council. 1999. Limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). EU Council Recommendation 1999/519/EG Official EU Journal L197: 59–70.

EU Council. 2007. Directive amending Council Directive 90/385/EEC on the approximation of the laws of the Member States relating to active implantable medical devices, Council Directive 93/42/EEC concerning medical devices and Directive 98/8/EC concerning the placing of biocidal products on the market. Directive 2007/47/EEC Official EU Journal L247: 21–55.

FDA. 2002. Diathermic interactions with implanted leads and implanted systems with leads. FDA Public Health Notifications, http://www.fda.gov/cdrh/safety/.

Foster KR, Adair ER. 2004. Modeling thermal responses in human subjects following extended exposure to radiofrequency energy. http://www.biomedical-engineering-online.com/content/3/1/4.

Gabriel S, Lau RW, Gabriel C. 1996. The dielectric properties of biological tissues. II. Measurements in the frequency range 10kHz-20GHz. Phys Med Biol 41:2251–2269.

Garrett CL, Draper DO, Knight KL. 2000. Heat distribution in the lower leg from pulsed short-wave diathermy and ultrasound treatments. J Athletic Training 35(1):50–55.

ICNIRP. 1998. Guidelines for limiting the exposure to time-varying electric, magnetic and electromagnetic fields. Health Phys 74:494–522.

IEC. 1998. Medical electrical equipment-Part 2: Particular requirements for the safety of short-wave therapy equipment. Standard IEC 60601-2-3 + Ad.1.

Knight KL, Draper DO. 2008. Therapeutic modalities. Baltimore: Lippincott Williams and Wilkins.

Leitgeb N, Schröttner J, Cech R. 2007. Perception of ELF electromagnetic fields: Excitation thresholds and inter-individual variability. Health Phys 92(6):591–595.

Lerman Y, Jacubovich R, Green MS. 2001. Pregnancy outcome following exposure to shortwaves among female physiotherapists in Israel. Am J Ind Med 39(5):499–504.

Li CY, Feng CK. 1999. An evaluation of radio frequency exposure from therapeutic diathermy equipment. Ind Health Oct 37(4): 465–468.

Lin JC. 2006. Biomedical applications of electromagnetic engineering. In: Bansal R, editor. Engineering electromagnetics: Applications. Boca Raton, FL: Taylor & Francis. pp. 211–233.

Martin CJ, McCallum HM, Heaton B. 1990. An evaluation of radiofrequency exposure from therapeutic diathermy equipment in the light of current recommendations. Clin Phys Physiol Meas 11(1):53–63.

Moseley H, Davison M. 1981. Exposure of physiotherapists to microwave radiation during microwave diathermy treatment. Clin Phys Physiol Meas 2(3):217–221.

Omerspahic A. 2007. Thermal diathermy and side-effects (in German). Thesis, Graz Univ Technol.

Pinski SL, Trohman RG. 2002. Interference in implanted cardiac devices, part II. Pacing Clin Electrophysiol 25(10):1496–1509.

Quellet-Hellstrom R, Stewart WF. 1993. Miscarriages among female physical therapists who report using radio- and microwave-frequency electromagnetic radiation. Am J Epidemiol 138(10):775–786.

Rentsch W. 1985. Short-wave and microwave therapy. Stuttgart: Gustav Fischer Verlag.

Schlemmer M, Lindner LH, Abdel-Rahman S, Issels RD. 2004. Principle, technique and indication of hyperthermia and partial body hyperthermia (in German). Radiologe 44:301–309.

Shah SG, Farrow A. 2007. Investigation of practices and procedures in the use of therapeutic diathermy: A study from the physiotherapist's health and safety perspective. Physiother Res Int 12(4):228–241.

Shields N, O'Hare N, Gormley J. 2004. An evaluation of safety guidelines to restrict exposure to stray radiofrequency radiation from short-wave diathermy units. Phys Med Biol 49(13):2999–3015.

Stuchly MA, Repacholi MH, Lecuyer DW, Mann RD. 1982. Exposure to the operator and patient during short wave diathermy treatments. Health Phys 42(3):341–366.

Taskinen H, Kyyrönen P, Hemminki K. 1990. Effects of ultrasound, shortwaves, and physical exertion on pregnancy outcome in physiotherapists. J Epid Commun Health 44:196–201.

Tuschl H, Neubauer G, Garn H, Duftschmid K, Winker N, Brusl H. 1999. Occupational exposure to high frequency electromagnetic fields and its effect on human immune parameters. Int J Occup Med Environ Health 12(3):239–251.

Weiland T. 1977. A discretization method for the solution of Maxwell's equations for six-component fields. Archive for Electronics and Communication (AEÜ) 31:116–120.

Wenk W. 2004. Elektrotherapie. Berlin: Springer.