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The Effect of Operator Hand Position and Workstation Furniture on Foot Current for Radio Frequency Heater Operators

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The dependence of foot current on operator hand position and workstation furniture was studied to better assess and reduce operator exposure where reactive field coupling predominates (i.e., 10 to 100 MHz and within 1 m of heaters). Reactive coupling contributions to foot current have not been studied in a systematic manner in the laboratory or the workplace. The measurement of current induced in a worker's extremities (i.e., foot, ankle, arm, and wrist) is the most feasible and accurate method to assess reactive field exposures. A total of 72 measurements was made with four workers who were operating two radio frequency (RF) heaters in a workplace. All measurements were made twice in randomized order. Operator posture/furniture and foot current readings were documented by simultaneous videotape recordings. Foot current was determined as a function of 1) the operator's hand position, and 2) the type of stool used. With one exception, foot current increased when the operator's hands were extended over the heater applicator plates. Videotape recordings documented that one operator had long arms and could easily reach over the plates of one particular heater without leaning toward the heater. In contrast, for all other foot current measurements, the operators had to lean toward the heater to reach over the plates. It was determined that foot current increased as the operator's upper torso was positioned closer to the heater. Thus, administrative controls or physical barriers that keep the operator's body farther from an RF heater can reduce foot current. There was no measurable change in foot current with the type of stool (plastic versus wooden) used. To obtain meaningful exposure evaluations for heater operators, industrial hygienists must determine the dependence of foot current on common hand and upper torso positions.
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Introduction

Radio frequency (RF) heaters operating at frequencies of 3 to 100 MHz are used to heat, melt, or cure nonmetallic (dielectric) materials that are poor conductors of heat or electricity, such as plastic, rubber, and glue. In RF dielectric heating, materials are heated uniformly and quickly. Generally, the RF energy is applied to an object for several seconds to heat the material. The RF source then remains off until the next piece of material is processed. Commonly, the source is energized 5 to 25 percent of the time during the processing cycle.[1]

There are about 100,000 RF heaters in use in the United States and over 250,000 workers exposed to RF emissions.[2] Studies by scientists at the National Institute for Occupational Safety and Health (NIOSH) and other research organizations have shown that exposure levels for dielectric heat sealers can exceed occupational exposure limits.[1,3-5]

Operators of RF dielectric heaters are often exposed near the heater (within 1 m) where the operator is reactively coupled to the RF source. Due to reactive coupling, the operator is connected to an electrical RF circuit that includes the heater and other conductive objects in the workplace.[4] Information on the contribution of reactive coupling to induced body currents has been reported previously in the literature.[4,6,7] The contribution of coupling to the RF energy absorption rate, the specific absorption rate (SAR), must be accounted for when assessing the total worker exposure. SAR (W/kg) is the primary basis for all US occupational limits for RF exposure.[8-10] During RF exposure, current flow is induced in the worker's body. The SAR can be determined from induced current measurements. Induced current determinations take into account the contribution of coupling to worker SAR.[4,9,11,12] Thus, for coupled conditions, the determination of induced currents is the best way to assess worker exposures. US occupational exposure guidelines include recommended measurement

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techniques for induced body current.[9,10] At present, equipment and techniques are available only to measure induced current in a worker's extremities (i.e., foot, ankle, arm, and wrist).

Workplace measurements with heater operators have shown the dependence of foot current on hand position and workstation furniture.[4,13–15] In addition, numerical modeling calculations have shown that hand position and workstation furniture can affect foot current for RF heater operators.[13,16,17] The worksite measurements show the same trends as the numerical modeling data.[4,13,14] These modeling data show increased foot current in simulating a situation where the operator's hands are positioned closer to RF heater plates. Researchers have reported that these enhanced currents are due to reactive field coupling.[12] Likewise, the foot current measurements of many investigators are consistent with strong reactive field coupling effects for RF heater operator exposures.[4,13–15,18,19] However, reactive coupling contributions to foot current have not been studied in a systematic manner in either the laboratory or workplace until now.

In the present study, systematic workplace measurements were conducted to investigate the effect of operator hand position and workstation furniture on foot current in RF heater operators. The foot current was measured for exposure situations where reactive field coupling predominated, meaning that the operators were located near an RF heater (i.e., within 1 m of heater from 10 to 100 MHz).

Materials and Methods

RF Dielectric Heaters

Two dielectric heaters were used in this study. Each heater had a parallel-plate applicator and was used to produce plastic waterbed mattresses. The heaters were located in a waterbed mattress manufacturing plant near Cincinnati, Ohio. Workers at the plant who normally operated the heaters were used as subjects in this study. Four workers operated one heater and 2 workers operated the other heater. There were 3 female operators and 1 male operator. All operators who participated as subjects had completed informed consent procedures required by the Human Subjects Review Board of NIOSH.

RF Measurements

The operating frequency of each heater was measured with a Global Specialties Corporation Continental Mini-Max frequency counter Model MM50 (New Haven, Connecticut). The mean-squared (ms) electric (E^2) and ms magnetic (H^2) field strengths were measured for each heater. A Holaday Industries HI-3003 Broadband Isotropic Survey Meter (Eden Prairie, Minnesota) with a Model STE-03 Electric Field Probe (0.5 to 6000 MHz) and a Model STH-03 Magnetic Field Probe (5 to 300 MHz) were used to measure the electric and magnetic field strengths under near-field conditions. The Holaday meter and probes were calibrated by the manufacturer and the calibrations were verified using standards traceable to the National Institute of Standards and Technology (NIST). The ms field strengths were measured at a distance of about 10 cm from the plane of the operator's body. The operator was in his or her normal operating position during field strength measurements. There are two reasons it was appropriate to measure field strength in this manner. First, the data were used only for comparison with previous measurements taken under similar conditions (10 to 15 cm from an operator present during measurements). Second, field strength data were not used for SAR calculations with computer modeling (which require the operator to be absent during field strength measurements). Exposure measurements were made for each heater at the level of the operator's eyes, waist, knees, and ankles.

Foot currents were determined by measuring the root-mean-squared RF voltage developed across a known impedance of a foot current sensor with a Ballantine Laboratories Model 3440A RF Voltmeter (Boonton, New Jersey).[11] The sensor is a platform consisting of two copper plates separated by a Plexiglas sheet and connected with a low resistance resistor. All foot current measurements were made with the operator's feet placed on the foot current sensor. A 1-second averaging time was used for foot current measurements in accordance with Institute of Electrical and Electronic Engineers procedures.[9] The use of the foot current sensor per se did not have an appreciable effect on induced foot current.[11,12] The voltage readings were divided by the appropriate impedance value to calculate the foot current. The impedance value was measured with a Hewlett-Packard Model 4815A vector-impedance meter using the technique of Gandhi *et al.*[11] The RF voltmeter and RF voltage probe were calibrated by the vendors (traceable to NIST) over the frequency range 0.5 to 108 MHz.

Foot current was determined as a function of 1) the operator's hand position, and 2) the type of stool the operator sat on. The operator's hands were positioned as follows: 1) both hands above the bottom applicator plate; 2) both hands touching a wooden table extension located directly in front of the bottom applicator plate; or 3) both hands in the operator's lap. In position 1 both hands were placed on top of a 1-inch thick Styrofoam spacer that was attached to the top of the bottom applicator plate. The operator sat on two different stools during foot current measurements. One stool was constructed from plastic (½-inch thick Plexiglas) and the other from wood (½-inch thick particle board). Each stool had the same dimensions (24½ inches high with a 15-inch diameter seat) and was identical except for the construction materials. Only dielectric materials (nylon screws, plastic glue, and wood glue) were used to assemble the stools. Thus, no metal components were present that could cause artifacts in foot current measurements. For measurements, the stool was located in front of the heater applicator plates. The front of the stool was located 12 inches from the front edge of the bottom parallel-plate applicator. The foot current sensor was placed in front of the stool. Adhesive tape was placed on the concrete floor to mark the locations of the foot current sensor and stool to ensure reproducibility in repeated measurements. For statistical considerations, all foot current measurements were made two times in randomized order for each exposure condition (i.e., hand position and type of stool). A total of 72 foot current measurements was made in this study.

Experimental Design and Analysis

The null hypotheses were that foot current was not affected by the type of stool (furniture), by hand position (operator posture), or by the interaction of the two.

The experimental design was a two-factor repeated measures one, in which there were two within-subject fixed factors: 1) type of stool (plastic or wooden); and 2) hand position (bottom plate, wooden table, or lap), and no between-subject factors. The dependent variable was foot current (mA). Each treatment combination was administered to each subject twice. The order of experimental conditions was randomized.

A repeated measures design was used in this study for two reasons. First, such a design controls for effects due to individual differences.[20] These effects could be quite substantial in measurements of this sort (e.g., effects due to differences in the type of shoes, gender, height, or weight). Second, order effects should be fairly minimal, because factors such as learning and fatigue would probably not play a role. The underlying model was:

$$Y_{ijkl} = M + P_i + S_j + H_k + (PS)_{ij} + (PH)_{ik} + (SH)_{jk} + (PSH)_{ijk} + \epsilon_{(ijk)l} \quad (1)$$

where: Y_{ijkl} = foot current for person i on stool j with hand position k and replicate l, l = 1,2
M = overall mean foot current
P_i = random effect due to person i (treated as a block), i = 1, . . . ,a
S_j = fixed effect due to stool j, j = 1,2
H_k = fixed effect due to hand position, k = 1,2,3
$\epsilon_{(ijk)l}$ = random error associated with stool j and hand position k for subject i and which has a distribution that is $N(0,\sigma^2)$; l = 1,2.

The other terms are interaction terms. Note that all interaction terms that include the letter P are for random effects. One can view this approach as using foot current minus the mean foot current for a person as the dependent variable. In effect, $(Y_{ijkl} - \overline{Y}_{i...})$ can be viewed as the dependent variable, where $\overline{Y}_{i...}$ is the mean current for subject i (following the explanation given by Maxwell and Delaney[20]). With this viewpoint, the above model would be rewritten as:

$$Y_{ijkl} - P_i = M + S_j + H_k + (PS)_{ij} + (PH)_{ik} + (SH)_{jk} + (PSH)_{ijk} + \epsilon_{(ijk)l} \quad (2)$$

and we would use $\overline{Y}_{i...}$ as an estimate for P_i.

The analysis was a univariate analysis of variance with use of the Greenhouse-Geisser adjustment. The Greenhouse-Geisser adjustment is appropriate when there is a lack of homogeneity of treatment-difference variances.[21]

In order to ascertain what portion of the variability was due to differences between subjects and what portion was due to repeated measurements on the same subject, we also did a components of variance analysis based on the above model.

TABLE I. Dependence of Foot Current on Hand Position and Stool Type: Heater 1*

	Mean Foot Current (mA ± SD)[A]	
Hand Position	**Operator 1**	**Operator 2**
Plastic stool		
Bottom plate	172.8 ± 0.0	89.5 ± 4.4
Wooden table	89.5 ± 4.4	80.3 ± 0.0
Lap	89.5 ± 4.4	98.8[B]
Wooden stool		
Bottom plate	172.8 ± 0.0	98.8 ± 8.7
Wood table	98.8 ± 0.0	86.5 ± 8.7
Lap	92.6 ± 0.0	97.5 ± 10.5

*Heater 1 operated at a measured frequency of 26.5 MHz.
[A]Mean of two measurements of foot current ± standard deviation (SD), root-mean-squared.
[B]Only one foot current measurement was made for this condition.

Videotaping of RF Measurements

Operator posture, type of stool, and foot current readings were documented by simultaneous videotape recordings. Two separate views were simultaneously videotaped using two Panasonic Model AG-450 cameras (Secaucus, New Jersey). The first camera was used to record the operator posture and type of stool. The second camera was used to record the meter showing the foot current reading. A Panasonic Model WJ-4600 special effects generator was used to generate a presentation that allows simultaneous, synchronized, on-screen observation of the meter showing the foot current reading with the operator posture and type of stool. The video records were analyzed for the influence of operator posture or stool type on foot current.

Results

The data showing the dependence of foot current on the operator's hand position are given in Tables I and II. Tables I and II show the results for heaters 1 and 2, respectively. Operators 1 and 2 were the same people for both heaters. Heaters 1 and 2 operated at measured frequencies of 26.5 and 19.5 MHz, respectively. With one exception, the foot

TABLE II. Dependence of Foot Current on Hand Position and Stool Type: Heater 2*

	Mean Foot Current (mA ± SD)[A]			
Hand Position	**Operator 1**	**Operator 2**	**Operator 3**	**Operator 4**
Plastic stool				
Bottom plate	189.3 ± 5.1	95.0 ± 1.0	135.8 ± 10.1	134.3 ± 2.0
Wooden table	107.9 ± 5.0	56.0 ± 7.6	97.2 ± 6.0	78.6 ± 2.1
Lap	102.9 ± 2.0	59.3 ± 1.0	92.9 ± 4.0	72.5 ± 7.6
Wooden stool				
Bottom plate	189.3 ± 5.1	95.0 ± 9.0	146.4 ± 15.1	122.2 ± 9.1
Wooden table	106.4 ± 3.0	54.7 ± 2.5	97.2 ± 2.1	71.8 ± 3.5
Lap	100.8 ± 3.0	57.9 ± 7.1	90.0 ± 0.0	74.7 ± 4.6

*Heater 2 operated at a measured frequency of 19.5 MHz.
[A]Mean of two measurements of foot current ± standard deviation (SD), root-mean-squared.

TABLE III. Analysis of Variance: Heater 2

Factor	F	df	p Value
Stool	0.57	1,3	0.5034
Hand position	29.24	2,6	0.0111*
Stool × hand position	0.13	2,6	0.7554*

*Greenhouse-Geisser adjusted.

current was at a maximum with the operator's hands extended above the bottom applicator plate. The exception was for the data of operator 2 on heater 1 shown in Table I. These data also indicate no measurable effect on foot current from the type of stool (plastic or wooden) used by the operators.

The analysis of variance was conducted on the data collected for heater 2. It was not the purpose of this study to investigate differences in foot current due to different heaters. Therefore, heater 1 was not included in the analysis. The results for heater 2 appear in Table III (the Greenhouse-Geisser adjustment is only necessary when there are three or more levels of a factor). A test did indicate a lack of homogeneity of treatment-difference variances, thus the Greenhouse-Geisser adjustment was appropriate.

Obviously there was a significant effect due to hand position, but not to stool type or the interaction of stool and hand. Multiple comparisons using Tukey's procedure yielded results as seen in Table IV. The components of variance are seen in Table V.

The negative variance is an artifact that occurs occasionally. We simply assume that this component has a variance of zero. Thus the within-subject variance was 4.32 percent of the total.

Tables VI and VII contain the relative foot current factors observed when the operator's hands were moved away from the bottom heater plate. Factors were calculated relative to the foot current with the operator's hands on the bottom plate. The equation used to calculate the factors is given at the bottom of Tables VI and VII. The data in these tables agree with that in Tables I and II, with factors ranging from 1.11 to 0.53.

In Table VIII the ms E^2 and H^2 field strength measurements are given for heaters 1 and 2. Electric field strength ranged from 1.4×10^4 to 0.9×10^3 V^2/m^2. Magnetic field strength ranged from 5.0×10^{-2} to 0.5×10^{-2} A^2/m^2.

Discussion

In this investigation, the dependence of foot current on operator hand position and workstation furniture was studied to better assess and reduce exposure for RF heater operators. The foot current measurements show good repeatability for the two trials that were conducted in randomized order (notice the small standard deviation values in Tables I and II). In addition, the small percentage variance (4.32% of the total variance) due to the "within-subject" component implies that the need for conducting two trials may not be very great (notice the components of variance calculations, "Results" section). The data in Tables I and II show the expected dependence of foot current on operator hand position, with one exception (operator 2 on heater 1, Table I). Due to her long arms, operator 2 did not have to move her upper torso closer to the heater 1 when extending her arms over the bottom applicator plate. In contrast, operator 2 had to lean closer to heater 2 (Table II, bottom plate) due to differences in heater dimensions and geometry from heater 1. Videotape recordings and investigator records documented these differences. Data for operator 2 on heater 1 are consistent with other research results showing decreased body current due to decreased reactive coupling when the operator's body is farther from the RF source.[5,12,22] These data indicate a strong dependence of foot current on the upper torso position of the operator (relative to the heater). For all the other data, the foot current was at a maximum when the operator's hands (and upper torso) were closest to the bottom applicator plate. As the hands were moved away from the plate, the foot current decreased and was at a minimum with the operator's hands in his/her lap.

The strong dependence of foot current on worker posture has important practical implications for industrial hygienists evaluating exposures. Foot current evaluation techniques are relatively new and the dependence of foot current on worker posture and exposure conditions is even less widely known. Further, the US exposure guide-

TABLE IV. Multiple Comparisons Using Tukey's Procedure

Hand Position	Mean	*N*	Grouping
Bottom plate	138.40	16	A
Wood table	83.71	16	B
Lap	81.35	16	B

TABLE V. Components of Variance for Multiple Comparisons

Component	Variance
Between subject	667.46
Between subject × stool	0.04
Between subject × hand position	134.15
Between subject × stool × hand position	−1.36
Within subject	36.17

TABLE VI. Relative Foot Current Factors for Different Hand Positions: Heater 1*

Hand Position	Operator 1	Operator 2
Plastic stool		
Bottom plate	1.00	1.00
Wooden table	0.53	0.91
Lap	0.53	1.11
Wooden stool		
Bottom plate	1.00	1.00
Wooden table	0.56	0.91
Lap	0.53	1.00

*Relative foot current factor = $\frac{\text{foot current (hand position to be evaluated)}}{\text{foot current (with hands on bottom plate)}}$

TABLE VII. Relative Foot Current Factors for Different Hand Positions: Heater 2*

Hand Position	Operator 1	Operator 2	Operator 3	Operator 4
Plastic stool				
Bottom plate	1.00	1.00	1.00	1.00
Wooden table	0.56	0.59	0.71	0.59
Lap	0.56	0.63	0.67	0.53
Wooden stool				
Bottom plate	1.00	1.00	1.00	1.00
Wooden table	0.56	0.59	0.67	0.59
Lap	0.53	0.63	0.63	0.63

*Relative foot current factor = $\frac{\text{foot current (hand position to be evaluated)}}{\text{foot current (with hands on bottom plate)}}$

lines[8-10] for foot current measurements do not inform the user about the large variation of foot current for common operator postures and exposure conditions. Thus, to obtain meaningful exposure evaluations for heater operators, industrial hygienists must determine the dependence of foot current on common hand and upper torso positions.

The dependence of foot current on hand position, observed in this study, is consistent with other measurement and modeling results. Previous measurements with heater operators show comparable dependence of foot current on hand position.[4,13-15] In addition, numerical modeling calculations have shown that hand position will affect foot current in RF heater operators.[13,16,17] These modeling data show increased foot current in simulating a situation where the operator's hands are moved closer to RF heater plates. This trend would be expected for exposures near RF heaters where reactive field coupling predominates. Other researchers have reported that these enhanced currents are due to the reactive field coupling.[4,12,22] Likewise, the foot current measurements from many other studies are consistent with strong reactive field coupling effects for RF heater operator exposures.[4,13-15,18,19]

The lack of difference in the results from the type of stool is consistent with the fact that both plastic and wood are low-loss dielectric materials with comparable dielectric constants.[23,24] The plastic stool was used because it was anticipated to not affect foot current measurements. The wooden stool was used because wood is a common construction material for stools used by RF heater operators in the workplace. Because the wooden and plastic stools had the same dimensions, any differences in foot current would have been due to differences in the construction materials. A comparison between a metal stool and either a wooden or plastic stool would be expected to show a difference in foot current, and should be tested. The reduction of foot current by nearly a factor of two (Tables VI and VII), further emphasizes the substantial difference that posture alone makes on induced foot current for the exposure conditions studied.

TABLE VIII. RF Field Strength (E^2, H^2) Measurements for Heaters 1 and 2*

Body Position	E^2 (V/m)^2, ms^A	H^2 (A/m)^2, ms
Heater 1		
Eyes	1.9×10^3	5.0×10^{-2}
Waist	5.0×10^3	1.1×10^{-2}
Knees	1.3×10^4	1.6×10^{-2}
Ankles	1.4×10^4	2.3×10^{-2}
Heater 2		
Eyes	1.4×10^4	1.4×10^{-2}
Waist	0.9×10^3	2.2×10^{-2}
Knees	3.0×10^3	0.5×10^{-2}
Ankles	2.6×10^3	3.4×10^{-2}

*Repeat field strength measurements were not made.
^{A}Mean-squared (ms) field strength.

E^2 and H^2 field strength data in Table VIII show the anticipated spatial variability over the operator's body. Previous field strength data collected on RF heaters showed comparable spatial variability.[1,3-5,7] The field strength measurements alone are of little value in predicting worker SAR values for near-field RF exposures. Numerical modeling techniques must be used to predict worker SAR values from field strength data. However, it is impractical and expensive for most industrial hygienists to make these modeling calculations. Few researchers can make such modeling calculations due to the expensive computer capabilities (a CRAY computer is usually necessary) and extensive electrical engineering expertise required.

Conclusions

First, the operator's hand and upper torso positions strongly influence the foot current under the conditions of reactive field coupling in this study. Further studies are needed to investigate whether the hand or upper torso position has more effect on foot current. Second, foot current was effectively reduced when the operator's hands were in his/her lap. Third, the different types of low-loss dielectric stools (wooden or plastic) used by an operator had no measurable effect on foot current. The effect on foot current for stools constructed of metal should be studied. Fourth, the field strength exposures exhibited a large spatial variation over the operator's body. Thus, a field strength measurement at one anatomical location does not determine worker exposure adequately.

Recommendations

For the common workplace condition of RF field reactive coupling, the following are practical recommendations based on the data presented in this article:

1. To obtain meaningful exposure evaluations for heater operators, industrial hygienists must determine the dependence of foot current on common hand and upper torso positions. Otherwise, abnormally low or high foot current could be recorded with misleading conclusions.
2. If operator foot current exceeds applicable standards, it can be reduced by keeping the operator's hands and upper torso as far from the RF heater as practical. Thus, administrative controls or physical barriers between the

RF heater and operator can be effective in reducing foot current.

Disclaimer

Mention of commercial products does not constitute an endorsement by NIOSH.

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