

Semen Quality and Hormone Levels Among Radiofrequency Heater Operators

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Approximately 9,000,000 US workers are occupationally exposed to radiofrequency (RF) radiation; over 250,000 operate RF dielectric heaters. Our purpose was to determine whether male RF heater operators experience increased adverse reproductive effects reflected in reduced semen quality or altered hormone levels. We measured incident RF heater radiation exposures and RF-induced foot currents at four companies. For 12 male heater operators and a comparison group of 34 RF-unexposed men, we measured 33 parameters of semen quality and four serum hormones. Despite wide variation in individual exposure levels, near field strengths and induced foot currents did not exceed current standard levels and guidelines. We observed minor semen quality and hormonal differences between the groups, including a slightly higher mean follicle-stimulating hormone level for exposed operators (7.6 vs 5.8 mIU/mL). Further occupational studies of RF-exposed men may be warranted. (J Occup Environ Med. 2000; 42:993–1005)

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Radiofrequency (RF) radiation refers to nonionizing electromagnetic energy in the frequency range 30 kilohertz to 300 gigahertz. Sources include radar, radio, television, satellite communications, microwave ovens, medical diathermy devices, and industrial heaters and welders. Approximately 9,000,000 US workers may be occupationally exposed to RF radiation.¹

RF sealers and dielectric heaters are used to heat, dry, emboss, melt, seal, or cure materials that are poor electrical conductors (dielectric). Applications include the manufacture of plastic and wood products and the embossing and drying of textile, paper, plastic, and leather products. These products are usually processed by placing the dielectric material between two parallel, metallic plates and applying high voltage between the plates. The applied voltage oscillates at a high frequency (3 to 100 megahertz [mHz]) and produces RF electromagnetic energy between the plates. As hydraulic or pneumatic pressure is applied to the dielectric material between the metallic plates, RF energy is used to process the material. Although most of the RF energy generated is absorbed by the material being processed, some energy is radiated into the environment, where it can be absorbed by the operator and nearby workers.

Electromagnetic energy has both an electric (E) and a magnetic (H) component. Because worker exposures from industrial dielectric heaters usually occur in the near-field (within one wavelength of the

source), both the E- and H-field strengths must be measured separately to fully evaluate the RF exposure to the heater operator. Studies have shown that these heater operators can be exposed to field strengths as high as 7.29×10^6 volt²/meter² (V²/m²) for the E-field and 42.5 ampere²/meter² (A²/m²) for the H-field.^{2,3} Additional surveys⁴⁻⁶ have confirmed that operator exposures often exceed the occupational exposure guidelines established by the Institute of Electrical and Electronics Engineers (IEEE). For the E-field these guidelines are 3.77×10^3 V²/m²; for the H-field a frequency-dependent standard for exposure ranges from $3 \times 10^{-1} - 2.7 \times 10^{-2}$ A²/m² for 30 to 100 mHz.⁷

RF energy must be absorbed to raise the temperature of the body or to injure tissues. The specific absorption rate (SAR), defined as the time rate of RF energy absorption per unit mass of the absorbing material (W/kg), is well correlated with the incidence of biological effects in many animal studies.⁸ Although the E- and H-field strengths can be measured, the rate of RF energy absorption in the worker's body cannot be directly measured. However, the E- and H-field exposure measurements can be used to estimate the SAR.

Most occupational exposure guidelines use readily measurable exposure quantities (E- and H-field strength). The field strength guidelines have been derived from the SAR selected as the basis for the guidelines. In most cases, the SAR selected ensures that the average SAR for the whole body will not exceed a specific absorption rate value that is one-tenth of the lowest SAR that has been shown to produce adverse effects in human or animal studies. Partial-body SARs (eg, for the extremities) are also specified in these guidelines. Gandhi et al showed that extremely high rates of energy deposition may occur in anatomically localized areas of RF heater operators (ie, partial-body SARs), even though whole-body

SARs are below recommended guidelines.⁹ Partial-body SARs can be determined by measurement of the current induced in the operator's body when the RF heater is operating. This RF-induced current is typically measured at the operator's wrist or feet. The parallel-plate applicators of RF heaters are usually located near the operator's waist. Other measured and calculated data have shown that SARs can be quite high in the heater operator's groin area,^{10,11} even when the operator is not in contact with the heater. However, operators must touch the control panel on the RF heater to process the materials. When an operator touches the heater, the partial-body SAR is typically 50 to 200 times higher than that without operator contact.¹² Thus, instrumentation has been developed to measure contact currents and exposure guidelines for contact currents have been established.^{13,14} The IEEE contact current guideline is 100 milliamperes (mA) from 0.1 to 100 mHz, and the Canadian occupational limit is 40 mA for exposures from 0.1 to 100 mHz.¹⁴

Adverse male reproductive effects have been associated with hyperthermia caused by RF radiation in animals¹⁵⁻²⁰ and in humans.²¹ Adverse effects from nonthermal RF radiation exposure (ie, exposure that causes no measurable rise in temperature) are also possible and may occur at much lower SARs than those required to induce hyperthermia.²² Testosterone levels in male rats decreased after up to 60 days of exposure to pulsed microwaves at nonthermal SAR levels.²³

In humans, two surveys found adverse male reproductive effects when occupation was used to infer RF exposure. Barron et al²⁴ identified an increase in "subfertility" (childlessness due to male sterility or unknown causes) in a group of 226 men occupationally exposed to RF radiation compared with 88 controls. Statistically significant decreases in sperm count and the number of normal, motile sperm were reported by Lan-

cranjan et al²⁵ in 31 men exposed to microwave radiation (RF radiation in the 0.3 to 300-gigahertz range) for an average of 8 years compared with 30 control men. Details of exposure conditions were not given by the authors. The objective of our study was to determine whether men who work with RF sealers experience increased adverse reproductive effects as reflected in reduced semen quality or altered hormone levels.

Methods

Description of Study Facilities

Four companies located in Maryland provided an initial combined group of 98 male RF heater operators. Water mattress manufacturers were chosen for this RF heater study because they employ primarily men to seal the long seams, corners, valves, and interior baffles of water mattresses. The RF heaters used had no protective shielding and were located in a central area of each plant. For these reasons, most personnel were considered to be exposed to RF radiation. In fact, RF radiation from several machines contributed to the exposure of each employee. A comparison group of nonexposed male workers was selected from a group of 140 workers at a nearby communications equipment manufacturing facility. The comparison group was selected from inspectors, technicians, and assemblers in quality assurance and fiber-optic assembly departments, where there was minimal exposure to physical and chemical agents. Soldering, an activity with potential lead exposure, was generally done in other departments in this facility, and the income and age ranges of these workers were similar to those of the RF heater operators.

Selection of Participants

Study participants were required to be 18 years of age or older. To ensure work exposure through at least one full spermatogenic cycle, participants were required to have worked full-time for at least 3

months at the companies selected. Lists of potential participants were generated from company personnel rosters at RF-exposed and unexposed facilities. Letters describing the study were sent to all potential participants, and a Fact Sheet describing the study and our current understanding of RF exposure and adverse health effects was distributed to workers at each study facility. Each potential participant was interviewed privately to explain the study and obtain informed consent. All who refused to participate answered a short Nonparticipant Questionnaire to compare basic demographic, reproductive, and motivational attributes of participants and nonparticipants. Participants with medical or exposure histories that were considered likely to affect the RF-reproductive profile relationship were excluded by consensus of the study andrologist, the study physician, and three health physicists, who were not aware of exposure status.

Questionnaire and Semen Collection

The study was conducted from May 23 to June 10, 1988. After an informed consent form was signed by the study participant, a reproductive questionnaire was administered to collect work and medical histories and demographic, lifestyle, and reproductive information. A physician then performed a limited reproductive physical examination and drew blood for hormonal analysis. Testicular volume was measured by using plastic templates.²⁶ A brief videotape was shown to each participant to explain sample collection. The videotape stressed three points: 2 days of sexual abstinence were requested prior to sample collection; the sample had to be collected by masturbation; and the sample had to be delivered to the National Institute for Occupational Safety and Health (NIOSH) field laboratory within 1 hour of ejaculation. At the time of collecting the semen sample, each

subject recorded on the collection jar label his abstinence time, collection time, and any unintentional spillage. At the time of delivery of the semen sample, each man was paid \$40 for participating in the study.

Laboratory Analyses

Semen analysis. Initial evaluation on receipt of each semen sample included the recording of semen temperature, turbidity, color, liquefaction time, volume, osmolality, and pH. Videotaped semen recordings, viability assessments, sperm counts, preparation of slides, and preservation of seminal plasma were also done at this time. Morphologic and morphometric analyses of slides, computer analyses of videotapes for motility and velocity, and seminal biochemistry were completed at a later time. Analysis methods for semen count, concentration, volume, viability, morphology,²⁷ morphometry,²⁸ and motility²⁹ have been described in detail previously, as have the colorimetric assays of zinc³⁰ and fructose,^{31,32} performed with seminal plasma.

Sperm chromatin structure assay. The sperm chromatin structure assay (SCSA) measures susceptibility of sperm DNA to acid-induced denaturation in situ.³³⁻³⁵ Briefly, sonication-freed sperm nuclei are treated with a low-pH buffer and then stained with acridine orange. The stained nuclei are measured by flow cytometry to quantitate the amount of green fluorescence (515 to 530 nanometers) corresponding to native double-stranded DNA and the amount of red fluorescence (>630 nanometers) corresponding to single-stranded, denatured DNA. The value for cells outside the main population provides an index for the percent of cells with abnormal chromatin structure, defined as an increased susceptibility to DNA denaturation. The extent of abnormality is expressed as the ratio of red fluorescence (denatured DNA) to total fluorescence (red + green, or denatured + native DNA) and as the standard deviation of this ratio. In the

NIOSH 8-month longitudinal study of semen quality in 45 unexposed workers,³⁶ repeated SCSA results from a single man showed very high levels of repeatability and precision. Previously reported SCSAs in humans have detected extensive damage in the chromatin structure of sperm from chemotherapy patients and in infertility clinic patients whose semen quality was considered normal by other criteria.^{37,38} Human sperm from unexposed men that are positive for altered chromatin structure have been shown to have DNA strand breaks.³⁹ Subfertile patients have shown higher SCSA values than fertile donors.³⁴ A recent study⁴⁰ showed that the SCSA data on semen from male partners of couples that achieved pregnancy within 3 months of unprotected intercourse were significantly different from samples from couples who achieved pregnancy within 4 to 12 months ($P < 0.01$) and from couples that had not achieved pregnancy by 12 months ($P < 0.001$). Thus, chemotherapy-altered chromatin structure produces SCSA profiles similar to that observed in male sub/infertility.

Hormonal analysis. A single blood sample was drawn from each participant. Most of the samples were drawn during morning working hours. Radioimmunoassays for follicle-stimulating hormone (FSH),⁴¹ luteinizing hormone (LH),⁴² prolactin,^{43,44} and total testosterone by extraction and chromatography radioimmunoassay^{45,46} were performed according to published methods.

Definition of Exposure

RF radiation survey. A radiofrequency radiation survey of all available heaters at each company in the study was conducted to determine mean RF heater exposures by company. Survey measurements were made with the operator of the machine at the time of the survey without regard to study participation status. The survey included the following measurements: (1) the E-

TABLE 1

Mean* Radiofrequency Radiation Exposures at Four Exposed Companies and One Unexposed Company

Facility Group	Electric Field Strength [§] (V ² /m ²)		Magnetic Field Strength [§] (A ² /m ²)		Average Induced Foot Current [§] (mA)		Maximum Induced Foot Current [§] (mA)	
	GM ($\times 10^3$)	GSD	GM ($\times 10^{-2}$)	GSD	AR mean ($\times 10^2$)	SD	AR mean	SD
Exposed [†]								
1	1.2	15.2	1.9	7.6	1.1	116.0	5.2	6.8
2	9.0	2.6	3.6	8.6	1.1	38.0	5.7	3.3
3	3.9	1.7	6.4	2.1	1.3	51.7	6.2	4.4
4	5.8	2.4	3.1	3.9	0.7	45.4	5.5	9.0
Unexposed [‡]	ND		ND		ND		ND	

* Geometric means (GM) and standard deviations (GSD) were calculated for E- and H-field data; arithmetic means (AR) and standard deviations (SD) were calculated for body current data. Machine operating frequencies ranged from 12 to 57 mHz; 93% of the machines had operating frequencies between 20.3 and 32.0 mHz.

[†] Exposed facility means did not differ from each other ($P > 0.10$).

[‡] ND, not detectable.

[§] Time-weighted averages.

and H-field strength incident on the operator at eye, chest, and groin levels; (2) the induced current in the operator's feet from the E-field; and (3) the frequency of the emitted RF radiation. A Continental Mini Max Frequency Counter Model MM50 (Continental Specialties Corporation, New Haven, CT) was used to determine the operating frequency of the heater, which was compared with equipment label frequency information when possible. The incident E- and H-field strengths were measured by using a Holaday HI-3003 Broadband Isotropic Survey Meter (Holaday Industries, Inc, Eden Prairie, MN). Two probes were used: one to measure the E-field strength in V²/m² and the other to measure the H-field strength in A²/m². The data were recorded with a Holaday HI-3320 Data Logger protected against RF interference.⁴⁷ The RF-induced foot current was determined with the heater operator standing on a dual-foot sensor.⁹ The foot current flowed through the sensor across a resistor of known impedance and was calculated from the measured voltage across the resistor and the known impedance. Voltage was measured by a Ballantine Model 3440A RF Millivoltmeter (Ballantine Laboratories, Inc, Boonton, NJ). The foot current data also were recorded with the Holaday data logger. Field

strength and foot current were measured for a minimum of one product cycle or a maximum of 6 minutes. Because the data logger sampled real-time product cycles that included "off time," the exposures were time-weighted average (TWA) values. The logged data were then transferred to a computer for review and analysis.⁴⁸

Continuous, real-time RF radiation exposure data were corrected for the frequency dependence of radiation survey instrumentation and reduced to mean indices of exposure for each company. Geometric means and standard deviations were calculated for E- and H-field strength data; arithmetic means and standard deviations were calculated for body current data. Average foot current was considered to be the most relevant surrogate for biological dose; it was selected as the continuous operator exposure variable for regression modeling. If individual foot current measurements of the study participant were unavailable, company mean values were substituted. Dichotomous exposure was used in all other analyses.

Survey for potential confounding exposures. The following chemicals were identified as possible airborne contaminants from the RF heat-sealing process: 1,1,1-trichloroethane, toluene, decane, 2-ethyl-

1-hexanol, undecane, dodecane, remaining total hydrocarbons, formaldehyde, hydrochloric acid, and sulfuric acid. We based this selection on a literature review, our previous experience with RF heaters at a water bed plant, and walk-through surveys at study facilities. The comparison group had potential exposure to lead; airborne lead sampling was conducted at the comparison plant only. For airborne sampling at all study plants, NIOSH sampling methods were used.⁴⁹ General area air samples were collected at a height approximating the breathing zone. NIOSH analytical methods⁴⁹ were used for sample analysis with enhancement modifications for the hydrocarbon⁴⁹ and formaldehyde⁵⁰ methods. For hydrocarbons, NIOSH Method 1500 was modified to use a 30-m J & W DB-5 capillary column (J & W Scientific Co, Folsom, CA) on a gas chromatograph with a flame ionization detector. For formaldehyde, NIOSH Method P and CAM 354 were modified to use a 30-m J & W DX-4 capillary column (J & W Scientific Co, Folsom, CA) on a gas chromatograph with a flame ionization detector. Dermal exposure to chemicals was assessed in the workplace by the industrial hygienist.

TABLE 2

Characteristics of Exposed Radiofrequency (RF) Heater Operators and Unexposed Workers

Characteristic	Exposed (n = 12)	Unexposed (n = 34)
Age (yr; mean ± SD)	32.3 ± 7.5	34.5 ± 9.3
Race/ethnicity (%)*		
White	8.3	85.3
Black	41.7	5.9
Asian	50.0	5.9
Hispanic	0.0	2.9
Body mass index (kg/m ² ; mean ± SD)	24.1 ± 3.4	26.2 ± 4.8
Testicular volume (mL; mean ± SD)		
Right	18.3 ± 5.2	20.7 ± 4.0
Left	19.3 ± 5.7	20.8 ± 3.7
Duration of employment [†] (yr; mean ± SD)	6.8 ± 4.5	13.4 ± 8.1
Duration of employment as an RF heater operator (yr; mean ± SD)	4.1 ± 3.7	–
Self-reported use of solder and solvents in current position (%) [‡]	0.0	35.3
Current tobacco user (%)	41.7	50.0
Cigarettes/day (current smokers; mean ± SD)	14.3 ± 8.5	19.1 ± 11.8
Surrogate use of marijuana (%)	41.7	29.4
Alcohol		
Drank in past yr (%)	66.7	85.3
Frequent/binge drinker (%) [§]	25.0	23.5
Caffeine (estimated mg/day; mean ± SD)	155 ± 157	215 ± 171
Current use of medications (%)	33.3	14.7
History of urogenital disorders	25.0	26.5
Ever fathered a pregnancy (%)	66.7	64.7
Total number of pregnancies fathered (fathers only; mean ± SD)	2.8 ± 1.4	2.4 ± 2.3
Total number of adverse pregnancy outcomes (fathers only; mean ± SD)	0.25 ± 0.46	0.32 ± 0.48
Ejaculations/wk (mean ± SD)	2.3 ± 1.3	2.9 ± 1.9
Reported concern about ability to father a child (%) [¶]	50.0	17.7
Four or more days abstinence before donation of semen sample (%)	33.3	20.6
Semen sample age of 80 min or more on receipt at NIOSH laboratory (%) [#]	16.7	44.1

* $P < 0.001$.† $P = 0.001$.‡ $P = 0.02$.

§ Drinking frequency at least 'a few times a week' and/or reported binge drinking.

|| Sexually transmitted disease, urinary tract infection, phimosis, or enlarged meatus.

¶ $P = 0.03$.# $P = 0.09$.

Statistical Analysis

The relationship between RF radiation exposure and the male reproductive profile was analyzed initially with stratified analysis of exposure status, the 37 semen quality and hormonal outcomes, and potential confounders and effect modifiers, followed by least squares linear regression and multivariate analysis of variance. PC-SAS[™] software was used for all statistical procedures.⁵¹

Some of the semen quality parameters (motility, morphometry, and morphology) represented measurements on individual cells. These values were averaged across all cells in

a single sampling to simplify the data analysis. Although morphology measures are inherently categorical, the average across 200 cells (ie, the proportion in a certain morphology class) had a sufficient number of values to be treated as continuous. Categorical analysis of these counts in multiple morphology categories cannot be conducted inasmuch as it violates the assumption of independence between entries in a categorical contingency table.

Residual plots were examined for evidence of non-normality; when necessary, a transformation that normalized most of the data (logarithm-

mic, arcsine, or inverse) was applied to each related group of dependent variables. Mantel-Haenszel tests and Breslow-Day tests for homogeneity of odds ratios were used to screen 37 variables derived from a priori medical, exposure, and lifestyle factors for potential confounding or effect modification of the relationships between exposure and a panel of 14 representative indices of semen quality and hormonal status. Potential confounders from this screening were added to an initial model that contained an exposure index and the a priori variables age of donor, age of semen sample, abstinence time, and

TABLE 3

Sperm Concentration, Count, pH, Osmolality, and Volume in Exposed Radiofrequency Heater Operators and Unexposed Workers*

Characteristic	Adjusted Mean	Mean	SD	n	95% CI†
Sperm concentration ($\times 10^6$ sperm/mL)					58, 191%
Exposed	47.0	58.1 [†]	2.8	12	
Unexposed	44.7	42.7	2.3	34	
Sperm count ($\times 10^6$ sperm/ejaculate)					36, 172%
Exposed	73.0	–	3.0	12	
Unexposed	93.0	–	3.2	34	
Semen pH [§]					–0.28, –0.0031
Exposed	8.0	–	0.2	12	
Unexposed	8.2	–	0.2	30	
Semen osmolality (mOsm)					–23.2, 7.4
Exposed	343.9	349.4	14.4	12	
Unexposed	351.8	349.8	24.6	33	
Semen volume (mL)					–1.42, 0.5
Exposed	2.1	–	1.5	12	
Unexposed	2.6	–	1.4	34	

* Concentration and count data were normalized with natural log transformations before analysis, then untransformed for these results. Multivariate analysis of variance test of exposure effect on the combined variables sperm concentration and count did not indicate an effect ($P = 0.61$).

† 95% confidence interval (CI) for the difference between means. For concentration and count only, the CI represents the 95% interval for the ratio of exposed and unexposed means.

‡ Adjusted for surrogate use of marijuana ($P = 0.03$) and sample age ($P = 0.06$).

§ $P = 0.45$, 2-sided t test.

|| Adjusted for sample age ($P = 0.01$).

surrogate self-reported use of marijuana.⁵² Because no significant evidence of interaction was found, interactive terms were not entered in our models.

Linear least squares regression analysis modeling with modified backward selection of confounders was performed for each dependent variable. Exposure to RF radiation was represented as dichotomous and continuous (as average foot current) in separate models. To address multiple-comparison issues, a multivariate analysis of variance was conducted for each related group of dependent variables (morphology, morphometry, motility, hormones, SCSA data, and sperm count/concentration). Final models were evaluated with collinearity and residual analyses. No evidence of multicollinearity was present in the analysis of independent variables during regression analysis. Residual analyses suggested that outliers were present for the variables percent oval (normal) sperm and sperm head ratio (width:

length). Because no laboratory or data management errors were discovered that may have caused these outliers, they were retained in the analyses.

To identify predictors of participation, information collected from both participants and nonparticipants (age, race, exposure status, number of pregnancies fathered, number of normal live births, proportion of pregnancies with normal outcome, perceived fertility problem) was analyzed with multiple logistic regression after stratified analysis as described above.

Results

Selection of Participants

During the study enrollment period, 27 RF-exposed and 14 unexposed men were eliminated from the original lists of 98 RF-exposed and 140 unexposed men for reasons including vasectomy, preexisting infertility, vacation/medical leave, or in-

sufficient RF exposure, leaving 71 exposed and 126 unexposed eligible men. Additionally, as the field study activities began, the largest of the four water mattress companies (employing 52 male RF heater operators) withdrew its support for the study, leaving 19 eligible exposed men. All current employees of the company that withdrew refused participation, and we were unable to contact most of the eligible workers who had been recently laid off. We incorporated this company's RF exposure measurements as company 1 in Table 1. We also included the reproductive profile of one recently laid off RF heater operator who participated in the study. Participation rates were calculated excluding this company.

Thirteen exposed and 51 unexposed eligible men agreed to participate and were enrolled in the study, for participation rates of 68.4% (13 of 19) exposed and 40.8% (51 of 126) unexposed. One exposed and eight unexposed study participants later withdrew from the study, for

TABLE 4
Sperm Motility, Viability, and Velocity in Exposed (*n* = 12) Radiofrequency Heater Operators and Unexposed (*n* = 33) Workers*

Characteristic	Mean	SD	Adjusted Mean	95% CI/CL [†]
Motility [‡] (%)			–	
Exposed	67.2	4.4		55.6, 77.9
Unexposed	52.4	5.9		44.0, 60.7
Viability by stain exclusion [§] (%)			–	
Exposed	75.0	0.6		71.0, 78.8
Unexposed	65.9	2.3		61.0, 70.7
Viability by hypoosmotic swelling (%)			–	
Exposed	69.1	1.6		62.3, 75.5
Unexposed	65.9	2.4		60.8, 70.9
Straight line velocity (μ/sec)			–	–5.4, 9.1
Exposed	40.5	11.0		
Unexposed	38.6	10.6		
Curvilinear velocity (μ/sec)				–5.5, 11.3
Exposed	57.0	15.0		
Unexposed	54.1	11.4		
Linearity			–	–0.1, 0.1
Exposed	0.7	0.1		
Unexposed	0.7	0.1		
Amplitude of lateral head displacement [¶] (μ)				79.1, 112.9%
Exposed	1.8	1.3	1.7 [#]	
Unexposed	1.9	1.3	1.9	
Beat cross-frequency (Hz)			–	–0.8, 1.1
Exposed	15.2	1.4		
Unexposed	15.0	1.4		

* Multivariate analysis of variance test of exposure effect on the combined motility and velocity variables did not indicate an effect (*P* = 0.31).

[†] Amplitude of lateral head displacement confidence interval (CI) represents the 95% interval for the ratio of exposed and unexposed means. CIs for motility and viability represent 95% intervals for separate exposed and unexposed means. All other CIs represent the 95% interval for the difference between means.

[‡] Motility and viability data were normalized with arcsine transformations before analysis, then untransformed for all reported results.

[§] *P* = 0.01, 2-sided *t* test.

^{||} Ratio of straight-line velocity: curvilinear velocity.

[¶] Amplitude of lateral head displacement was normalized with a natural log transformation before analysis, then untransformed for reported results.

[#] Adjusted for age (*P* = 0.005).

final participation rates of 63.2% (12 of 19) exposed and 34.1% (43 of 126) unexposed.

Of the 56 men who participated in the study (12 exposed men from participating study companies, 1 exposed participant from the study company that refused to participate, and 43 unexposed men), 5 were excluded from analysis for preexisting medical conditions that were judged to have potential impact on reproductive health, 4 were excluded for prior occupational exposure to radar, and 1 was excluded because of re-

peated x-ray exposure during the 3 months preceding the study. Data analyses were thus based on information from 12 RF-exposed and 34 unexposed participants.

Reasons for participation or refusal were examined from questionnaire information. For 52% of the participants, the \$40 incentive was an important reason for participation; it was the primary reason for participation for 19.6%. Of the nonparticipants, 50% stated that the study's masturbation requirement was an important reason for re-

fusal, and 25% had an important objection to the study's required physical and blood drawing. Multiple logistic regression on factors collected from both participants and nonparticipants indicated that race reported as black (odds ratio, 0.2; 95% confidence interval, 0.08 to 0.7), exposed status (odds ratio, 5.8; 95% confidence interval, 0.4 to 22.1), and reported perceived fertility concern (odds ratio, 2.9; 95% confidence interval, 1.0 to 8.5) were predictors of participation. For men who had fathered a pregnancy, one or more pregnancies not ending in a normal live birth replaced perceived fertility concern in the model.

Characteristics of the Groups

Table 2 summarizes RF radiation-exposed and comparison group medical, exposure, and lifestyle characteristics. Exposed RF heater operators were primarily Pakistani and black (92%), whereas 85% of the comparison participants were white. The RF heater operators reported significantly fewer years of total employment (6.8 ± 4.5) than the comparison group (13.4 ± 8.1). Fifty percent of the heater operators reported that participation in the study was "somewhat" or "very" important because "... it may help me to learn why I am having trouble fathering children," whereas only 18% of the comparison group reported similar motivation. Solder and solvent exposures were reported by 35.3% of the comparison participants and none of the RF heater operators. More comparison group participants than RF heater operators reported semen sample ages of 80 minutes or more (44% vs 17%). These differences were examined in data analysis. Few of these differences necessitated adjustment of means; these adjustments are noted in the tabulated results. Occupational exposure to potentially confounding chemicals was evaluated at all facilities.

TABLE 5
Sperm Morphology* in Exposed Radiofrequency Heater Operators and Unexposed Workers

Characteristic	Mean	Adjusted Mean	95% CI†
Normal (oval) forms			
Exposed	80.5	–	78.1, 83.2
Unexposed	78.5	–	76.5, 81.1
Abnormal forms			
Macrocephalic			
Exposed	2.0	–	1.1, 2.7
Unexposed	1.6	–	1.0, 1.7
Microcephalic			
Exposed	1.0	1.0‡	0.5, 1.3
Unexposed	1.3	0.9	0.6, 1.4
Absent heads			
Exposed	2.6	–	1.7, 3.3
Unexposed	2.5	–	1.8, 2.8
Tapered heads			
Exposed	1.8	–	0.8, 2.4
Unexposed	1.3	–	0.6, 1.4
Double heads§			
Exposed	1.2	0.9¶	0.5, 1.6
Unexposed	2.1	1.8	1.3, 2.3
Amorphous heads			
Exposed	1.8	–	0.9, 2.4
Unexposed	1.7	–	1.1, 1.9
Tail defects			
Exposed	2.4	–	1.1, 3.2
Unexposed	3.7	–	2.4, 4.2
Immature forms			
Exposed	6.7	–	4.2, 8.6
Unexposed	7.6	–	5.0, 8.5

* The arithmetic mean for each characteristic represents the average of two slides (200 cells read per slide). Morphologic characteristics do not total to 100 percent because of rounding. Morphologic data were normalized with arcsine transformations before analysis, then untransformed for all other results. Multivariate analysis of variance test of exposure effect on this group of dependent variables did not indicate an effect ($P = 0.68$).

† 95% confidence interval (CI) for the difference between means.

‡ Adjusted for age ($P = 0.0007$), surrogate use of marijuana ($P = 0.015$), and use of pain medications in the past 3 months ($P = 0.0066$).

§ $P = 0.07$, 2-sided t test.

¶ Adjusted for age ($P = 0.01$).

Extent of Exposure

RF radiation exposures. Incident E- and H-field strength and induced foot current measurements are reported by company in Table 1. A total of 39 individuals were surveyed at the water bed companies, including 8 of the 12 exposed participants in the semen quality/hormonal analyses. The E- and H-field strengths were best described by a lognormal distribution, but foot currents were normally distributed. Mean values and standard deviations were calculated for each company. Wide variation in RF heater design, function,

and shielding are responsible for the large geometric standard deviations observed. Mean TWA E- and H-field exposures ranged from 1.00 to $5.58 \times 10^4 \text{ V}^2/\text{m}^2$ and 2.00×10^{-4} to $5.28 \times 10^{-1} \text{ A}^2/\text{m}^2$, respectively, at the four water mattress companies. The arithmetic means of maximum foot currents ranged from 5.90×10^{-3} to $2.87 \times 10^2 \text{ mA}$, and mean TWA foot currents ranged from 1.00×10^{-4} to $2.37 \times 10^1 \text{ mA}$. There were no statistically significant differences between companies for mean E- and H-field strengths, or maximum or mean foot current ex-

posures.⁵³ For the study participants who were tested, the RF heater operator study participant mean TWA foot currents ranged from 4.49×10^{-1} to $1.25 \times 10^1 \text{ mA}$.

The E- and H-field strength and foot currents were also measured at the comparison plant. Mean exposures were lower than the visual detection levels of the respective meters and were not considered to constitute significant RF radiation exposure for the comparison group.

Confounding exposures. A total of 259 air samples were collected at RF-exposed and unexposed companies. The following chemical analyses were performed: 1,1,1-trichloroethane ($n = 23$), toluene ($n = 23$), decane ($n = 23$), dodecane ($n = 23$), undecane ($n = 23$), 2-ethyl-1-hexanol ($n = 23$), remaining total hydrocarbons as undecane ($n = 23$), formaldehyde ($n = 32$), hydrochloric acid ($n = 30$), and sulfuric acid ($n = 30$). Six samples were collected for airborne lead at the RF-unexposed plant only. All the formaldehyde, toluene, decane, dodecane, undecane, 2-ethyl-1-hexanol, remaining total hydrocarbons as undecane, and lead concentrations were below the limits of detection for the method used.

At the comparison plant, the hydrochloric acid concentrations were above the limit of detection in 1 of 12 air samples ($0.162 \text{ mg}/\text{m}^3$). Although these are area rather than personal samples, the concentrations are substantially lower than the Permissible Exposure Limit⁵⁴ (ceiling) of $7 \text{ mg}/\text{m}^3$. At the comparison plant, sulfuric acid concentrations were above the limit of detection in 1 of 12 air samples ($0.647 \text{ mg}/\text{m}^3$). The Permissible Exposure Limit for sulfuric acid is a TWA of $1 \text{ mg}/\text{m}^3$.⁵⁴

Some 1,1,1-trichloroethane concentrations were above the limit of detection at two facilities: a radiofrequency heater facility in a non-RF sealing area and the comparison plant. The detectable 1,1,1-trichloroethane concentrations in the non-RF sealing area were 27.00 and 29.01 mg/m^3 ($n = 3$). The detectable con-

TABLE 6

Sperm Morphometry in Exposed Radiofrequency Heater Operators ($n = 12$) and Unexposed ($n = 33$) Workers*

Characteristic	Mean	SD	95% CI†
Length (μm)			-0.1, 0.2
Exposed	4.7	0.3	
Unexposed	4.6	0.3	
Width (μm)			-0.1, 0.2
Exposed	2.9	0.1	
Unexposed	2.9	0.2	
Area (μm^2)			-0.4, 0.8
Exposed	9.2	0.7	
Unexposed	9.0	0.9	
Perimeter (μm)			-0.3, 0.6
Exposed	12.6	0.6	
Unexposed	12.5	0.6	
Width:length ratio			-0.02, 0.02
Exposed	0.7	0.03	
Unexposed	0.7	0.03	
Oval factor‡			-0.03, 0.4
Exposed	0.6	0.1	
Unexposed	0.6	0.1	

* Multivariate analysis of variance test of exposure effect on the combined morphometry variables did not indicate an effect ($P = 0.30$).

† Confidence intervals (CIs) represent the 95% CI for the difference between means.

‡ 4π area/perimeter².

centrations in the comparison plant were 14.00, 15.04, 16.44, and 39.25 mg/m^3 ($n = 10$). The Permissible Exposure Limit for 1,1,1-trichloroethane is a TWA of 1900 mg/m^3 .⁵⁴

Although some workers reported that intermittent dermal solvent exposures could occur, no dermal exposures were observed.

Semen and Hormonal Characteristics

Sperm concentration/count: semen pH, osmolality, volume. Exposed and unexposed groups were not found to differ in sperm count, concentration, semen volume, or osmolality (Table 3). The proportion of men with sperm concentrations of less than 20 million/mL did not differ between exposed and unexposed groups (16.6% and 14.7%). Mean semen pH was slightly lower for exposed samples (8.01) than for unexposed samples (8.15).

Sperm motility, viability, and velocity. Exposed and unexposed groups were not found to differ for mean motility and velocity variables (Table 4). Samples from exposed

men had a higher percent viability by both hypoosmotic swelling and stain exclusion methods.

Sperm morphology and morphometry. Mean percent normal (oval) sperm and the distribution of abnormal sperm morphology did not differ between exposed and unexposed groups, with the exception of a marginally higher proportion of double-headed sperm in the unexposed group (Table 5). None of the mean measures of sperm morphometry or their coefficients of variation differed between exposed and unexposed groups (Table 6). Analyses were conducted with and without outliers, which were present for percent oval (normal) sperm and sperm head ratio (width:length). For percent oval (normal) sperm, inclusion or exclusion of outliers did not change the model. For sperm head ratio, exclusion of two influential outliers caused RF exposure to become marginally significant in the model. The outliers were retained in the final models because no justification was found for their removal.

Hormones, biochemistry, and sperm chromatin structure assay. Exposed and unexposed groups did not differ for total testosterone, LH, or prolactin (Table 7). The exposed workers, however, had a higher mean FSH level than unexposed workers (7.6 vs 5.8 mIU/mL, $P = 0.05$). Differences between exposure groups were not found for the three measures of SCSA (Table 7). Results of modeling with continuous exposure (mean foot current) were consistent with dichotomous exposure models as described above, with the exception that the difference in FSH levels between exposure groups was not present in the continuous model.

Discussion

The results for the 37 measures of semen quality and endocrine function that we examined in this cross-sectional survey were generally similar to those found in the NIOSH Longitudinal Study of unexposed workers^{28,36,55} and to those of comparison groups of earlier NIOSH male reproductive studies.⁵⁶⁻⁵⁸ Because adequate statistical power was dependent on worker and management support from all four water mattress companies, withdrawal of the largest company resulted in insufficient study power for some of the analyses despite a 63% response rate at the other water mattress companies. Because of the small sample size for this study, effects on semen quality and hormone levels due to RF exposure cannot be ruled out, and additional studies are warranted.

For four outcome variables examined, differences were noted in mean test values for exposed and unexposed men. The first two differences, marginally lower pH and greater viability of the exposed group samples, may be artifacts of the exposed participants' shorter average travel time to the NIOSH field laboratory. When we added sample age to our results, however, it did not appear to confound these results, although age was a significant confounder of osmolality.

TABLE 7

Hormones, Seminal Biochemistry, and Sperm Chromatin Structure Assay in Exposed Radiofrequency Heater Operators and Unexposed Workers*

Characteristic	Mean	SD	n	95% CI†
Total testosterone (ng/mL)				76.1, 119.1%
Exposed	498.5	140.0	12	
Unexposed	523.8	139.0	34	
Follicle-stimulating hormone‡ (mIU/mL)				100.3, 171.6%
Exposed	7.6	1.6	12	
Unexposed	5.8	1.4	34	
Luteinizing hormone (mIU/mL)				83.7, 149.3%
Exposed	11.5	1.6	12	
Unexposed	10.3	1.5	34	
Prolactin (ng/mL)				60.7, 127.8%
Exposed	4.3	1.7	12	
Unexposed	4.9	1.7	34	
Zinc in seminal plasma (mg/100 mL)				53.9, 133.6%
Exposed	10.6	2.0	11	
Unexposed	12.4	1.9	32	
Fructose in seminal plasma (mg/100 mL)				-24.1, 118.0
Exposed	303.8	115.5	11	
Unexposed	256.9	92.5	29	
Mean ratio of denatured:total sperm DNA§				
Exposed	0.21	-	12	0.20, 0.23
Unexposed	0.22	-	32	0.21, 0.24
SD of ratio of denatured:total sperm DNA				70.7, 109.7%
Exposed	0.0013	0.0014	12	
Unexposed	0.0015	0.0014	32	
% Sperm cells outside the main population				60.0, 147.2%
Exposed	11.9	1.6	12	
Unexposed	12.6	2.0	32	

* All variables reported except fructose and mean ratio of denatured:total sperm DNA were normalized with natural log transformations before analysis, then untransformed for reported results. The mean ratio of denatured:total sperm DNA was normalized with an inverse transformation before analysis, then untransformed for reported results. Multivariate analysis of variance tests of exposure effect on the four hormones and the three sperm chromatin structure assay variables did not indicate an effect ($P = 0.22$ and 0.12 , respectively).

† Confidence interval (CI) for fructose represents the 95% interval for the difference between means. CIs for the mean ratio denatured:total sperm DNA represent 95% intervals for separate exposed and unexposed means. All other CIs represent the 95% interval for the ratio of exposed and unexposed means.

‡ $P = 0.05$, 2-sided t test.

§ Interpretation of mean channel of (red/(red + green) fluorescence). For details of the sperm chromatin structure assay, see Methods.

|| Refers to sperm nuclei demonstrating the presence of denatured DNA. For details of the sperm chromatin structure assay, see Methods.

A marginal difference was also detected in a higher proportion of double-headed sperm in samples from unexposed men. A similar result was reported in the NIOSH study of metal casting workers who were exposed to 2-ethoxyethanol.⁵⁸ As in that study, the small magnitude of the difference and lack of consistency with other results suggests that the difference may be due to a multiple-comparisons effect or other source of bias. In our set of tests, we attempted to address multiple-comparison problems by using multivariate analysis of variance for related outcomes; none of these multivariate models reiterated the

significant differences observed in univariate testing. If the null hypothesis is true, approximately 2 of our 37 results might be expected to differ at levels of statistical significance by chance alone.

The fourth difference noted, an increased mean FSH level in samples from RF-exposed men, must be interpreted with caution because of the small sample size. The increase may be consistent with a subclinical testicular effect caused by RF hyperthermia or nonthermal processes. All of the participants' FSH levels were well within the limits of clinically established normal ranges.⁵⁹ Markedly increased FSH can indicate per-

manent destruction of the germinal epithelium, as was the case for some workers who became permanently sterile after exposure to the nematocide dibromochloropropane.⁶⁰ The expected concurrent increased LH levels and decreased sperm count/concentration observed in those workers were not observed in this study.

Hyperthermia, whether from RF radiation or other circumstances, is a well-documented cause of adverse male reproductive effects. Scrotal hyperthermia has been associated with increased FSH, increased LH, and low sperm counts.⁶¹ When RF exposures are hyperthermic (SAR

>5 W/kg), animal studies have reported decreased testicular weight,^{15,16} degeneration of germinal cells,¹⁷ reductions in sperm count and morphologic changes,^{18,19} and neuroendocrine effects.²⁰ Semen quality in animals may be also be affected by nonthermal RF radiation levels.⁶² In humans, an experimental study of six volunteers also suggested thermal RF effects on the germinal epithelium.²¹ These men were exposed to shortwave radiation (probably 27 MHz) for an average of 45 minutes until their core temperatures reached 40.5 to 41°C. Sperm counts were reduced to approximately 50% of preexposure values at 42 to 50 days after exposure, but they returned to normal levels after an average duration of 25 days. Repeated radiation treatment caused similar or more severe results. No data were collected on gonadotrophin levels. Data are not available on nonthermal reproductive effects of RF radiation in humans.

Were the exposures to the RF heater operators in this study sufficient to cause a moderate increase in FSH levels? It is unlikely that any of the confounding chemical exposures measured were of sufficient magnitude to affect the results. For RF exposure, company geometric mean E- and H-field strengths did not differ significantly from one another or from the IEEE values of 3770 V²/m² and 0.30 A²/m² at 30 MHz.⁷ Induced mean foot currents were all less than or equal to the IEEE occupational guideline of 200 mA,⁷ and a dose-response effect with increasing current was not seen in our models. However, differences from the IEEE guidelines may be obscured by the variance of this small sample size and the wide variation in exposure levels. We noted that about two-thirds of the heater operators were individually exposed at levels exceeding the IEEE guidelines. The IEEE guidelines were established to ensure that the average whole-body SAR will not exceed 0.4 W/kg, which is estimated to be tenfold

lower than the lowest SAR value documented to produce adverse human or animal effects. Also, the IEEE guidelines have been set such that a partial-body SAR will not exceed 20 W/kg for an appendage. Previous data indicate that SARs in the groin area can be quite high, even when measured exposures are below recommended guidelines.^{10,11} In this study, the deviance of individual exposures from IEEE guidelines suggests that for at least some operators, RF exposures may be at a level capable of inducing biological effects.

It is possible that the modestly increased FSH levels of the RF heater operators indicate a chronic RF radiation effect on germinal epithelium with sufficient compensatory increase in gonadotrophin levels to maintain normal semen quality. However, further studies of these issues must be undertaken before firm conclusions are drawn concerning the association between increased FSH levels and the RF radiation exposure of heater operators.

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References

1. Centaur Associates, Inc. *Final Report: Study of Radiofrequency and Microwave Radiation (Phase I) Prepared for Occupational Safety and Health Administration*. Alexandria, VA: Centaur Associates, Inc; 1982:50–61.
2. Cox C, Murray WE, Foley ED. Occupational exposures to radiofrequency radiation (18–31 MHz) from RF dielectric heat sealers. *Am Ind Hyg Assoc J*. 1982; 43:149–153.
3. Conover DL, Murray WE, Foley ED, Lary JM, Parr W. Measurement of electric- and magnetic-field strengths from industrial radio-frequency (6–38 MHz) plastic sealers. *Proc IEEE*. 1980;68:17–20.
4. Joyner KH, Bangay MJ. Exposure survey of operators of radiofrequency dielectric

heaters in Australia. *Health Physics*. 1986;50:333–344.

5. Desideri E, Fantacci M, Micco L, et al. Environmental and health investigation in female workers exposed to radiofrequency electromagnetic fields [in Italian]. *La Medicina del Lavoro*. 1985;76: 399–411.
6. Mild KH, Kolmodin-Hedman B, Urdal L, et al. Effects on human beings of high exposure to radiofrequency radiation—a study of health and exposure of plastic welding machine operators [in Swedish]. *Arbete och Halsa*. 1987;10:1–66.
7. Institute of Electrical and Electronics Engineers Standards Coordinating Committee SCC 28 on Non-Ionizing Radiation Hazards. *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*. New York: IEEE; 1991. IEEE C95.1–1991.
8. National Council on Radiation Protection and Measurements. *Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Fields: Recommendations of the National Council on Radiation Protection and Measurements*. Bethesda, MD: NCRP; 1986:274–279. NCRP Report No. 86.
9. Gandhi OP, Chen JY, Riazi A. Currents induced in a human being for plane-wave exposure conditions 0–5 MHz and for RF sealers. *IEEE Trans Biomed Eng*. 1986;33:757–767.
10. Chen JY, Gandhi OP. Electromagnetic deposition in an anatomically-based model of man for leakage fields of a parallel-plate dielectric heater. *IEEE Trans Microwave Theory Techniques*. 1989;37:174–180.
11. Guy AW, Webb MD, Sorensen CC. Determination of power absorption in man exposed to high-frequency electromagnetic fields by thermographic measurements on scale models. *IEEE Trans Biomed Eng*. 1976;23:361–371.
12. Williams P, Mild KH. *Guidelines for the Measurement of RF Welders*. Umea, Sweden: National Institute of Occupational Health, Department of Medicine; 1991. Report No. ISRN. AI/UND-91/8-SE.
13. Stuchly MA, Kozłowski JA, Symons S, Lecuyer DW. Measurements of contact currents in radiofrequency fields. *Health Physics*. 1991;60:547–557.
14. Bureau of Radiation and Medical Devices. *Limits of Exposure to Radiofrequency Fields at Frequencies From 10kHz-300GHz (Safety Code 6)*. Ottawa: Canada Communications Group; 1991.
15. Berezniatskaya AN, Kazbekov IM. Studies on the reproduction and testicular

- microstructure of mice exposed to microwaves. In: Gordon ZV, ed. *Biological Effects of Radiofrequency Electromagnetic Fields*. Arlington, VA: US Joint Publications Research Service; 1974: 221–229. JPRS 63321.
16. Maniey J, Le Ruz P, Pluiren G. Effects of microwaves on development of gonads and adrenal glands in the newborn rat. *Effets Biologiques des Rayonnements non Ionisants—Utilization et Risques Associes: Proceedings of the Ninth International Congress of the Societe Francaise de Radioprotection*. 1978;255–264.
 17. Varma MN, Traboulay EA Jr. Biological effects of microwave radiation on the testes of Swiss mice. *Experientia*. 1975; 31:301–302.
 18. Saunders RD, Darby SC, Kowalczuk CI. Dominant lethal studies in male mice after exposure to 2.45 GHz microwave radiation. *Mutation Res*. 1983;117:345–356.
 19. Kowalczuk CI, Saunders RD, Stapleton HR. Sperm count and sperm abnormality in male mice after exposure to 2.45 GHz microwave radiation. *Mutation Res*. 1983;122:155–161.
 20. Mikolajczyk H. Microwave-induced shifts of gonadotropic activity in anterior pituitary gland of rats. In: Johnson CC, Shore ML, eds. *Biological Effects of Electromagnetic Waves*. Rockville, MD: Food and Drug Administration; 1976: 377–383. US DHEW No. 77–8010.
 21. MacLeod J, Hotchkiss RS. The effect of hyperpyrexia upon spermatozoa counts in men. *Endocrinology*. 1941;28:780–784.
 22. Elder JA, Cahill DF, eds. *Biological Effects of Radiofrequency Radiation*. Research Triangle Park, NC: Health Effects Research Laboratory, ORD, US Environmental Protection Agency; 1984. US EPA document 600/8–83-026F.
 23. Navakatikian MA, Tomashevskaya LA. Phasic behavioral and endocrine effects of microwaves of nonthermal intensity. In: Carpenter DO, Ayrapetyan SN, eds. *Biological Effects of Electric and Magnetic Fields*. San Diego: Academic Press; 1994:333–342.
 24. Barron CI, Love AA, Baraff AA. Physical evaluation of personnel exposed to microwave emanations. *J Aviation Med*. 1955;26:442–452.
 25. Lancranjan I, Maicanescu M, Rafaila E, Klepsch I, Popescu HI. Gonadic function in workmen with long-term exposure to microwaves. *Health Physics*. 1975;29: 381–383.
 26. Takihara H, Sakatoku J, Fujii M, Nasu T, Cosentino MJ, Cockett ATK. Significance of testicular size measurements in andrology. I. A new orchimeter and its clinical application. *Fert Steril*. 1983;39: 836–840.
 27. Schrader SM, Ratcliffe JM, Turner TW, Hornung RW. The use of new field methods of semen analysis in the study of occupational hazards to reproduction: the example of ethylene dibromide. *J Occup Med*. 1987;29:963–966.
 28. Schrader SM, Turner TW, Simon SD. Longitudinal study of semen quality of unexposed workers: sperm head morphometry. *J Androl*. 1990;11:32–39.
 29. Schrader SM, Turner TW, Breitenstein MJ, Simon SD. Longitudinal study of semen quality of unexposed workers. I. Study overview. *Reprod Toxicol*. 1988;2: 183–190.
 30. Fuentes J, Miro J, Riera J. Simple colorimetric method for seminal plasma zinc assay. *Andrologia*. 1982;14:322–327.
 31. Mann T. *The Biochemistry of Semen and of the Male Reproductive Tract*. New York: Wiley; 1964.
 32. Polakoski KL, Kopta M. Seminal plasma. In: Zaneveld LJD, Chatterton RT, eds. *Biochemistry of Mammalian Reproduction*. New York: Wiley and Sons; 1982.
 33. Evenson DP. Flow cytometry evaluation of male germ cells. In: Yen A, ed. *Flow Cytometry: Advanced Research and Clinical Applications*. vol I. Boca Raton: CRC Press; 1989:217–246.
 34. Evenson DP, Darzynkiewicz Z, Melamed MR. Relation of mammalian sperm chromatin heterogeneity to fertility. *Science*. 1980;210:1131–1133.
 35. Evenson DP, Higgins PJ, Gruenberg D, Ballachey BE. Flow cytometric analysis of mouse spermatogenic function following exposure to ethylnitrosourea. *Cytometry*. 1985;6:238–253.
 36. Evenson DP, Jost LK, Baer RK, Turner TW, Schrader SM. Individuality of DNA denaturation patterns in human sperm as measured by the sperm chromatin structure assay. *Reprod Toxicol*. 1991;5:115–125.
 37. Fossa SD, DeAngelis P, Kraggerud SM, Evenson D, Theodorsen L, Clausen OPF. Prediction of posttreatment spermatogenesis in patients with testicular cancer by flow cytometric sperm chromatin structure assay. *Cytometry (Commun Clin Cytometry)*. 1997;30:192–196.
 38. Evenson DP, Klein FA, Whitmore WF, Melamed MR. Cytometric evaluation of sperm from patients with testicular carcinoma. *J Urol*. 1984;132:1220–1225.
 39. Aravindan GR, Bjordahl J, Evenson DP. Susceptibility of human sperm to in situ DNA denaturation is strongly correlated with DNA strand breaks identified by single-cell electrophoresis. *Exp Cell Res*. 1997;236:231–237.
 40. Evenson DP, Jost LK, Marshall D, et al. Utility of the sperm chromatin structure assay as a diagnostic and prognostic tool in the human fertility clinic. *Hum Reprod*. 1999;14:1039–1049.
 41. Odell WD, Rayford P, Ross GT. Simple partially automated method for radioimmunoassay of human thyroid stimulating, growth, luteinizing and follicle stimulating hormones. *J Lab Clin Med*. 1967;70: 973–980.
 42. Odell WD, Ross GT, Rayford PL. Radioimmunoassay of human luteinizing hormone. *Metab Clin Exp*. 1966;15:287–289.
 43. Aubert AL, Becker RL, Saxena BB, Raiti S. Report of the National Pituitary Agency. Collaborative study of the radioimmunoassay of human prolactin. *Endocrinology*. 1974;38:1115–1120.
 44. Sinha YN, Selby FW, Lewis UJ, Vanderlaan WP. A homologous radioimmunoassay for human prolactin. *J Clin Endocrinol Metab*. 1973;36:509–516.
 45. Bartke A, Steele RE, Musto N, Caldwell BV. Fluctuations in plasma testosterone levels in adult male rats and mice. *Endocrinology*. 1973;92:1223–1228.
 46. Abraham GE. Radioimmunoassay of plasma steroid hormones. In: Heftman E, ed. *Modern Methods of Steroid Analysis*. New York: Academic Press; 1973:452–470.
 47. Cox C, Grajewski BA, Edwards RM, Murray WE, Conover DL. Two systems for collection, storage, and analysis of measurements made with RF field survey instruments. *Appl Ind Hyg*. 1989;4:286–290.
 48. Edwards RM, Cox C, Grajewski BA. A computer program for use with the Holiday HI-3320 or Metrosonics dl-332 data logger. *Appl Ind Hyg*. 1989;4:291–306.
 49. National Institute for Occupational Safety and Health. *Manual of Analytical Methods*. 3rd ed. vols 1 and 2. Cincinnati, OH: Department of Health and Human Services, NIOSH; 1984. NIOSH Publication No. 84-100.
 50. National Institute for Occupational Safety and Health. *Manual of Analytical Methods*. 2nd ed. vol 7. Cincinnati, OH: Department of Health and Human Services, NIOSH; 1982. NIOSH Publication No. 82-100.
 51. SAS Institute, Inc. *SAS/STAT User's Guide, Release 6.03 Edition*. Cary, NC: SAS Institute; 1988.
 52. Sudman S, Bradburn NM. Asking threatening questions about behavior. In: *Asking Questions*. San Francisco: Josey-Bass Publishers; 1982:54–87.
 53. Cox C, Grajewski BA, Murray WE, Edwards RM, Smith JM. RF radiation ex-

- posures of dielectric heater operators within the waterbed manufacturing industry. *Abstr Ann Mtg Am Ind Hyg Conf.* 1990;382:256.
54. Air contaminants. *Fed Reg.* April 6, 1990;55:12819.
55. Schrader SM, Turner TW, Simon SD. Longitudinal study of semen quality of unexposed workers: sperm motility characteristics. *J Androl.* 1991;12:126–131.
56. Welch LS, Schrader SM, Turner TW, Cullen MR. Effects of exposure to ethylene glycol ethers on shipyard painters: II. male reproduction. *Am J Ind Med.* 1988; 14:509–526.
57. Ratcliffe JM, Schrader SM, Steenland K, Clapp DE, Turner T, Hornung RW. Semen quality in papaya workers with long term exposure to ethylene dibromide. *Br J Ind Med.* 1987;44:317–326.
58. Ratcliffe JM, Schrader SM, Clapp DE, Halperin WE, Turner TW, Hornung RW. Semen quality in workers exposed to 2-ethoxyethanol. *Br J Ind Med.* 1989;46: 399–406.
59. Tietz NW, ed. *Clinical Guide to Laboratory Tests.* 3rd ed. Philadelphia: WB Saunders; 1995.
60. Eaton M, Schenker M, Whorton MD, Samuels S, Perkins C, Overstreet J. Seven-year follow-up of workers exposed to 1,2-dibromo-3-chloropropane. *J Occup Med.* 1986;28:1145–1150.
61. Miesusset R, Bujan L, Plantavid M, Grandjean H. Increased levels of serum follicle-stimulating hormone and luteinizing hormone associated with intrinsic testicular hyperthermia in oligospermic infertile men. *J Clin Endocrinol Metab.* 1989;68:419–425.
62. Manikowska E, Luciani JM, Servantie B, Czarski P, Obrenovitch J, Stahl A. Effects of 9.4 GHz microwave exposure on meiosis in mice. *Experientia.* 1979;35:388–390.

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