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Effect of Exposure to a Radiofrequency Electromagnetic Field on Body Temperature in Anesthetized and Non-Anesthetized Rats

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Exposure to a radiofrequency (RF) signal at a specific absorption rate (SAR) of 4 W/kg can increase the body temperature by more than 1 °C. In this study, we investigated the effect of anesthesia on the body temperature of rats after exposure to an RF electromagnetic field at 4 W/kg SAR. We also evaluated the influence of body mass on rats' body temperature. Rats weighing 225 and 339 g were divided into sham- and RF-exposure groups. Each of the resulting four groups was subdivided into anesthetized and non-anesthetized groups. The free-moving rats in the four RF-exposure groups were subjected to a 915 MHz RF identification signal at 4 W/kg whole-body SAR for 8 h. The rectal temperature was measured at 1-h intervals during RF exposure using a small-animal temperature probe. The body temperatures of non-anesthetized, mobile 225 and 339 g rats were not significantly affected by exposure to an RF signal. However, the body temperatures of anesthetized 225 and 339 g rats increased by 1.9 °C and 3.3 °C from baseline at 5 and 6 h of RF exposure, respectively. Three of the five 339 g anesthetized and exposed rats died after 6 h of RF exposure. Thus, anesthesia and body mass influenced RF exposure-induced changes in the body temperature of rats. Bioelectromagnetics. 2020;41:104–112. © 2019 Bioelectromagnetics Society.

Keywords: **RF-EMF; anesthesia; Sprague–Dawley rat; rectal temperature**

INTRODUCTION

Mobile wireless telecommunication services have expanded dramatically over the last decade, and the levels of radiofrequency electromagnetic field (RF-EMF) irradiation and energy in the environment have increased as a consequence [World Health Organization, 2010; Kim et al., 2015, 2018]. This has increased public concerns regarding the potential detrimental health effects of exposure to RF-EMF [ICNIRP, 1998].

RF exposure can increase body temperature in a dose-dependent way, the so-called thermal effect. The predominant consequence of the thermal effect, which is typically induced by RFs more than 100 kHz, is increased body temperature. An increase in body temperature more than 1 °C can result in heat exhaustion and heat stroke, which may be fatal [ICNIRP, 1998; IEEE, 2006]. If body temperature increases by a physiologically significant amount, thermoregulatory mechanisms (sweating and increased peripheral blood flow) may delay, reduce, or

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prevent a measurable increase in temperature. EMF exposure-induced heating is typically distributed throughout the body, and the heat is eventually lost to the environment due to thermoregulatory responses. However, if prolonged, the excess heat generated by RF-EMF exposure can impair these responses and result in hyperthermia [D'Andrea, 1999].

Heat generation in exposed tissue [Jia et al., 2007] and organs [Kojima et al., 2004] was observed following the exposure to a high-intensity RF signal, which may affect physiological functions in animals. Indeed, whole-body [Jauchem and Frei, 1997] and local [Masuda et al., 2011] exposure to a high-intensity RF signal reportedly increased the body temperature in animals. Also, RF-exposed rats exhibited marked changes in various physiological parameters, including cardiovascular and respiratory responses, as well as increased body temperature [Jauchem and Frei, 1997; Jauchem et al., 2000]. Prolonged exposure to an EMF at more than 4 W/kg specific absorption rate (SAR) can overwhelm the thermoregulation response [Lu et al., 1987; D'Andrea, 1999; Ohtani et al., 2016]. Also, 1 h of exposure to a 1,439-MHz time-division multiple access fields at a brain-average SAR of 7.5 W/kg (peak SAR of 11 W/kg or whole-body average SAR of 1.7 W/kg) did not alter the body temperature in rats, but such exposure at a brain-average SAR of 25 W/kg (peak SAR of 39 W/kg or whole-body average SAR of 5.7 W/kg) raised the body temperature by 2 °C [Yamaguchi et al., 2003]. However, in another study, exposure to an EMF at an average of 4 W/kg whole-body SAR did not significantly alter the body temperature [Kim et al., 2013a,b, 2015, 2018; Paik et al., 2016; Wyde et al., 2018].

We hypothesized that rat core temperature would not be affected by RF exposure when the rats were awake and mobile, as a normal thermoregulatory function would work, but the body temperature of anesthetized rats would be elevated during exposure to RF irradiation, due to disrupted thermoregulation. Thus, we investigated the effect of anesthesia on the body temperature of 225 and 339 g rats after RF exposure to 4 W/kg whole-body SAR for 8 h.

MATERIALS AND METHODS

Animals

Male Sprague–Dawley rats (Dea-Han Biolink, Seoul, ROK; $n = 102$) were used. The rats were allowed to adapt to the new environment for 1 week according to applicable guidelines [Balcombe, 2006]. They were housed in an air-conditioned room at 22 ± 2 °C under a 12/12-h light/dark cycle with access to food (Dea-Han Biolink, Seoul, Republic of Korea) and water ad libitum.

The rats weighed on average 225 g (6 weeks old) and 339 g (9 weeks old) at the beginning of the study. The animal experiments were approved by the institutional ethics committee for animal experiments (110405-25).

Whole-Body RF Exposure System

We used a reverberation chamber with a RF identification (RFID) signal source operating at 915 MHz as an RF-EMF exposure system [Kim et al., 2013a,b], specifically, a whole-body exposure system (IRETEC, Anyang, ROK) for animal experiments [Jung et al., 2008; Wu et al., 2010]. The internal dimensions of the reverberation chamber were $2.2 \times 2.1 \times 1.5\ m^3$. A wooden table (1.4 m in length, 1.0 m in width, and 0.7 m in height) was placed in the center of the chamber. Eight cages (each $390 \times 235 \times 180\ mm^3$) could be placed on the table, and each cage could contain two rats without affecting the field uniformity. The field distribution and uniformity in the reverberation chamber were measured using a three-axis isotropic probe (HI-6105; ETS-Lindgren, Cedar Park, TX).

The whole-body average SAR of a rat model (US Air Force Research Laboratory—AFRL, Dayton, OH) was calculated for the measured electric field strength using a commercial finite-difference time-domain tool (XFDTD version 6.5; Remcom, State College, PA) for the incident plane waves in six orthogonal directions with two polarizations. Electromagnetic waves came from all directions at equal amplitudes in the experimental region of the reverberation chamber. To calculate the variation in SAR, we used a scaled rat model modified from an Air Force research laboratory (AFRL, Dayton, OH) adult rat model (221 mm). This model has 36 tissues, a mass of 339 g, and a voxel size of $0.39 \times 0.39 \times 0.42\ mm^3$. The maximum output power of the system was 60 W, and the exposure level and exposure time were established using a computer. An 11-bit digital personal identification number diode attenuator (Model 349; General Microwave, Farmingdale, NY) was used to control the output power level, and the amplified RFID signal was supplied to the chamber.

Experimental Design and RFID Exposure

To assess the effect of RF-EMF exposure at 4 W/kg whole-body SAR on temperature, we monitored the rats' rectal temperature at 1-h intervals. Also, the effect of RF exposure on the temperatures of

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225 and 339 ml volumes of water in 500 ml polyethylene terephthalate glycol bottles (Thermo Fisher Scientific, Waltham, MA) was assessed. A 0.9% normal saline solution was used as the one-component fluid.

The rats were divided into sham-exposed and RF-exposed groups; these were further subdivided into 225 and 339 g groups. In addition, to assess the effect of consciousness on body temperature after RF exposure, the rats were subdivided into anesthetized and non-anesthetized groups. Therefore, the 225 and 339 g rats were randomly assigned to the following eight groups: two non-anesthetized sham-exposure groups ($n = 20$ per group) and two anesthetized sham-exposure groups ($n = 6$, 225 g rats; $n = 5$, 339 g rats); two non-anesthetized RF-exposure groups ($n = 20$ per group) and two anesthetized RF-exposure groups ($n = 6$, 225 g rats; $n = 5$, 339 g rats). For RF exposure, two rats were placed in a cage ($390 \times 235 \times 180\ mm^3$) in a reverberation chamber. The rats were divided into sham-exposed and RF-exposed groups; these were further subdivided into 225 and 339 g groups. In addition, to assess the effect of consciousness on body temperature after RF exposure, the rats were subdivided into anesthetized and non-anesthetized groups. Therefore, the 225 and 339 g rats were randomly assigned to the following eight groups: two non-anesthetized sham-exposure groups ($n = 20$ per group) and two anesthetized sham-exposure groups ($n = 6$, 225 g rats; $n = 5$, 339 g rats); two non-anesthetized RF-exposure groups ($n = 20$ per group) and two anesthetized RF-exposure groups ($n = 6$, 225 g rats; $n = 5$, 339 g rats). For RF exposure, two rats were placed in a cage ($390 \times 235 \times 180\ mm^3$) in a reverberation chamber regardless of the rats' weights.

The RF exposure was maintained for 8 h, with short breaks at 1-h intervals for measurement of body temperature. To minimize the time lag of temperature measurements, only four rats were examined in each experiment; the experiments were repeated as necessary to achieve the required number of rats.

Non-anesthetized rats in the sham- and RF-exposure groups were allowed free movement without restraint. Anesthetized rats in the sham- and RF-exposure groups were anesthetized by intraperitoneal injection of 400 mg/kg of 10% chloral hydrate (Sigma, St. Louis, MO) in phosphate-buffered saline. The rats were immobilized by the effect of the anesthesia and maintained in a ventral recumbent position to maintain airway patency during RF exposure.

The mean time for induction of anesthesia was less than 5 min (data not shown), and its duration was about 3 h post-dosing (data not shown). The level of anesthesia was monitored for 8 h after RF exposure. The anesthetized rats in the sham-exposure group were transferred to a reverberation chamber for 8 h. The RF input power was set to 56 W for 339 g rats and to 49 W for 225 g rats to maintain a whole-body average SAR of 4 W/kg. The rats did not have access to food or water during RF exposure. After completion of the experiment, a cotton blanket was applied for rats that exhibited a decrease in body temperature more than 1 °C.

Measurement of Body Temperature

Rats' body temperatures (°C) were measured at 1-h intervals beginning 1 h before and ending 8 h after RF exposure using a small-animal thermometer (Test 925; Testo, Lenzkirch, Germany) during a short (<90 s) interruption of RF exposure. To minimize any variability in body temperature due to interruption of RF-EMF exposure, the procedure was carried out by an experienced scientist.

The temperatures of 225 and 339 ml volumes of water in 500 ml; bottles were monitored at 1-h intervals using a Luxtron 812 two-channel fiberoptic thermometer (LumaSense Technologies, Santa Clara, CA) during the 8-h exposure to an RF signal of a power identical to that used for the rats.

According to the ICNIRP guideline, the health-relevant increase of body core temperature is approximately 1 °C [ICNIRP, 1998]. On the basis of this guideline, we defined changes in core temperature of more than 1 °C as clinically significant. Therefore, although temperature increases were induced by RF exposure, they were not clinically significant because the temperatures were within the normal physiological range.

Statistical Analysis

Values are mean ± standard deviation. One-way repeated-measures analysis of variance (ANOVA) was performed to compare the values. A $P < 0.05$ was considered indicative of statistical significance. Data were analyzed using SPSS ver. 23.00 (SPSS, Chicago, IL).

RESULTS

Effect of RF Exposure on Body Temperature in 225 g Rats

Before RF exposure, the average body temperature of non-anesthetized 225 g rat ($n = 20$, 10 each in the sham- and RF-exposure groups) was 37.9 ± 0.2 °C, compared with 37.3 ± 0.4 and 37.8 ± 0.2 °C, respectively, at 8 h after RF exposure. The body temperatures of non-anesthetized 225 g rats in the sham- and RF-exposure

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TABLE 1. Rectal Temperatures of 225 g Rats Following Exposure to RF-EMF Were Measured for 8 h at 1 h intervals Using an Animal Rectal Probe

	Non-anesthetized						Anesthetized					
	Sham			RF			Sham			RF		
225 g	Average	±SD	ΔT	Average	±SD	ΔT	Average	±SD	ΔT	Average	±SD	ΔT
pre							37.9	0.0		37.9	0.0	
0 h	37.9	0.2	0.0	37.9	0.3	0.0	38.0	0.0	0.0	38.0	0.1	0.0
1 h	37.4	0.4	−0.5	37.8	0.1	−0.1	37.1	0.0	0.0	37.4	0.1	0.1
2 h	37.3	0.5	−0.6	37.4	0.2	−0.5	36.8	0.1	−0.8	37.7	0.1	−0.5
3 h	37.2	0.5	−0.7	37.6	0.1	−0.3	36.4	0.1	−1.2	38.1	0.2	−0.2
4 h	36.8	0.5	−1.1	37.6	0.2	−0.3	35.9	0.1	−1.5	38.0	0.1	0.2
5 h	37	0.4	−0.9	37.7	0.1	−0.2	35.9	0.2	−2.0	37.8	0.1	0.1
6 h	37.1	0.3	−0.8	37.7	0.2	−0.2	36.2	0.2	−2.0	37.8	0.1	−0.1
7 h	37.3	0.3	−0.6	37.8	0.3	−0.1	36.5	0.1	−1.7	37.6	0.1	−0.1
8 h	37.2	0.4	−0.7	37.8	0.2	−0.1	36.9	0.0	−1.4	37.9	0.1	−0.3

Data are mean ± standard deviation of 10 rats (non-anesthesia) and 6 rats (anesthesia); "ave" represents the average rectal temperatures measured every 1 h from 18 h after onset of RF-EMF exposure. ΔT indicates the difference between the baseline temperature and temperature during exposure.

RF = radiofrequency; RF-EMF = radiofrequency electromagnetic field; SD = standard deviation.

groups were significantly different ($F(1,18) = 17.377$, $P = 0.007$; one-way repeated-measures ANOVA; Table 1). However, after completion of 8 h of RF exposure, the body temperature of non-anesthetized 225 g rats in the RF-exposure group was maintained within less than 1 °C ($F(1,10 = 3.283)$, $P = 0.027$, $n = 6$, one-way repeated-measures ANOVA; Fig. 1A). Therefore, the temperature changes induced by RF exposure were not clinically significant because they were still within the normal physiological range. Before anesthesia, the body temperatures of anesthetized 225 g rats in the sham- and RF-exposure groups were 37.9 ± 0.1 and 38.0 ± 0.3 °C, respectively. After 1 h of anesthesia, the body temperatures of anesthetized rats in the sham- and RF-exposure groups decreased to 37.1 ± 0.2 and 37.4 ± 0.5 °C, respectively. The body temperatures of anesthetized 225 g rats in the sham-exposure group decreased to 35.8 ± 0.7 °C after 5 h of anesthesia, plateaued for 1 h, and subsequently recovered to 36.9 ± 0.1 °C, but not to the pre-anesthetic value (Fig. 1B). After completion of the experiment, a cotton blanket was applied to any anesthetized rat whose body temperature had decreased by more than 1 °C; this rapidly restored the body temperature (not shown). The body temperatures of anesthetized rats in the RF-exposure group decreased by less than 1 °C after 1 h of anesthesia and recovered to 38.1 ± 0.1 °C at 2 h after RF exposure. The body temperatures of anesthetized rats in the RF-exposure group was 0.05 °C higher after RF exposure compared with baseline ($F(1,8) = 2.884$), $P = 0.15$, one-way repeated-measures ANOVA; Fig. 1B). When the baseline rectal temperature of the sham-exposed rats was compared with the rectal temperature of the anesthetized rats, the latter was up to 1.9 °C higher with RF exposure (at 5 h after anesthesia) compared with the baseline value ($F(1,10) = 16.879$, $P = 0.002$, one-way repeated-measures ANOVA; Fig. 1B). Thus, anesthesia significantly reduced the body temperature of 225 g rats, and the decrease was restored by RF exposure.

Effect of RF Exposure on the Body Temperature of 339 g Rats

Before RF exposure, the body temperatures of the non-anesthetized 339 g rats in the sham- and RF-exposure groups ($n = 10$ each) were 37.9 ± 0.4 and 38.0 ± 0.4 °C, respectively. After 8 h of RF exposure, the body temperatures of non-anesthetized rats in the sham- and RF-exposure groups ($n = 10$ each) were 36.9 ± 0.2 and 37.3 ± 0.3 °C, respectively. The differences in body temperature between sham- and RF-exposed rats were not significant ($F(1,18) = 0.305$, $P = 0.588$, $n = 10$, $P > 0.05$, one-way repeated-measures ANOVA; Table 2). During RF exposure for 8 h, the body temperature of non-anesthetized 339 g rats in the RF-exposure group was maintained within less than 1 °C ($F(1,10) = 3.277$, $P = 0.030$, $n = 6$, one-way repeated-measures ANOVA; Fig. 2A). The body temperatures of the 339 g anesthetized rats in the sham- and RF-exposure groups were 37.9 ± 0.6 and 38.1 ± 0.3 °C, respectively, before anesthesia. The body temperature of anesthetized 339 g rats gradually decreased to 34.4 ± 0.5 °C after the initial 3 h of anesthesia and recovered thereafter, albeit not to the pre-anesthetic value. Therefore, after completion of the 8-h experiment, the body temperature was rapidly restored using a cotton blanket (data not shown).

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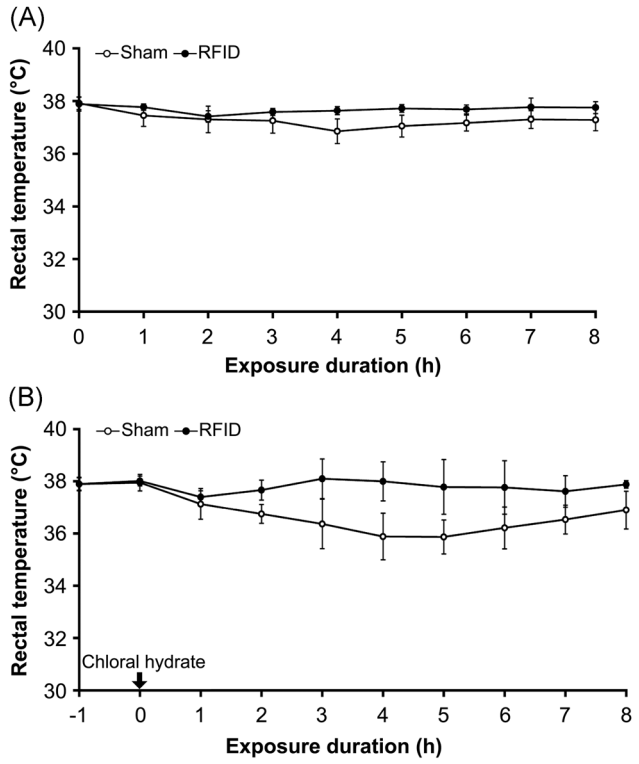


Fig. 1. Rectal temperatures of 225 g rats following exposure to RF-EMF were measured for 8 h at 1 h intervals using an animal rectal probe. (**A**) In the absence of anesthesia, the body temperature of rats in the RF-EMF- and sham-exposure groups differed by less than 1 °C. (**B**) Under anesthesia, the body temperature increased by 1.6 °C after 6 h in the RF-EMF-exposure group compared with the sham-exposure group. Data are mean ± standard deviation of 10 rats (non-anesthesia) and six rats (anesthesia). RF-EMF, radiofrequency electromagnetic field; RFID, radiofrequency identification. Significant at $P < 0.01$.

The body temperature of anesthetized 339 g rats in the RF exposure group ($n = 5$) increased gradually during RF exposure and reached 41.6 °C at 6 h of RF exposure in three rats. Therefore, RF exposure was immediately stopped at 6 h to avoid an extreme increase in body temperature. However, the body temperature did not drop, and the three rats died within 1 h. The body temperature in the remaining two rats also increased to 39.2 °C and 39.4 °C, but their temperatures eventually returned to normal. The body temperature of anesthetized 339 g rats increased by 3.3 °C after 6 h of RF exposure, compared with a 2.3 °C decrease in anesthetized sham-exposed 339 g rats ($F(1,8) = 65.550$, $P = 0.00$, $n = 5$, one-way repeated-measures ANOVA; Fig. 2B). After completion of the experiment, the body temperature was rapidly restored using a cotton blanket (data not shown).

Effect of RF Exposure on Water Temperature

During RF exposure, the temperatures of the 225 and 339 ml volumes of water increased by 4.1 ± 0.1 and 4.1 ± 0.1 °C, respectively (data not shown). There were no differences between the bottles in the magnitude or pattern of the RF exposure-induced changes in temperature ($F(1,4) = 2.179$, $P = 0.177$, $n = 3$, one-way repeated-measures ANOVA).

DISCUSSION

We report that exposure to an RF signal at 4 W/kg whole-body SAR caused a statistically significant increase in body temperature; however, it was not clinically significant in awake and mobile 225 and 339 g rats as the change in core temperature was still within the normal range. Also, the body temperature of anesthetized 225 g rats fluctuated by less than 1 °C during RF exposure. Under RF exposure, the core temperature significantly increased in RF-exposed rats compared with sham-exposed rats; however, the increase was less than 1 °C. According to the ICNIRP guideline, regardless of statistical significance, a temperature increase within 1 °C is still within the normal physiologic range. The body temperature of typical adult rats varies between 37.5 °C and 38.5 °C, and the normal rectal temperature is typically 37.5–37.8 °C. However, the body temperature of three of five anesthetized 339 g rats increased gradually to 41.6 °C after 6 h of exposure to an RF signal at 4 W/kg whole-body SAR. These rats died despite cessation of the scheduled 8-h RF exposure 2 h earlier. The body temperature in the remaining two rats returned to normal, and they recovered. Therefore, we suggest that both anesthesia and body mass influence RF exposure-induced changes in the body temperature of rats.

Body temperature in live animals, including humans, is tightly regulated and the range of fluctuations is always limited to less than 1 °C [Adair and Black, 2003]. The regulation of body temperature is a critical function of the nervous system [Tan and Knight, 2018], more specifically, of the hypothalamus [Imrie and Hall, 1990]. At typical ambient temperatures, thermal balance can be achieved without energy expenditure. Under severe conditions, several thermoregulatory mechanisms including alteration of vasomotor tone may be activated [Lin and Lin, 1981; Roberts, 1988].

General anesthesia can impair thermoregulation. Under anesthesia, rats' body temperatures decreased markedly, from 36–37 °C to 32–33 °C (3.5–4.5 °C below baseline) [Kiyatkin and Brown, 2005]. This

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TABLE 2. Rectal Temperature of 339 g Rats Following Exposure to RF-EMF Was Measured for 8 h at 1 h Intervals Using an Animal Rectal Probe

	Non-anesthetized						Anesthetized					
	Sham			RF			Sham			RF		
339 g	Average	±SD	ΔT	Average	±SD	ΔT	Average	±SD	ΔT	Average	±SD	ΔT
pre							37.9	0.6		38.1	0.3	
0 h	37.8	0.4	0	37.8	0.2	0	37.5	0.6	−0.4	37.1	0.4	−1
1 h	37.3	0.2	−0.5	38.1	0.1	0.3	35.7	0.6	−2.2	37.6	0.3	−0.5
2 h	36.9	0.2	−0.9	37.8	0.2	0	34.8	0.5	−3.1	38.2	0.3	0.1
3 h	36.9	0.0	−0.9	37.7	0.2	−0.1	34.4	0.5	−3.5	39.1	0.7	1
4 h	36.9	0.3	−0.9	37.7	0.2	−0.1	34.7	1.0	−3.2	39.5	0.7	1.4
5 h	36.8	0.2	−1	37.7	0.1	−0.1	35.0	1.0	−2.9	40.4	0.8	2.3
6 h	36.8	0.2	−1	37.7	0.4	−0.1	35.6	0.9	−2.3	40.6	0.9	2.5
7 h	36.9	0.3	−0.9	37.5	0.4	−0.3	36.2	0.8	−1.7			
8 h	36.9	0.3	−0.9	37.3	0.3	−0.5	36.5	0.6	−1.4			

Data are mean ± standard deviation of 10 rats (non-anesthesia) and 6 rats (anesthesia); "ave" represents the average rectal temperatures measured every 1 h from 1 to 8 h after onset of RF-EMF exposure. ΔT indicates the difference between the baseline temperature and the temperature during exposure.
RF = radiofrequency; RF-EMF = radiofrequency electromagnetic field; SD = standard deviation.

finding may explain why body temperature increased only in anesthetized rats during exposure to RF-EMF. The body temperatures of awake rats were maintained within the normal range, even during exposure to RF-EMF at 4 W/kg whole-body SAR. Under anesthesia, several factors can perturb thermoregulation, including a reduction in or cessation of behavioral responses and attenuated hypothalamic function, metabolic rate, and effector responses [Imrie and Hall, 1990].

General anesthesia-induced hypothermia is caused by core-to-peripheral redistribution of body heat, resulting in a 1–1.5 °C decrease in core temperature during the first hour. After anesthesia for 3–5 h, the core temperature reaches a steady-state [Sessler, 2008]. In this study, the body temperature of 225 and 339 g rats decreased gradually for 4 h and recovered slowly thereafter, although not to the pre-anesthesia level. These rats needed blankets to maintain their body temperatures.

In the guidelines of ICNIRP [1998], a whole-body SAR of 0.4 W/kg was set as the safety standard for humans. In this study, rats were exposed to RF-EMF at 4 W/kg SAR, 10-fold more than the safety standard for humans. This safety standard was developed using data from several animal studies performed in the 1970s and 1980s [de Lorge, 1979, 1984]. Exposure to RF-EMF at 4 W/kg SAR was reported not to alter the core temperature of rats [Kim et al., 2013a, 2015]. Our results may explain the discrepancies in the RF-EMF exposure-associated changes in body core temperature in awake compared with anesthetized rats. Heat exposure, diseases, drugs, and immobilization can induce hyperthermia in live animals. Several animal studies cited in the ICNIRP guidelines [1998] were carried out under anesthesia using restraints. Under general anesthesia, the heat absorbed during RF-EMF exposure cannot be readily monitored and adjusted properly.

In a prior study, male rhesus monkeys were exposed frontally to 2,450-MHz microwaves at 4, 16, 32, 42, 52, 62, and 72 mW/cm^2 [de Lorge, 1979] while they performed a vigilance task in a Styrofoam restraint chair. In these monkeys, the vigilance behavior was not significantly affected at power densities of 4–62 mW/cm^2; however, at 72 mW/cm^2, the performance decreased significantly and the average rectal temperature increased by 1 °C above the control level within 1 h. The increases in body temperature were generally highly correlated with behavioral decrements [Ghassemi Nejad and Sung, 2017]. Also, a power of 50–70 mW/cm^2 was required to increase the body temperature by more than 1 °C [de Lorge, 1979]. Thus, at 2.45 GHz and a power density of 67 mW/cm^2, a whole-body SAR of 4–5 W/kg was required to increase the rectal temperature by 1 °C [de Lorge, 1984]. Thus, exposure to an RF-EMF at 4 W/kg whole-body SAR increased the body temperature by 1 °C and induced behavioral abnormalities. In a mouse study to determine the thermal regulatory and thermal breakdown thresholds, in-tube restrained mice were exposed to 905 MHz RF-EMF at whole-body SARs of 2, 5, 10, 12, 16, and 20 W/kg for 2 h [Ebert et al., 2005]. They used B6C3F1 mice with a mass of 20, 24, or 29 g and NMRI mice with a mass of 36 g. They measured the rectal temperature under anesthetic conditions. The SAR levels between 2 and

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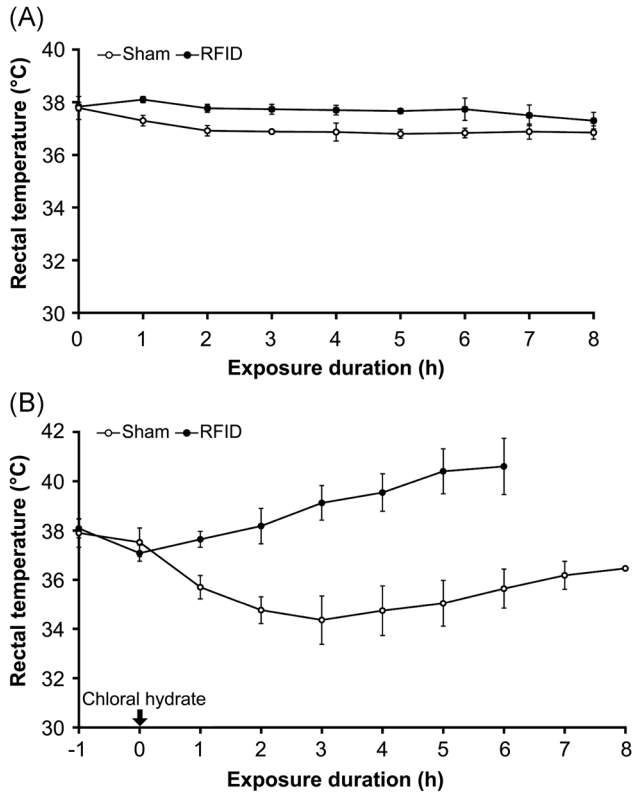


Fig. 2. Rectal temperature of 339 g rats following exposure to RF-EMF was measured for 8 h at 1 h intervals using an animal rectal probe. (**A**) In the absence of anesthesia, the body temperature of rats in the RF-EMF- and sham-exposure groups differed by less than 1 °C. (**B**) Under anesthesia, the body temperature increased by 5.0 °C after 6 h in the RF-EMF-exposure group compared with the sham-exposure group. Data are mean ± standard deviation of 10 rats (non-anesthesia) and 5 rats (anesthesia). RF-EMF = radiofrequency electromagnetic field; RFID = radiofrequency identification. Significant at $P < 0.01$.

5 W/kg were determined as the thermal regulatory threshold, whereas the breakdown of regulation was observed at 10.1 ± 4 W/kg for B6C3F1 mice and at 7.7 ± 1.6 for NMRI mice. They suggested that the thresholds depended on body mass and metabolic rate [Ebert et al., 2005]. These results in mice support our findings in rats. Exposure to EMF at more than 4 W/kg SAR has been shown to induce thermal effects and perturb the behavior of rodents and nonhuman primates [Lu et al., 1987; D'Andrea, 1999; Adair and Black, 2003; D'Andrea et al., 2007; Lai, 2008; Ohtani et al., 2016]. Our findings demonstrated similar results in anesthetized animals.

Several factors influence homeostatic mechanisms in live animals; for example, restrained rats frequently exhibit hyperthermia, likely due to impaired heat dissipation. Chloral hydrate is commonly used to induce anesthesia in rats and to immobilize them [Rodrigues et al., 2006]. In this study, we administered 400 mg/kg chloral hydrate intraperitoneally to anesthetize and immobilize the rats for 3 h. This dose ensured gentle emergence from anesthesia. The body temperature of anesthetized animals may be affected by the ambient temperature, age, disease, pregnancy, heart rate, and body size and type [Aydin et al., 2011; Kim, 2016; Wyde et al., 2018].

After RF exposure, the body temperature of 225-g rats decreased (<1 °C) after 1 h of anesthesia and subsequently recovered to the pre-anesthetic level at 8 h. Thus, RF-EMF exposure helped to restore the body temperature of anesthetized 225 g rats.

RF-EMF exposure following anesthesia reportedly promotes recovery from hypothermia in rats [Lai et al., 1984]. Also, the duration of pentobarbital anesthesia in rat was shortened by attenuation of the hypothermia following exposure to 2,450 MHz RF-EMF [Lai et al., 1984]. These findings agree with our results showing faster recovery to normal temperatures in 225 g rats after RF exposure. The rats in the control group, but not those in the RF-exposure group, required a cotton blanket to restore their body temperature.

After completion of RF exposure, the body temperature of the anesthetized RF-exposed, but not of the control 339 g rats, increased by more than 4 °C. These findings suggest that exposure of awake rats to a 4 W/kg RF signal did not have an adverse thermal effect. The anesthetized 339 g rats were also more vulnerable to RF exposure than the 225 g rats. Indeed, larger rats are reportedly more sensitive to RF exposure-induced increases in body temperature than the smaller rats [Wyde et al., 2018]. The smaller surface-to-mass ratio of large rats is advantageous at low temperatures, and the reverse is true for small rats [Riesenfeld, 1981]. Therefore, the ratio of body mass to the surface area, in conjunction with other factors, modulates thermoregulation.

This study has several limitations. We measured the rectal temperature at 1-h intervals using a small-animal thermometer, which may have induced stress in the rats. Stress, in addition to anesthesia, causes a rise in body temperature in laboratory animals [Dallmann et al., 2006]. Therefore, a less stressful method of measuring body temperature is needed. Although the procedures were performed by experienced staff, measuring body temperature is time-consuming. Thus, a better method of measuring body temperature is needed. To overcome these limitations, three to four rats were enrolled in each trial; therefore, the total number of rats was reached by repeating the experiments. We did not investigate the whole-body SAR RF-EMF exposure level that caused an increase

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of body temperature of 1 °C in awake rats. We did not evaluate the behavioral changes because simultaneous monitoring of changes in behavior and body temperature was not feasible. Finally, we used only a 900 MHz RF signal; thus, further investigation using signals of other frequencies and strengths is needed.

CONCLUSION

The body temperature of awake, mobile rats following exposure for 8 h to an RF signal at 4 W/kg whole-body SAR varied by less than 1 °C. Also, body mass may influence body temperature after RF exposure. However, we do not claim that RF-EMF exposure at more than 4 W/kg SAR is safe, and our findings should not influence the ICNIRP safety guidelines. Further studies are needed to examine the effect of exposure to RF signals on body temperature in more detail.

REFERENCES

Adair ER, Black DR. 2003. Thermoregulatory responses to RF energy absorption. Bioelectromagnetics Suppl 6:S17–S38.

Aydin C, Grace CE, Gordon CJ. 2011. Effect of physical restraint on the limits of thermoregulation in telemetered rats. Exp Physiol 96:1218–1227.

Balcombe JP. 2006. Laboratory environments and rodents' behavioural needs: A review. Lab Anim 40:217–235.

D'Andrea JA. 1999. Behavioral evaluation of microwave irradiation. Bioelectromagnetics Suppl 4:64–74.

D'Andrea JA, Ziriax JM, Adair ER. 2007. Radio frequency electromagnetic fields: Mild hyperthermia and safety standards. Prog Brain Res 162:107–135.

Dallmann R, Steinlechner S, von Horsten S, Karl T. 2006. Stress-induced hyperthermia in the rat: Comparison of classical and novel recording methods. Lab Anim 40:186–193.

de Lorge JO. 1979. Operant behavior and rectal temperature of squirrel monkeys during 2.45-GHz microwave irradiation. Radio Sci 14:217–225.

de Lorge JO. 1984. Operant behavior and colonic temperature of *Macaca mulatta* exposed to radio frequency fields at and above resonant frequencies. Bioelectromagnetics 5: 233–246.

Ebert S, Eom SJ, Schuderer J, Apostel U, Tillmann T, Dasenbrock C, Kuster N. 2005. Response, thermal regulatory threshold and thermal breakdown threshold of restrained RF-exposed mice at 905 MHz. Phys Med Biol 50:5203–5215.

Ghassemi Nejad J, Sung KI. 2017. Behavioral and physiological changes during heat stress in *Corriedale ewes* exposed to water deprivation. J Anim Sci Technol 59:13.

ICNIRP (International Commission on Non-Ionizing Radiation Protection). 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys 74:494–522.

IEEE (Institute of Electrical and Electronics Engineers). 2006. IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3 kHz to 300 GHz. New York, NY: Institute of Electrical and Electronics Engineers.

Imrie MM, Hall GM. 1990. Body temperature and anaesthesia. Br J Anaesth 64:346–354.

Jauchem JR, Frei MR. 1997. Body heating induced by sub-resonant (350 MHz) microwave irradiation: Cardiovascular and respiratory responses in anesthetized rats. Bioelectromagnetics 18:335–338.

Jauchem JR, Ryan KL, Frei MR. 2000. Cardiovascular and thermal effects of microwave irradiation at 1 and/or 10 GHz in anesthetized rats. Bioelectromagnetics 21:159–166.

Jia F, Ushiyama A, Masuda H, Lawlor GF, Ohkubo C. 2007. Role of blood flow on RF exposure induced skin temperature elevations in rabbit ears. Bioelectromagnetics 28:163–172.

Jung KB, Kim TH, Kim JL, Doh HJ, Chung YC, Choi JH, Pack JK. 2008. Development and validation of reverberation-chamber type whole-body exposure system for mobile-phone frequency. Electromagn Biol Med 27:73–82.

Kim HS, An YS, Paik MJ, Lee YS, Choi HD, Kim BC, Pack JK, Kim N, Ahn YH. 2013a. The effects of exposure to 915 MHz radiofrequency identification on cerebral glucose metabolism in rat: A [F-18] FDG micro-PET study. Int J Radiat Biol 89:750–755.

Kim HS, Paik MJ, Kim YJ, Lee G, Lee YS, Choi HD, Kim BC, Pack JK, Kim N, Ahn YH. 2013b. Effects of whole-body exposure to 915 MHz RFID on secretory functions of the thyroid system in rats. Bioelectromagnetics 34:521–529.

Kim HS, Paik MJ, Lee YH, Lee YS, Choi HD, Pack JK, Kim N, Ahn YH. 2015. Eight hours of nocturnal 915 MHz radiofrequency identification (RFID) exposure reduces urinary levels of melatonin and its metabolite via pineal arylalkylamine N-acetyltransferase activity in male rats. Int J Radiat Biol 91:898–907.

Kim HS, Park JS, Jin YB, Do Choi H, Kwon JH, Pack JK, Kim N, Ahn YH. 2018. Effects of exposure to electromagnetic field from 915 MHz radiofrequency identification system on circulating blood cells in the healthy adult rat. Bioelectromagnetics 39:68–76.

Kim MS. 2016. Investigation of factors affecting body temperature changes during routine clinical head magnetic resonance imaging. Iran J Radiol 13:e34016.

Kiyatkin EA, Brown PL. 2005. Brain and body temperature homeostasis during sodium pentobarbital anesthesia with and without body warming in rats. Physiol Behav 84: 563–570.

Kojima M, Hata I, Wake K, Watanabe S, Yamanaka Y, Kamimura Y, Taki M, Sasaki K. 2004. Influence of anesthesia on ocular effects and temperature in rabbit eyes exposed to microwaves. Bioelectromagnetics 25:228–233.

Lai H, Horita A, Chou CK, Guy AW. 1984. Effects of acute low-level microwaves on pentobarbital-induced hypothermia depend on exposure orientation. Bioelectromagnetics 5: 203–211.

Lai H. 2008. Biological effects of radiofrequency electromagnetic field. In: Wnek GE, Bowlin GL, editors, *Encyclopedia of Biomaterials and Biomedical Engineering*, 2nd ed. New York, NY: Informa Healthcare. pp 254–261.

Lin JC, Lin MF. 1981. Temperature-time profile in rats subjected to selective microwave irradiation of the brain. IEEE Trans Biomed Eng 28:29–31.

Lu ST, Lebda NA, Lu SJ, Pettit S, Michaelson SM. 1987. Effects of microwaves on three different strains of rats. Radiat Res 110:173–191.

1521186x, 2020, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/bem.22236 by University Of British Columbia, Wiley Online Library on [10/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Masuda H, Hirata A, Kawai H, Wake K, Watanabe S, Arima T, Poulletier de Gannes F, Lagroye I, Veyret B. 2011. Local exposure of the rat cortex to radiofrequency electromagnetic fields increases local cerebral blood flow along with temperature. J Appl Physiol (1985) 110:142–148.

Ohtani S, Ushiyama A, Maeda M, Hattori K, Kunugita N, Wang J, Ishii K. 2016. Exposure time-dependent thermal effects of radiofrequency electromagnetic field exposure on the whole body of rats. J Toxicol Sci 41:655–666.

Paik MJ, Kim HS, Lee YS, Choi HD, Pack JK, Kim N, Ahn YH. 2016. Metabolomic study of urinary polyamines in rat exposed to 915 MHz radiofrequency identification signal. Amino Acids 48:213–217.

Riesenfeld A. 1981. The role of body mass in thermoregulation. Am J Phys Anthropol 55:95–99.

Roberts WW. 1988. Differential thermosensor control of thermoregulatory grooming, locomotion, and relaxed postural extension. Ann N Y Acad Sci 525:363–374.

Rodrigues SF, de Oliveira MA, Martins JO, Sannomiya P, de Cassia Tostes R, Nigro D, Carvalho MH, Fortes ZB. 2006. Differential effects of chloral hydrate- and ketamine/xylazine-induced anesthesia by the S.C. route. Life Sci 79:1630–1637.

Sessler DI. 2008. Temperature monitoring and perioperative thermoregulation. Anesthesiology 109:318–338.

Tan CL, Knight ZA. 2018. Regulation of body temperature by the nervous system. Neuron 98:31–48.

World Health Organization. 2010. WHO research agenda for radiofrequency fields. Geneva, Switzerland: World Health Organization.

Wu T, Hadjem A, Wong MF, Gati A, Picon O, Wiart J. 2010. Whole-body new-born and young rats' exposure assessment in a reverberating chamber operating at 2.4 GHz. Phys Med Biol 55:1619–1630.

Wyde ME, Horn TL, Capstick MH, Ladbury JM, Koepke G, Wilson PF, Kissling GE, Stout MD, Kuster N, Melnick RL, Gauger J, Bucher JR, McCormick DL. 2018. Effect of cell phone radiofrequency radiation on body temperature in rodents: pilot studies of the National Toxicology Program's reverberation chamber exposure system. Bioelectromagnetics 39:190–199.

Yamaguchi H, Tsurita G, Ueno S, Watanabe S, Wake K, Taki M, Nagawa H. 2003. 1439 MHz pulsed TDMA fields affect performance of rats in a T-maze task only when body temperature is elevated. Bioelectromagnetics 24:223–230.

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