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Thermal responses of rats exposed to continuous or intermittent 915 MHz mobile phone RF signals

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ABSTRACT

The thermal effects of a mobile phone emitting radiofrequency electromagnetic fields (RF-EMFs) are well known, but the in vivo impact of different exposure patterns has not been directly demonstrated. This study aimed to compare the in vivo effects of continuous and intermittent exposure to 915 MHz LTE-modulated mobile phone signals under conditions that simulate typical mobile phone use.

Male Sprague–Dawley rats were exposed either continuously at whole-body averaged specific absorption rates (SAR) of 0, 4, 6, or 8 W/kg, or intermittently at 0 or 8 W/kg using 10-min on/off cycles. Rectal and interscapular temperatures were recorded during 9 h of continuous exposure or 10 h of intermittent exposure. Comparisons were made under two matched conditions: continuous exposure at 8 W/kg for 5 h versus intermittent exposure at 8 W/kg for 10 h (equal RF-on time), and continuous 4 W/kg versus intermittent 8 W/kg (50% duty cycle; equal time-averaged SAR).

Under equal cumulative RF-on time, intermittent 8 W/kg exposure caused only a brief temperature increase, whereas continuous 8 W/kg exposure resulted in a gradual and sustained rise. Under equal time-averaged SAR, continuous 4 W/kg showed no temperature change, whereas intermittent 8 W/kg caused a transient rise. No significant effects were observed at 6 W/kg continuous exposure, and sham groups remained stable.

These findings provide direct, comparative in vivo evidence that both SAR level and exposure pattern significantly influence thermal outcomes during exposure to mobile phone RF signals.

1. Introduction

The increasing prevalence of radiofrequency electromagnetic fields (RF-EMFs) in daily life has raised significant concerns about their potential biological effects. RF-EMFs are emitted from various sources such as mobile phones, base stations, Wi-Fi networks, and numerous wireless-enabled devices, resulting in chronic low-level exposure for humans. At frequencies above 100 kHz, thermal effects are a developed mode of biological interaction, with energy absorption leading to tissue heating (Kim et al., 2022). This potential risk of thermal effects demands scientific attention and further research.

To protect humans against adverse thermal effects, international safety guidelines, such as those issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), have established conservative limits on the whole-body specific absorption rate (SAR): 0.08 W/kg for the general public and 0.4 W/kg for occupational exposure. These limits are based on experimental evidence that a core body temperature increase exceeding 1 °C may compromise physiological homeostasis, forming a basis for research and regulatory standards (Adair and Black, 2003). To understand the thermal effects according to the different RF exposure modes, various body temperatures need to be monitored under different experimental conditions.

In animal studies, thermal effects may depend on the level of RF-induced thermal load and various experimental conditions, such as restraint and mobility (de Lorge, 1979, 1984). Thermoregulation is a critical aspect of biological defense against thermal load. Core body

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temperature is maintained through coordinated autonomic, endocrine, and behavioral mechanisms (Morrison and Nakamura, 2011; Tan and Knight, 2018). However, when thermal input exceeds the body's regulatory capacity, core temperature may rise to potentially harmful levels. In the context of RF exposure, temperature elevation >1 °C is widely accepted as the threshold for biologically meaningful heating.

While early studies reported that continuous RF exposure at a SAR of 4 W/kg could induce core temperature increases exceeding 1 °C, these findings were typically obtained under restrained or limited-mobility conditions (ICNIRP, 1998). In contrast, more recent studies involving freely moving animals reported no significant thermal elevation under comparable exposure levels (Kim et al., 2020, 2022), suggesting that intact thermoregulation can mitigate RF-induced heating. Similarly, Bala et al. (2025) reported that whole-body exposure at 4 W/kg is not a thermal stressor in freely moving rodents.

However, despite growing awareness of the importance of exposure dynamics, most experimental studies have relied on continuous exposure protocols, which do not reflect real-world patterns such as fluctuating mobile usage or intermittent wireless signals. Crucially, very few studies have directly compared continuous and intermittent RF exposure under matched SAR and total energy conditions. This lack of direct comparison limits our ability to evaluate exposure patterns as an independent determinant of thermal effects.

This study tested the hypothesis that continuous versus intermittent RF exposure differentially affects body temperature in rats. Prior studies have primarily examined continuous RF exposure, and only limited attention has been given to intermittent exposure. As a result, direct comparisons between continuous and intermittent exposure patterns remain insufficient, leaving uncertainty about whether exposure dynamics themselves influence biological outcomes. To address this gap, we designed an experiment comparing continuous and intermittent RF exposure under two matched conditions: (1) equivalent cumulative RF-on time and (2) equivalent time–averaged SAR. This approach aimed to isolate the effect of exposure pattern while controlling for total energy input.

2. Materials and methods

2.1. RF chamber system

An RF reverberation chamber system for small animals was used as described previously (Kim et al., 2013a; Kim et al., 2013b; Kim et al., 2020). Two chambers, one for sham exposure and one for RF exposure, were maintained under controlled conditions, including ventilation, temperature (22 ± 2 °C), humidity, and a 12-h light/dark cycle. Accordingly, RF-exposed and sham-exposed animals were studied simultaneously under identical environmental conditions. Animals had ad libitum access to gamma-irradiated RodFeed (Dea-Han Biolink) and filtered tap water. The exterior dimensions (L × W × H) of the chamber are 2.3 × 2.3 × 1.5 m. An LTE source with a frequency of 915 MHz was generated using a signal generator (E4438C; Keysight Technologies, Santa Rosa, CA, USA). The input signal was amplified using a high-power amplifier (HPA-272+; Mini-Circuits, Brooklyn, NY, USA), and the output power level (maximum: 100 W) was regulated using a system controller (KSS-SC 349; Korea Shield System Co., Cheongju, Korea). A customized software program (Korea Shield System Co.) controlled the RF signal exposure level and duration. The input power was monitored in real-time using a power sensor (E9301A, Keysight) and a power meter (E4478B, Keysight) through a 20-dB directional coupler (ZGDC20-372HP+, Mini-Circuits). The field uniformity of the reverberation chamber was measured at 24 points within the working volume using an isotropic field probe (HI-6005; ETS-Lindgren), ensuring the field distribution remained within ±2 dB over a 1-min average. The 1-min averaging period provides statistically sufficient sampling of stirrer positions to achieve convergence of the mean field value in accordance with IEC 61000-4-21 (Annex A.4) (IEC, 2011). Therefore, the same ±2 dB uncertainty is considered applicable to the 10-min averaged exposure used in the 10 min ON/10 min OFF experimental protocol. SAR distribution was calculated for each caged rat using a rat phantom (Electronics and Telecommunications Research Institute, Daejeon, Korea) featuring 40 tissues and a voxel size of 1 mm.

2.2. Study design

This study investigated body temperature changes in freely moving male Sprague-Dawley rats (~339 g, 11 weeks old; Dea-Han Biolink, Seoul, Korea). The animal housing and exposure rooms were within 5 m of each other, and transferring the animals to the exposure chamber took less than 30 s. To minimize handling-related thermal stress, animals were moved to the exposure chamber at least 1 h before exposure to allow for acclimatization. The exposure system was stabilized for at least 1 h before each session. A total of 46 rats were implanted with subcutaneous transponders for peripheral (interscapular) temperature monitoring; in this study, readings were sampled hourly. Of these, 36 were allocated to continuous exposure experiments and divided into three sham groups (0 W/kg, n = 6 each; total = 18) and three RF exposure groups at whole-body SARs of 4, 6, or 8 W/kg using 915 MHz LTE-modulated fields (n = 6 each). The remaining 10 rats were used in the intermittent exposure experiment and assigned to a sham group (0 W/kg, n = 4) or an RF group (8 W/kg, n = 6), exposed with 10-min on/off cycles. The sham group size for the intermittent protocol was limited to four animals, as baseline sham data had already been established in the continuous exposure experiments. In addition, the intermittent and continuous protocols were conducted sequentially within the same experimental sessions under identical temporal and environmental conditions, thereby minimizing the likelihood of sham variability and ensuring comparability across protocols.

Continuous exposures were conducted for 9 h at SARs of 4, 6, or 8 W/kg. The 4 W/kg condition was selected as a non-thermal reference based on previous findings showing no detectable increases in core temperature; 6 W/kg represented a moderate SAR level, and 8 W/kg a high-intensity condition. Intermittent exposure was implemented only at 8 W/kg using a 50% duty cycle (10-min on/off) for 10 h, yielding a cumulative RF-on time of 5 h and a time–averaged SAR of 4 W/kg.

To evaluate the effect of exposure dynamics, two comparisons were performed: (1) continuous 8 W/kg for 5 h versus intermittent 8 W/kg for 10 h (matched cumulative RF-on time), and (2) continuous 4 W/kg versus intermittent 8 W/kg (50% duty cycle) for 8 h (matched time–averaged SAR). For the equal RF-on-time comparison, the first 5 h segment of the 9 h continuous 8 W/kg exposure was used to match the 5 h cumulative on time of the 10 h intermittent protocol (50% duty). These comparisons were intended to isolate the influence of exposure pattern on thermoregulatory responses, independent of SAR level or total energy input.

All animals were randomly assigned and housed in identical reverberation chambers under controlled environmental conditions. During exposures, the rats remained unrestrained and were allowed to move freely. To achieve whole-body SARs of 4, 6, and 8 W/kg, the chamber input power was adjusted to 11.6, 19.9, and 29.3 W, respectively.

2.3. Thermometers

Two thermometers were employed to measure temperatures at the same time: a rectal thermometer for assessing core temperature and a temperature transponder for monitoring interscapular temperature. A rectal thermometer (Testo 925; Testo, Lenzkirch, Germany) with an accuracy of ±0.5 °C and a resolution of 0.1 °C. A transponder system consisting of an implantable sensor (IPTT-300-HTEC) and a handheld reader (DAS-8027 IUS; Bio Medic Data Systems) with a stated accuracy of ±0.2 °C between 34 and 42 °C was used. All temperature measurements were conducted by a single trained individual using a standardized protocol across all animals. All temperature measurement devices

were calibrated before the experiment according to the manufacturer's instructions. Rectal probes were inserted 6 cm into the rectum to maintain a consistent measurement depth across animals.

Before starting RF exposure, the accuracy of the transponder was evaluated in 12 transponder-implanted rats by comparing both temperature readings simultaneously using correlation, regression, and Bland–Altman analysis, with an acceptable error margin of ±0.5 °C (see Supplementary Methods).

2.4. Transponder implantation

A temperature transponder (IPTT-300-HTEC; Bio Medic Data Systems, Seaford, DE, USA) was implanted subcutaneously into the interscapular region of a male Sprague-Dawley rat (n = 46), three days before RF exposure. All procedures were designed to minimize animal stress, and monitoring was conducted by trained personnel experienced in rodent handling. The procedure was performed under inhalation anesthesia using 5% isoflurane (Abbott Core Laboratory System, Lake Forest, IL, USA), and a syringe-type device was used for subcutaneous implantation. All instruments were sterilized, and the same person performed all implantations to ensure consistency. Each procedure took about 5 min. After implantation, rats were individually housed under controlled conditions and monitored for recovery and any signs of local inflammation or infection. The implantation site was disinfected and treated with topical antibiotic ointment. All animals maintained stable baseline temperatures and showed no signs of inflammation during the 3-day recovery period (data not shown).

2.5. Temperature monitoring

Temperatures were recorded hourly during continuous exposures (Fig. 1A) and every 2 h during the 10-h intermittent exposure, immediately at the start of each 10-min OFF phase (Fig. 1B). To minimize time-related bias, the measurement order between sham and RF groups was alternated hourly. Core temperature was measured with a rectal thermometer and interscapular temperature with the implanted transponder during a brief pause (<3 min). Rectal and transponder temperature measurements required less than 30 s per animal. Thus, each time-point measurement for a group (six animals) was completed within <3 min. In the intermittent-exposure protocol, the 2-h measurement interval was chosen to minimize handling-induced hyperthermia and avoid disturbing the natural RF-related thermal response. Because the cumulative RF-on time per cycle was relatively short (10-min on/10-min off), frequent measurements during OFF phases could have confounded the exposure-related effect by adding stress-related heat. A 2-h interval was therefore considered a balanced approach that reduces stress-related artifacts while adequately capturing the main temporal dynamics of RF-induced body-temperature change. An increase of> 1 °C in core temperature was considered physiologically meaningful. Thermal effects were compared at identical SAR values and matched cumulative RF-on times.

Rectal and interscapular temperatures were compared across exposure patterns at equivalent cumulative RF exposure durations. The temperature values measured in sham-exposed rats were used as an internal reference. All animals were of the same sex and age, housed under identical conditions, and handled by experienced researchers. Baseline temperatures were recorded in the housing room 1 h before exposure onset and averaged over two measurements to ensure pre-exposure stability.

2.6. Ethics statement

This study was approved by the Ethics Committee on Animal Experiments of Ajou University School of Medicine (Suwon, Korea) under approval no. 171222-47.

2.7. Statistical analyses

Statistical analyses were conducted using SPSS Statistics 29 (IBM Corp., Armonk, NY, USA). Temperature data are expressed as mean ± standard deviation (SD), with $p < 0.05$ considered statistically significant. Repeated-measures general linear models (GLMs) assessed temporal changes in body temperature; Mauchly's sphericity test and Greenhouse–Geisser (GG) corrections were applied when required. Welch's two-sample t-tests (Welch's t) for each time point in Fig. 2A–D were performed as exploratory pairwise comparisons without multiplicity adjustment. For Fig. 3A and B, group means of ΔT (RF – Sham) were compared descriptively between continuous and intermittent exposure patterns; Welch's two-sample t-tests were additionally conducted at each time point as exploratory analyses but are not shown in the figure. Effect sizes are reported as partial eta-squared (partial η^2) for GLM results. Error bars represent SD in Fig. 2A–D (within-group variability) and standard error (SE) in Fig. 3A and B (precision of the mean difference). All Welch's *t*-test results were cross-checked with the Mann–Whitney *U* test and yielded identical significance outcomes (data not shown).

3. Results

Body temperature measured by the subcutaneous transponder showed a moderate correlation with rectal measurements ($r = 0.59$, $p < 0.01$), with a mean difference of 0.08 °C, within the predefined accuracy range. Bland-Altman analysis further confirmed the absence of systematic bias between the two methods (Supplementary Fig. S1).

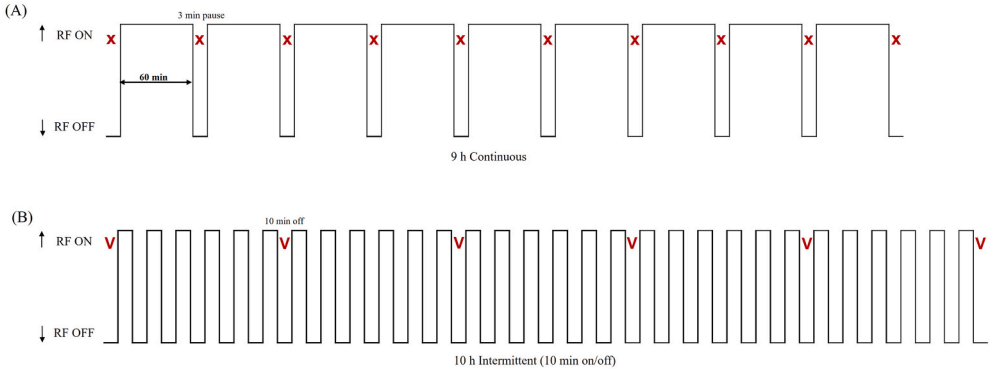

Fig. 1. RF exposure protocols and temperature measurement schedules. (A) Continuous exposure at whole-body SARs of 0, 4, 6, and 8 W/kg for 9 h, with body temperature recorded hourly. Black bars indicate RF-on periods; white gaps indicate RF-off periods; X symbols mark measurement time points (3-min pause per measurement). (B) Intermittent exposure at 0 and 8 W/kg using 10-min RF-on/10-min RF-off cycles for 10 h, with temperature measured every 2 h during RF-off phases. V symbols mark measurement points.

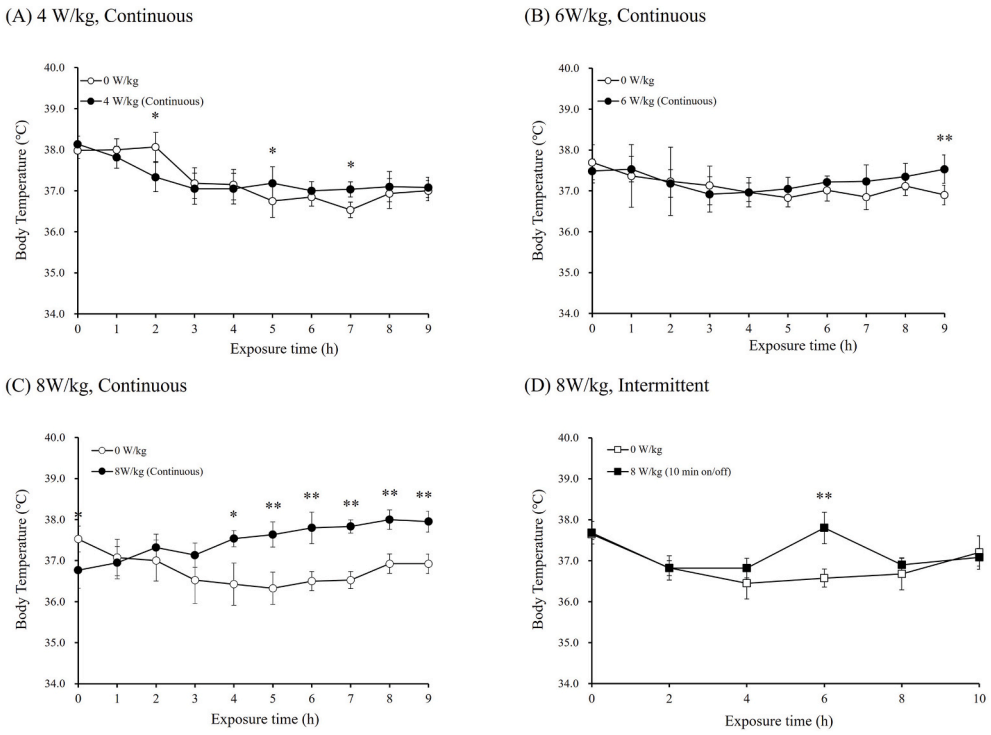

Fig. 2. Rectal temperature time-course during continuous and intermittent RF exposure (A) Continuous 4 W/kg (n = 6 per group); (B) Continuous 6 W/kg (n = 6 per group); (C) Continuous 8 W/kg (n = 6 per group); (D) Intermittent 8 W/kg with 10-min on/off cycles (sham: n = 4; RF: n = 6). Values are presented as mean ± SD. Asterisks (Welch's *t*-test, exploratory): $p < 0.05$ (*), $p < 0.01$ (**). Interscapular temperature data are provided in Supplementary Table S1–S4.

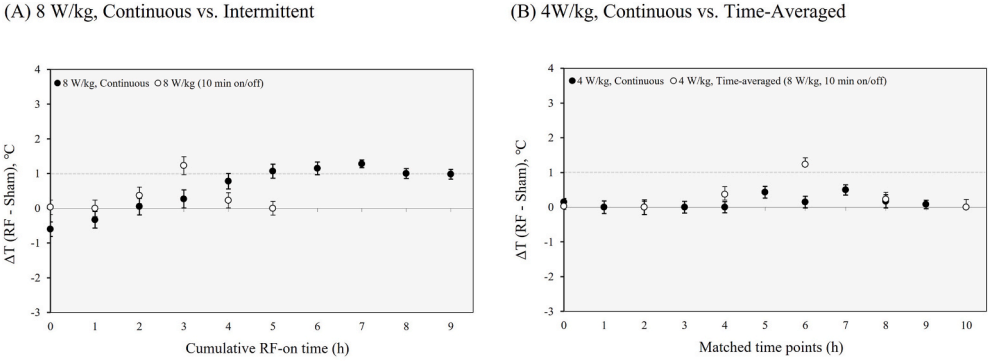

Fig. 3. Comparative rectal ΔT (RF – Sham) between exposure patterns. ΔT represents the mean inter-group temperature difference (RF − Sham). (A) ΔT at 8 W/kg plotted against cumulative exposure time. Continuous (1–5 h) and intermittent (2–10 h; 10-min on/off) exposures were compared. Body temperature was measured at 1-h intervals during continuous exposure and at 2-h intervals during intermittent exposure. (B) ΔT under time-averaged 4 W/kg conditions, comparing continuous 4 W/kg with intermittent 8 W/kg (10-min on/off) at matched time points (0, 2, 4, 6, 8 h). Sample sizes: (A) continuous exposure: n = 6 per group; intermittent exposure: sham n = 4, RF n = 6. (B) used the same animals as in (A). Values are presented as mean ± SE (reflecting the precision of mean differences). Welch's two-sample t-tests at each time point were performed as exploratory analyses and are not displayed. Corresponding interscapular-temperature data are provided in Supplementary Table S5.

3.1. Temperature changes in continuous exposure

At a whole-body SAR of 4 W/kg, baseline rectal temperatures were 37.98 ± 0.19 °C in sham-exposed rats and 38.13 ± 0.14 °C in RF-exposed rats ($p = 0.16$; Fig. 2A), indicating no baseline difference. Welch's t-tests showed small but statistically significant differences at 2 h, 5 h, and 7 h ($p < 0.05$), yet all were <0.3 °C and therefore biologically negligible. Mauchly's sphericity test was non-significant ($p = 0.34$), confirming that the sphericity assumption was met and no correction was required. Repeated-measures GLM detected a statistically significant group × time interaction ($F(9, 90) = 3.46$, $p = 0.001$); however, this interaction reflected only minor, transient fluctuations (<0.3 °C) rather than any sustained shift in thermal response, indicating no biologically meaningful divergence between groups. Interscapular (transponder-based) temperatures displayed comparable temporal patterns (Supplementary Table S1).

At a whole-body SAR of 6 W/kg, baseline rectal temperatures were 37.70 ± 0.43 °C in sham-exposed rats and 37.48 ± 0.29 °C in RF-exposed rats ($p = 0.35$; Fig. 2B), indicating no baseline difference. Welch's *t*-test showed that rectal temperature in RF-exposed rats was significantly higher at 9 h than in sham-exposed rats ($p < 0.01$), with a mean ΔT of 0.45 °C, yet this rise remained <1 °C and was therefore biologically negligible. Mauchly's sphericity test was non-significant ($p = 0.051$), confirming that the sphericity assumption was met and no correction was required. Repeated-measures GLM revealed no significant group × time interaction ($F(9, 90) = 1.87$, $p = 0.07$), indicating

similar temporal patterns between the two groups. Interscapular temperatures showed no significant differences at any time point (Supplementary Table S2).

At a whole-body SAR of 8 W/kg, baseline rectal temperatures were 37.53 ± 0.31 °C in sham-exposed rats and 36.77 ± 0.45 °C in RF-exposed rats ($p = 0.02$; Fig. 2C), showing a small initial difference likely due to inter-individual variability from the limited sample size ($n = 6$). After 1 h of exposure, the rectal-temperature difference decreased to 0.13 °C and was no longer significant ($p = 0.20$, Supplementary Fig. S2). Rectal temperature in RF-exposed rats subsequently increased by more than 1 °C compared with sham, beginning at 4 h and remained significantly elevated through 9 h ($p = 0.01$ at 4 h and $p < 0.0001$ thereafter). Mauchly's sphericity test was significant ($p = 0.002$), indicating violation of the sphericity assumption; therefore, the GG correction was applied. Repeated-measures GLM revealed a significant group × time interaction ($F(9, 90) = 20.40$, $p < 0.001$; GG-corrected $F(3.8, 38.0) = 12.9$, $p < 0.001$, partial $\eta^2 = 0.67$), confirming a sustained thermal response in the RF-exposed group. Interscapular temperatures displayed a similar rising trend (Supplementary Table S3).

3.2. Temperature changes in the intermittent exposure

At 8 W/kg intermittent exposure (Fig. 2D), baseline rectal temperatures were 37.68 ± 0.28 °C in the RF-exposed group ($n = 6$) and 37.65 ± 0.13 °C in the sham group ($n = 4$), with no significant baseline difference ($p = 0.91$). Both groups showed a temperature change of less than 1 °C during the first 4 h. At 6 h, rectal temperature in RF-exposed groups showed a transient peak that was 1.22 °C higher than that of the sham group (37.80 ± 0.38 °C; Welch's *t*-test, $p < 0.001$). By 8 h, the between-group differences were no longer statistically significant ($p > 0.05$). Individual trajectories for all rats are shown in Supplementary Fig. S3 (sham) and S4 (RF) to document within-group variability.

Mauchly's sphericity test was non-significant ($p = 0.30$), so no correction was required. Repeated-measures GLM showed a strong main effect of time ($F(2.94, 23.5) = 19.72$, $p < 0.001$, partial $\eta^2 = 0.71$) and a significant time × group interaction ($F(2.94, 23.5) = 8.46$, $p < 0.00$, partial $\eta^2 = 0.51$), confirming the transient RF-associated thermal peak. Interscapular temperatures displayed similar temporal patterns (Supplementary Table S4).

3.3. Comparison of changes between continuous and intermittent exposure

Thermal responses were first compared between continuous 8 W/kg exposure for 5 h and intermittent 8 W/kg exposure with 10-min on/off cycles for 10 h, which provided the same cumulative RF-on time of 5 h (Fig. 3A). Continuous exposure produced a gradual and sustained rise in rectal temperature, reaching a peak difference of about 1.3 °C compared with the sham group at 6 h and remaining elevated thereafter. In contrast, intermittent exposure showed a sharper but transient peak difference of about 1.22 °C relative to the sham group at 6 h, which subsequently declined despite the ongoing on/off cycles. Repeated-measures GLM detected a significant main effect of time ($F(3.60, 64.8) = 6.40$, $p < 0.001$, partial $\eta^2 = 0.26$) and a significant time × exposure-pattern × group interaction ($F(3.60, 64.8) = 10.35$, $p < 0.001$, partial $\eta^2 = 0.37$), demonstrating that the temporal progression of temperature differences differed markedly between continuous- and intermittent-exposed rats relative to their sham controls. Mauchly's sphericity test showed no violation ($p > 0.05$), so no GG correction was applied.

A second comparison was performed to match time-averaged SAR at 4 W/kg, contrasting continuous 4 W/kg exposure (9 h) with intermittent 8 W/kg exposure (10-min on/off, time-averaged 4 W/kg; 10 h) (Fig. 3B). Continuous 4 W/kg exposure produced little or no temperature difference relative to the sham group across time, whereas intermittent 8 W/kg (time-averaged 4 W/kg) again produced a transient peak difference at 6 h that subsequently declined despite the ongoing cycles. A small difference at 2 h (0.3 °C) in the continuous 4 W/kg group was attributed to a brief fluctuation in the sham-group rather than RF-induced heating and was absent at higher-SAR continuous exposures or in interscapular readings, suggesting a condition-specific artifact. GLM analysis again confirmed these patterns, with significant main effects of time ($F(3.03, 48.5) = 6.40$, $p < 0.001$, partial $\eta^2 = 0.29$) and a significant time × exposure-pattern × group interaction ($F(3.03, 48.5) = 10.35$, $p < 0.001$, partial $\eta^2 = 0.39$). Mauchly's sphericity test showed no violation ($p > 0.05$), so no GG correction was applied. These results demonstrate that intermittent exposure elicits a transient thermoregulatory response not observed under continuous exposure at either matched cumulative RF-on time or matched time-averaged SAR, underscoring the physiological relevance of exposure dynamics in shaping thermal outcomes.

4. Discussion

This study provides in vivo evidence that the temporal pattern of RF exposure, specifically continuous versus intermittent delivery, significantly influences body temperature in male rats under the present experimental conditions, independent of SAR magnitude or exposure duration. At 8 W/kg, continuous RF exposure induced sustained hyperthermia exceeding 1 °C from the fourth to the ninth hour, whereas intermittent exposure produced only a brief peak at the sixth hour that subsequently declined. When cumulative RF-on time was matched, intermittent exposure elicited a larger transient rise than continuous exposure, suggesting that recovery intervals limit cumulative heat storage despite stronger short-term responses. Rectal and interscapular temperatures showed similar temporal trends, with slightly attenuated peripheral peaks likely reflecting heat dissipation via vasodilation.

We demonstrated that thermal responses can vary substantially under equivalent SAR conditions depending on exposure dynamics. Both cumulative RF-on time and time–averaged SAR might shape the thermoregulatory outcome. Under matched cumulative RF-on time (continuous 8 W/kg for 5 h vs. intermittent 8 W/kg for 10 h, 10-min on/off), both modes caused temperature elevations greater than 1 °C, but with markedly different temporal profiles: continuous exposure produced a gradual and sustained rise, whereas intermittent exposure produced only a transient increase followed by recovery even during the exposure. This pattern indicates that intermittent recovery intervals act as a buffer, preventing cumulative heat storage and allowing restoration of thermal balance. Under matched time-averaged SAR conditions (continuous 4 W/kg vs. intermittent 8 W/kg at 50% duty cycle for 8 h), continuous exposure caused no appreciable changes. In contrast, intermittent exposure elicited a transient thermal response, occasionally exceeding the biologically relevant threshold of $\Delta T > 1$ °C. Thus, intermittent delivery of RF energy can provoke thermoregulatory reactions even when average SAR values fall within non-thermal safety limits.

No biologically relevant changes occurred at 4 or 6 W/kg, which are consistent with a practical threshold near 8 W/kg in healthy young male rats in this setting. These findings align with the U.S. NTP study (Wyde et al., 2018), in which intermittent exposure at 8 W/kg induced significant temperature increases in young males, and even greater rises (>1 °C) in pregnant and aged rats, while 4 or 6 W/kg produced little or no change in young males.

The current findings suggest that the temporal pattern of RF energy delivery, along with cumulative dose, may influence thermoregulatory responses. Although behavioral data were not collected in a structured manner, this limitation should be considered when interpreting potential behavioral correlates of thermoregulatory changes. This observation is consistent with the established thermophysiological principle that the body's capacity to dissipate heat depends on both the magnitude of thermal load and the dynamic regulatory response it triggers (Tan and Knight, 2018).

The use of unrestrained, freely moving animals in this study allowed temperature measurement without anesthesia at any stage. This design avoided confounding from anesthesia, which alters autonomic thermoregulation by lowering vasoconstriction and shivering thresholds (Lenhardt, 2018; Sessler, 2008), and from physical restraint, which can limit heat dissipation and cause hyperthermia (Aydin et al., 2011). While such experimental constraints are useful for defining worst-case scenarios, they do not represent typical environmental or occupational exposures. Under wakeful and unrestrained conditions, thermoregulatory mechanisms remain functional, and comparable RF exposures have generally not produced marked temperature increases. Consistent with this, studies conducted with unrestrained free-moving rats observed no substantial temperature elevation at 4 W/kg, a level reported to raise body temperature by more than 1 °C under restrained and anesthetized conditions (Kim et al., 2020, 2022). In a study, core body temperature was monitored in rats exposed to RF-EMF at a wbSAR level of 4 W/kg for 3 h (1.95 GHz). It increased by 0.49 °C after approximately 26 min of exposure and reached about 0.62 °C at the end of exposure in rats (Bala et al., 2025). In contrast, phantom measurements showed temperature increases of more than 3 °C at the same exposure condition. These findings indicate that thermoregulatory responses in rats remained intact, allowing compensation for increased thermal loads at this exposure level. However, these studies were conducted under continuous exposure conditions and did not examine whether exposure dynamics influence the temporal evolution of thermal responses. In contrast, the present study shows that intermittent exposure can produce different thermoregulatory trajectories even under physically equivalent absorbed RF conditions.

In vitro systems lack thermoregulatory capacity, allowing examination of RF exposure pattern effects on thermal and cellular outcomes without this variable. This provides a complementary perspective to in vivo studies, as the absence of active heat dissipation makes it possible to isolate pattern-related effects. In human skin fibroblasts, intermittent exposure (5 min on/10 min off) at 1 W/kg SAR reduced heat shock factor 1 (HSF1) bioluminescence resonance energy transfer (BRET) signals, whereas continuous exposure produced no change; at 4 W/kg SAR, no pattern-related differences were observed (Joushomme et al., 2023). In another study, 2.45 GHz RF at matched average SARs (50 or 100 W/kg) showed that continuous exposure at 200 W/kg increased medium temperature to 44.1 °C and suppressed cell growth, while intermittent exposure, even with higher peak SARs (300–1500 W/kg), caused neither heating nor growth suppression (Takashima et al., 2006). These findings indicate that exposure pattern can influence heat accumulation and cellular outcomes in the absence of thermoregulation.

Human data align with these experimental findings, despite the ethical constraints that limit high-SAR testing in people. In a study of mobile-phone RF exposure (900 MHz; SAR 1.23 W/kg), tympanic temperature was higher than sham during continuous exposure, whereas intermittent exposure reduced tympanic temperature by up to 0.11 °C compared with sham (Bortkiewicz et al., 2012). Taken together, the animal, in vitro, and human observations support the consideration of exposure pattern, alongside SAR thresholds, when evaluating RF-induced thermal effects and the role of thermoregulation. Although absolute SARs are not directly comparable between species, the convergence in pattern-dependent responses conceptually supports our interpretation.

Rectal measurement is widely regarded as the gold standard for core body temperature. Still, various factors such as probe placement or animal handling can limit the applicability of direct temperature measurement in large-scale experiments. In the NTP study, subcutaneous interscapular temperature measurement using the same type of transponder as in the present study was employed, although its validity as a surrogate for core temperature has been debated (Kuhne et al., 2020). In the current study, we first compared rectal and interscapular temperatures in the same animals under RF-sham conditions. We observed that rectal and interscapular temperatures were highly consistent within the margin of error (n = 12 rats, Supplementary Fig. S1), and this agreement persisted even under exposure conditions up to 8 W/kg (Supplementary Table S1–S4).

These findings are consistent with the physiological principle that, under moderate thermal loads, freely moving rodents exhibit minimal differences between core and peripheral temperatures (McAllen et al., 2010; Romanovsky, 2014). Under such conditions, thermoregulatory mechanisms such as vasodilation and behavioral adjustments can maintain a relatively uniform body temperature distribution. However, when SAR levels are higher or ambient temperature rises to extreme levels, exceeding thermoregulatory capacity, the core-peripheral temperature gradient may become more pronounced. Both values may also be different in older or heavier animals.

Although the sample sizes in each group were limited (n = 4–6), the use of repeated-measures GLM enhanced statistical power by accounting for within-subject variance across time points. Consistent patterns across rectal and interscapular measurements, together with robust time × group interactions, support the reliability of these findings despite the small group size. The main inference of this study relied on the significant time × group interaction detected by the repeated-measures GLM, whereas time-point t-tests were exploratory and not adjusted for multiplicity.

These results should not be interpreted as evidence that intermittent RF exposure is without risk. Under the short-term exposure conditions examined, its thermal effects were transient and reversible; however, the potential impact of prolonged or repeated intermittent exposure remains to be determined. From a human safety perspective, our findings suggest that identical time–averaged SAR levels might not always produce equivalent biological effects. Current RF safety limits primarily focus on SAR thresholds, without explicitly addressing exposure dynamics such as pattern, recovery intervals, or timing. While the present study alone does not provide sufficient grounds for revising these standards, it offers empirical data that could be useful for future RF risk assessments and regulatory considerations.

Several limitations should be noted. First, a baseline imbalance was observed at 8 W/kg, where RF-exposed rats had significantly lower rectal temperatures than sham controls at the start of exposure. Baseline measurements were obtained before RF exposure; therefore, this difference cannot be attributed to RF treatment and likely reflects random inter-individual variability due to the small group size rather than a true RF effect. Although subsequent ΔT_0 analyses accounted for relative changes over time, the possibility that baseline variation influenced early-phase responses cannot be fully excluded. Such early variability may reflect transient temperature fluctuations associated with animal handling before full thermal stabilization. Early responses associated with animal handling that stabilize after sufficient time have been reported by Sylvester et al. (2024) and Bala et al. (2025). Therefore, adequate pre-exposure stabilization and monitoring temperatures before and after RF exposure are important for distinguishing true RF-induced thermal responses from handling-related transients. Nevertheless, in the present study, baseline-adjusted analyses yielded consistent temporal patterns, suggesting that this imbalance did not materially affect the overall interpretation (Supplementary Fig. S2).

The study involved only young adult male rats of a single strain and a single RF frequency (915 MHz) over a relatively short duration. Thermal responses such as behavioral thermoregulation (e.g., posture or activity changes) and evaporative heat loss were not systematically monitored, and localized SAR distribution or tissue-specific thermal gradients were not assessed. Thermoregulatory capacity may differ by sex, age, or strain, and future studies should explore these factors to enhance generalizability. This study also did not examine downstream outcomes such as histological changes, inflammatory markers, or oxidative stress, which limits the interpretation of whether transient thermal changes have lasting biological consequences. The 2-h measurement interval was selected to minimize potential handling stress and ensure that each measurement represented at least 30 min of cumulative RF-on exposure,

thereby reducing redundancy in short-term readings. However, this approach may have underestimated transient peaks. More frequent and longer sampling could better characterize short-lived maxima and recovery patterns. Testing additional SAR levels (e.g., 7 W/kg) could refine the threshold for notable thermal responses. Moreover, only a single intermittent pattern (10-min on/off) was examined; future studies using different duty ratios or cycle lengths would be valuable to determine whether the transient thermoregulatory responses observed here are generalizable across exposure paradigms. Achieving an intermittent protocol corresponding to a time–averaged SAR of 8 W/kg would have required approximately 18 h of total exposure duration, and such longer durations might have revealed additional temperature peaks or altered thermoregulatory patterns, which were beyond the scope of this study. In addition, monitoring metabolic or behavioral adaptations that help maintain body temperature would provide important clues to understanding RF-induced thermoregulation. Therefore, whether the transient changes observed here have any biological sequelae remains uncertain.

5. Conclusion

The present findings indicate that the exposure pattern is a key determinant of the thermal effects of radiofrequency. Thus, exposure dynamics, together with SAR magnitude, should be considered in RF safety evaluations. The data also support the use of interscapular subcutaneous temperature measurement as a practical alternative to rectal probes in case of large-scale animal studies under moderate thermal stress. The implantation procedure is still invasive, but after that, temperature can be monitored noninvasively. Further investigations are warranted to clarify how temporal factors and biological variability interact to shape thermal responses and their potential biological consequences.

Data accessibility statement

All datasets generated and analyzed during the current study are provided in the Supplementary Materials.

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CRediT authorship contribution statement

Hye Sun Kim: Conceptualization, Data curation, Investigation, Validation, Visualization, Writing – original draft. **YoungIm Kim:** Investigation, Methodology, Validation, Visualization, Writing – original draft. **Sang Bong Jeon:** Methodology, Software. **Jung-Ick Moon:** Methodology, Software. **Hyung Do Choi:** Conceptualization, Resources, Software. **Ae-Kyoung Lee:** Methodology, Software. **Young Hwan Ahn:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2026.104464.

Data availability

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