Research Square

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Active temperature regulation improves nocturnal hot flashes and sleep in menopausal women

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Research Article

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Abstract

Menopausal hot flashes (HFs) frequently disrupt sleep, adversely affecting quality of life. Non-pharmacological interventions targeting temperature regulation during sleep remain underexplored. This study conducted a 14-night crossover trial with 98 peri- and post-menopausal women (1,219 nights; mean ± SD: 54.1 ± 6.7 y), comparing HF frequency when women slept for 7 nights with active temperature regulation (ATR) ON vs. 7 nights OFF. Core temperature was tracked for 24-hours and skin temperature was tracked overnight during each ATR condition. For both menopausal women taking and not taking hormone replacement therapy, ATR reduced nocturnal HFs by 56 ± 39%, and improved menopausal symptom severity by 9 ± 41% and reported sleep quality by 10 ± 39%. HF reduction via ATR likely occurred by keeping women within their thermoneutral zone, indicated by lower core and skin temperatures throughout the night, with ATR ON. These findings suggest that ATR helps stabilize overnight body temperatures in menopausal women, thus reducing HFs and improving sleep quality. Therefore, ATR may serve as a non-pharmacological intervention for managing menopausal symptoms and improving sleep quality.

Introduction

Consistent, high-quality sleep supports cardiovascular health[1], metabolic regulation[2], and optimal cognitive functioning[3] in healthy adults. However, the menopausal transition, which can begin as early as 30–35 years[4], is marked by profound and often underrecognized sleep disruptions that often last 7 years[5] and may contribute to the increased chronic disease risk after menopause[6–8]. One of the major contributors to reduced sleep quality is nocturnal hot flashes (HFs) which impact nearly 80% of menopausal women[9]. HFs lead to increased nighttime awakenings and reduced sleep efficiency, subsequently degrading quality of life and workplace productivity[10,11,3]. By 2030, an estimated 1.2 billion women, representing approximately 14% of the global population, will be menopausal[12], underscoring the need for timely and effective interventions that reduce nocturnal HFs to improve sleep, and thereby reduce disease burden and improve quality of life.

Hormonal changes during menopause lead to two major changes in the brain related to increased HF onset and frequency: 1) narrowing of the thermoneutral zone (TNZ) in the hypothalamic preoptic brain area[13] leads to more frequent deviations in body core temperature (T_C) outside of this range, thus activating heat-dissipation responses, including peripheral vasodilation, sweating, and HFs[14], and 2) hyper-active kisspeptin-neurokinin B-dynorphin (KNDy) neurons extending into the hypothalamic preoptic brain area, where heat signals are received and heat-loss responses, including HFs, originate[13]. Additionally, independent of menopause, thermoregulatory function declines with age[15], which further exacerbates challenges women face to keep body temperature within this narrowed menopausal TNZ, so as to avoid nocturnal HFs.

Hormone replacement therapy (HRT) is commonly prescribed to treat menopausal vasomotor symptoms and remains the most effective intervention for reducing HFs[16], with demonstrated benefits for sleep quality in many women[17,18]. However, HRT does not eliminate all HFs (average 77% reduction in weekly HFs)[19] and is not appropriate or accessible for all women due to contraindications, side effects, increased disease risk, and individual treatment preferences[20,21]. Consequently, non-pharmacological interventions should be recommended as first-line approaches for managing sleep disruption from HFs during menopause[22,23]. Interventions that target overnight temperature regulation are especially compelling, as warmer sleep environments are associated with increased nocturnal HF occurrence[24], whereas cooling during sleep may help maintain body temperature within the TNZ and reduce nocturnal HFs, thus improving sleep during menopause[25].

Despite a strong physiological rationale, the literature examining temperature-based interventions for menopausal nocturnal HFs remains limited. One study in menopausal women (peri- and post-menopausal women 45–59 years) found that using an active temperature-regulating (ATR) water-based mattress cover throughout the night reduced nocturnal HF frequency by 52% and improved subjective sleep quality[25] after eight weeks of use. However, this study was limited by a few factors. First, the sample size was small (n = 15) and did not collect information about participant HRT status, so it is unclear whether women taking HRT may also benefit from ATR solutions. Second, the researchers did not collect data about subjectively-reported menopausal symptoms, which should be considered in tandem with physiological outcomes. Finally, body temperatures (i.e. T_C and/or skin temperatures) were not measured, which limits the ability to identify potential mechanisms that could be impacting HF reduction through ATR.

A possible mechanism driving HF reduction may be that T_C and skin temperatures are lower when sleeping on a temperature-regulated mattress cover, and therefore body temperatures stay within the TNZ and thus reduce HFs. This idea is supported by a study where postmenopausal women slept on a high-heat capacity mattress (HHCM) versus a regular mattress for one night each and found that T_C and skin temperatures were significantly cooler (-0.20°C and − 0.37°C, respectively) when sleeping on the HHCM. However, this study did not evaluate nocturnal HF frequency so it is unclear whether the reduction in T_C did in fact reduce HFs. HHCM also do not actively cool throughout the night or on an individualized basis. Furthermore, this study also did not evaluate whether taking HRT modified the body temperature-cooling effects of HHCM. Given that HRT leads to slightly higher T_C on average[26] and alters thermoregulatory function[27], it may be that an ATR mattress cover differentially affects menopausal women using vs. not using HRT. As a result, it remains unclear whether overnight ATR can effectively manage body temperature to reduce nocturnal HFs and improve menopausal symptoms for peri- and post-menopausal women taking vs. not taking HRT.

Therefore, the goal of this study was to evaluate how overnight ATR modifies nocturnal HF frequency, menopausal symptom severity, and subjective sleep quality in peri- and post-menopausal women, including both those taking and not taking HRT. Importantly, T_C and skin temperatures were assessed throughout the night with ATR ON vs. OFF to evaluate how ATR may reduce HFs via body temperature reductions.

Results

Participants

Participants (n = 98) used their preferred temperatures during ATR ON (see SI Autopilot for more information). There were no statistically significant differences in participant-preferred ATR temperature selections across the night by HRT status (mean ± SDs; HRT vs. No HRT: Bedtime = 26.0 ± 4.1°C vs. 25.8 ± 4.8°C, Initial Phase = 25.7 ± 3.3°C vs. 25.2 ± 3.8°C, or Final Phase = 26.6 ± 2.9°C vs. 26.4 ± 3.7°C; all independent t-tests, $p > 0.05$; SI Table 2).

Physiological Outcomes With ATR

Changes in Hot Flash Frequency from ATR OFF to ON

With ATR ON (vs. OFF), participants reported almost 1 fewer HF each night (means ± SD: ATR OFF = 1.5 ± 1.4; ATR ON = 0.5 ± 0.6; mean ± SD of absolute change from ATR OFF to ON = -1.0 ± 1.1 HFs/night; $p < 0.001$), independent of HRT use (Table 1; Fig. 1). This translates to a 56% nightly HF reduction on average with ATR ON (means ± SD: -56 ± 39%, $p < 0.001$, n = 98; No HRT = -57 ± 35%, n = 52; HRT = -57 ± 39%, n = 35) (Table 1). Furthermore, 85% (n = 83/98) of women experienced a decrease in nocturnal HFs with ATR ON. In the present study, a small subset of participants (n = 4) with low nocturnal HF frequency with ATR OFF exhibited increased nocturnal HF frequency during ATR ON (HF group means ± SD: ATR OFF = 0.3 ± 0.3 vs. ATR ON = 0.5 ± 0.6; absolute change from ATR OFF to ON = + 0.2 ± 0.3 HFs/night). Given the extremely low nocturnal HF frequency in this group during ATR OFF, the observed average of ~ 50%+ increase in nocturnal HFs is the result of a nightly increase of less than 0.5 HFs (see SI Increased hot flashes). The four participants with low nocturnal HF frequency during ATR OFF were included in the present HF analysis, which means there were even greater overall decreases in nocturnal HF frequency when these individuals were removed from the analysis (mean ± SD: -60 ± 32% nightly HF reduction, n = 94). Between ATR OFF and ON conditions, ambient room temperature was not different ($p = 0.54$).

Table 1
Means ± SD of nocturnal hot flashes (HFs) per night based on HRT status during ATR OFF vs. ON

Group	ATR OFF (mean ± SD)	ATR ON (mean ± SD)	Mean Change (ON - OFF)	Percent Change (ON - OFF)
All women (n = 98)	1.5 ± 1.4	0.5 ± 0.6	-1.0 ± 1.1 **	-56 ± 39
Women not using HRT(n = 52)	1.7 ± 1.5	0.6 ± 0.7	-1.1 ± 1.3 *	-57 ± 35
Women using HRT (n = 35)	1.0 ± 1.0	0.3 ± 0.5	-0.7 ± 0.8 *	-57 ± 39

Note

Mean change (i.e. mean of ATR ON - mean of ATR OFF) and percent change (Eq. 1) is reported for HFs, including standard deviations. Symbols represent statistically significant differences between ATR OFF vs. ON, where * is $p < 0.01$ and ** is $p < 0.001$ (Wilcoxon-Signed Rank or paired t-test, depending on data parametricity).

Hot Flash Frequency Based on Time-of-Night and Sleep Stage

A subset (n = 38; mixed peri- and post-menopausal and mixed HRT status) of women, hereafter referred to as the “timestamp subset”, provided timestamps for each nightly HF event. For the timestamp subset, HFs were analyzed based on the sleep stage and time of night in which they occurred. The majority of nocturnal HFs (independent of ATR condition) occurred during light sleep (61 ± 20%), followed by REM sleep (17 ± 20%), wake (11 ± 13%), deep sleep (7 ± 7%), and time out of bed (4 ± 8%). HFs followed a temporal pattern, where frequency increased throughout the night: 13 ± 17% occurred early (0–2 hours after sleep onset), 29 ± 14% in the middle (2–4 hours after sleep onset), and 56 ± 21% late in the night (≥ 4 hours after sleep onset).

Core and Skin Temperature Changes with ATR ON Compared to HF Frequency

During each ATR condition, a subset of postmenopausal participants (n = 60), hereafter referred to as the “body-temperature subset”, swallowed a gastrointestinal pill on Night 3 to measure T_C and recorded skin temperature at three sites on Nights 2–4. When evaluating HF frequency related to T_C and skin temperature changes with ATR ON, this study found that ATR ON was also associated with significantly lower T_C, lower foot skin temperature, and slightly increased chest skin temperature (all $p < 0.001$; Table 2; Fig. 2). The non-HRT group had the largest T_C and foot skin temperature changes (-0.17°C and − 1.03°C, respectively) between ATR OFF and ON (both $p < 0.001$, Table 2). Chest skin temperature changed the most (+ 0.27°C) for the HRT group ($p < 0.01$, Table 2) between ATR OFF and ON. Forehead skin temperature was not significantly different between ATR OFF and ON ($p > 0.05$) overall or within HRT status groups.

Our data indicate that ATR likely reduces nocturnal HFs by keeping T_C slightly lower than normal (i.e. ATR OFF) during sleep (Table 2). Specifically, nocturnal HFs decreased by -0.15 ± 0.03 events per night (mean estimate ± SE) for each 10% increase in sleep time with $T_C < 36.5$°C ($p < 0.001$). ATR ON increased the amount of sleep time women spent with $T_C < 36.5$°C by 24 ± 4% ($p < 0.001$).

Table 2
Mean ± SE core (T_C) and skin temperatures during ATR OFF vs. ON by HRT status

HRT Use	Metric	ATR OFF (mean ± SE)	ATR ON (mean ± SE)	Mean Absolute Change (ON - OFF)
All women (HRT & no HRT combined)	**T_C** (°C) (n = 59, k = 304)	36.66 ± 0.16	36.50 ± 0.16 **	-0.16 ± 0.15
	MWST (°C) (n = 59, k = 369)	33.8 ± 0.1	33.8 ± 0.1	0.0 ± 0.1
	Chest skin temperature (°C) (n = 59, k = 369)	34.9 ± 0.1	35.2 ± 0.1 **	+ 0.3 ± 0.1
	Forehead skin temperature (°C) (n = 58, k = 363)	32.4 ± 0.2	32.6 ± 0.2	+ 0.2 ± 0.1
	Foot skin temperature (°C) (n = 59, k = 369)	34.5 ± 0.1	33.8 ± 0.1 **	-0.8 ± 0.1
No HRT	**T_C** (°C) (n = 29, k = 168)	36.62 ± 0.03	36.46 ± 0.03 **	-0.17 ± 0.03
	MWST (°C) (n = 30, k = 189)	33.7 ± 0.1	33.7 ± 0.1	0.0 ± 0.1
	Chest skin temperature (°C) (n = 30, k = 189)	34.8 ± 0.1	35.1 ± 0.1 *	+ 0.3 ± 0.1
	Forehead skin temperature (°C) (n = 30, k = 189)	32.2 ± 0.3	32.5 ± 0.3	+ 0.3 ± 0.2
	Foot skin temperature (°C) (n = 30, k = 189)	34.5 ± 0.2	33.5 ± 0.2 **	-1.0 ± 0.2
HRT	**T_C** (°C) (n = 30, k = 136)	36.70 ± 0.03	36.54 ± 0.03 **	-0.15 ± 0.03
	MWST (°C) (n = 29, k = 180)	33.9 ± 0.1	34.0 ± 0.1	+ 0.1 ± 0.1
	Chest skin temperature (°C) (n = 29, k = 180)	34.9 ± 0.1	35.2 ± 0.1 *	+ 0.3 ± 0.1
	Forehead skin temperature (°C) (n = 28, k = 174)	32.5 ± 0.2	32.6 ± 0.2	+ 0.2 ± 0.01
	Foot skin temperature (°C) (n = 29, k = 180)	34.6 ± 0.1	34.1 ± 0.1 *	-0.5 ± 0.2

Note

Mean (i.e. mean of ATR ON - mean of ATR OFF) changes in core (T_C) and skin temperature metrics between ATR OFF and ON (estimated marginal means and SEs from linear mixed effects models utilizing mean values across nights per metric). ATR ON values with * indicate a statistically significant difference between ATR OFF and ON where $p < 0.01$ and ATR ON values with ** indicate a statistically significant difference between ATR OFF and ON where $p < 0.001$(CR2-adjusted linear mixed-effects estimates).

Objective Sleep Metrics Related to ATR and Nocturnal HFs

Objective sleep metrics including sleep duration, sleep efficiency, sleep onset latency, and sleep stages (light, REM, deep, or wake after sleep onset) were not significantly different between ATR conditions (all $p > 0.05$). Additionally, there were no significant correlations between the percent changes (Eq. 1) in objective sleep metrics and nocturnal HFs.

Perceptual Outcomes

Menopausal Symptom Severity

Across all participants (n = 80), self-reported menopausal symptom severity, quantified by total MRS score, was improved by 8.9 ± 41.3% sleeping with ATR ON vs. OFF (means ± SD: -2.5 ± 4.9 points out of 44 total points, $p < 0.001$; Table 3). Note that lower MRS scores reflect more mild menopausal symptoms. Additionally, women reported lower menopausal symptom severity scores across all sub-domains (psychological, somatic, and urogenital) with ATR ON (Table 3). The psychological (mood-related and cognitive symptoms) subscore decreased by -6.9 ± 57.5% (-0.9 ± 2.4 points, $p = 0.002$), the somatosensory (vasomotor and musculoskeletal) subscore decreased by -14.7 ± 40.1% (-1.2 ± 1.9 points, $p < 0.001$), and the urogenital (sexual and bladder problems) subscore increased by 0.39 ± 58.3% (-0.5 ± 1.7 points, $p = 0.04$). Neither menopausal nor HRT status modified these results (all $p > 0.05$), indicating that ATR ON significantly reduced all MRS scores regardless of status.

Perceived Sleep Quality

Having ATR OFF vs. ON led to significant improvements in subjective sleep quality ratings both in the overall PSQI rating and the subcomponent ratings (Table 3). Overall, there was a 10.3 ± 38.7% improvement in PSQI scores (-1.3 ± 2.5 points overall, where lower scores are better; $p < 0.001$). Sub-

component analyses showed significant improvements in subjective sleep quality (Table 3). Sleep duration (-0.20 ± 0.60 points, $p = 0.008$), sleep quality (-0.46 ± 0.67 points, $p < 0.001$), and sleep efficiency (-0.28 ± 0.98 points, $p = 0.021$) all improved, while sleep disturbances (-0.23 ± 0.62 points, $p = 0.004$) declined (Table 3). Additionally, 12.5% (n = 10/80) of participants reported at least a 50% improvement in overall sleep quality and 10% (n = 8/80) of participants had at least a 52% improvement in subjective sleep quality. These findings indicate that people reported sleeping longer and better with ATR ON. Neither menopausal nor HRT status modified these results (all $p > 0.05$).

Table 3
Menopause Rating Scale (MRS) and Pittsburgh Sleep Quality Index (PSQI) scores between ATR conditions (OFF vs. ON) for participants (n = 80)

Survey	Metric (n = 80)	ATR OFF (mean ± SD)	ATR ON (mean ± SD)	Mean Change (points) (ON - OFF)	Percent Change (%) (ON - OFF)	P-val (for mean change)
Menopause Rating Scale (MRS)	Overall Score (0–44)	14.2 ± 7.1	11.7 ± 5.7	-2.5 ± 4.9 **	-8.9 ± 41.3	**< 0.001**
	Psychological subscore (0–16)	4.8 ± 3.3	3.9 ± 3.0	-0.9 ± 2.4 *	-6.9 ± 57.5	**0.003**
	Somatosensory subscore (0–16)	5.6 ± 2.5	4.4 ± 2.1	-1.2 ± 1.9 **	-14.7 ± 40.1	**< 0.001**
	Urogenital subscore (0–12)	3.8 ± 2.7	3.3 ± 2.5	-0.5 ± 1.7 ▯	0.39 ± 58.3	**0.047**
Pittsburgh Sleep Quality Index (PSQI)	Overall Score (0–21)	7.63 ± 3.22	6.30 ± 2.72	-1.33 ± 2.46 **	-10.3 ± 38.7	**< 0.001**
	Subjective sleep quality (0–3)	1.54 ± 0.59	1.08 ± 0.50	-0.46 ± 0.67 **	-22.5 ± 42.8	**< 0.001**
	Sleep latency (0–3)	1.21 ± 0.94	1.20 ± 1.02	-0.01 ± 0.75	4.5 ± 59.0	0.957
	Sleep duration (0–3)	0.88 ± 0.74	0.68 ± 0.57	-0.20 ± 0.60 *	-11.7 ± 45.5	**0.008**
	Habitual sleep efficiency (0–3)	0.90 ± 0.95	0.63 ± 0.80	-0.28 ± 0.98 ▯	-10.0 ± 68.0	**0.021**
	Sleep disturbances (0–3)	1.59 ± 0.52	1.36 ± 0.51	-0.23 ± 0.62 *	-6.7 ± 43.2	**0.004**
	Sleep medication use (0–3)	0.68 ± 1.14	0.68 ± 1.13	0.00 ± 0.63	4.5 ± 48.3	1.000
	Daytime dysfunction (0–3)	0.84 ± 0.70	0.69 ± 0.61	-0.15 ± 0.70	-8.1 ± 56.5	0.066

Note: Values are presented as means ± standard deviation (SD) for overall and sub-component-specific scoring of both MRS and PSQI. For both instruments, higher scores represent worse metrics. "Mean Change (ON – OFF)" is the mean of participant score differences between ATR ON vs. OFF, with negative change values indicating higher scores during ATR OFF. Percent change (Eq. 1) is the mean of individual percent changes between ATR OFF vs. ON. Paired t-tests or Wilcoxon signed-rank tests were applied based on normality of data. Statistically significant *p*-values are indicated as follows: ▯ = $p < 0.05$, * = $p < 0.01$, ** = $p < 0.001$. Italicized text indicates a subscore or component of the MRS or PSQI questionnaire, respectively.

Morning Metrics Correlated with HF Frequency

Each morning, participants rated their sleep satisfaction and thermal comfort. The daily metric changes from ATR OFF to ON were correlated to the change in HF frequency from ATR OFF to ON. The reduction in HFs from ATR OFF to ON was significantly correlated with improvements in all perceptual variables (all $p < 0.01$) except for ease of falling asleep ($p = 0.11$; Fig. 3). Specifically, greater reductions in nocturnal HFs from ATR OFF to ON were associated with larger increases in thermal comfort ($r = -0.58$), sleep satisfaction ($r = -0.45$), calmness of sleep ($r = -0.56$), feeling refreshed upon waking ($r = -0.38$), restedness ($r = -0.44$), and ease of waking ($r = -0.38$). Additionally, a greater decrease in nocturnal HFs with ATR ON was linked to participants reporting that they felt cooler overnight ($r = 0.46$).

Discussion

This study found that after one week of sleeping with ATR, on average, nocturnal HFs were reduced by 56%, menopausal symptom burden was improved by 9%, and subjective sleep quality increased by 10%. These improvements occurred regardless of menopausal phase (peri- vs. post-menopausal) or HRT status. The HF improvements with ATR ON were associated with more time spent sleeping with T_C below 36.5°C and cooler foot skin temperatures, compared to ATR OFF. To our knowledge, this is the first study to demonstrate short-term (1-week) nocturnal HF reductions with ATR while highlighting overnight changes in T_C and skin temperature and related improvements in menopausal symptoms and sleep quality.

Our findings of a 56% nocturnal hot flash reduction are similar to a previous study in 15 menopausal women sleeping on an ATR for 8 weeks; they experienced a 52% reduction in nocturnal HFs[25]. We show that these findings are applicable to a larger sample size (n = 98 vs. n = 15) and that the positive effects of ATR on nocturnal HFs occur in those taking HRT, and across both peri- and post-menopausal women, in a much shorter time period (1 vs. 8 weeks).

Unique to our study, reductions in nocturnal HFs with ATR were associated with significantly more time spent sleeping with T_C below 36.5°C and cooler foot skin temperatures (see Table 2; Fig. 2). As previously discussed, two brain changes during menopause drive increased HF onset and frequency: 1) narrowing of the brain's TNZ, and 2) overgrown heat-sensitive KNDy neurons in the brain[13]. Since sleeping on ATR led to cooler T_C and foot skin temperatures, it may be that HFs are reduced when sleeping on ATR by keeping women within their TNZ during sleep. This hypothesis is supported by evidence showing that even modest elevations in T_C can precipitate vasomotor events during menopause[28]. As the women's average T_C in this study was 36.6–36.7°C, a 0.1–0.2°C decrease (i.e. <36.5°C) could plausibly be the small reduction in T_C required to reduce HF frequency and keep women within their TNZ[29] for more of their time spent asleep. However, more mechanistic research is required to better understand each individual's TNZ and how ATR modifies this TNZ, and therefore reduces nocturnal HFs.

ATR also significantly lowered foot skin temperature, which likely also contributed to ATR-related HF reduction. The hands and feet have more thermoreceptors than the core, which exhibit greater thermosensitivity to cold, compared to warmth[30,31]. Therefore, keeping the feet cooler during sleep with ATR ON could reduce cutaneous afferent thermosensory signalling to the brain (via transient-receptor-potential-activated channels in the skin[32]) and therefore prevent downstream thermoeffector responses, like vasodilation and sweating (HF symptoms), from being triggered[13,30]. Also, lower foot temperatures potentially indicate peripheral cooling, where blood is cooled via arterial-venous anastomoses[33,34] in the feet and hands, and is then circulated back towards the core to keep the body within the TNZ. Prior studies have demonstrated that peripheral (forehead & wrist) skin cooling can influence nocturnal HFs[33,35]. Similar to this study's findings, one pilot study (n = 5) using a wrist-cooling device reported a 50% nightly decrease in severe nocturnal HFs among postmenopausal women[36]. Existing studies on peripheral cooling for HF reduction are limited by cooling only a small skin surface area, and they often do not adjust to overnight physiological changes during sleep and/or rely on manual activation. In contrast, ATR supports prolonged overnight thermal stability by adapting to each individual's physiological changes throughout the night, therefore providing nocturnal HF relief across the night in 85% of women.

Cooler overnight body temperatures during sleep appear to have effects beyond reduced nocturnal HFs. ATR use was associated with improvements in overall menopausal symptom severity and sleep quality (see Table 3). To our knowledge, this is the first study to demonstrate improvements in overall MRS scores in the context of overnight temperature-regulation interventions. Perceptual metrics reported each morning were directly related to nocturnal HF reductions, wherein a larger nocturnal HF reduction was related to an improved perceptual metric (see Fig. 3). Notably, these subjective benefits of sleeping with ATR were observed regardless of menopausal or HRT status, underscoring the clinical relevance of ATR for women who choose not to use HRT[17,22,27]. Again, these data highlight the potential role of ATR as a complementary, non-pharmacological therapy across the menopausal transition.

Limitations. Although this study found that T_C and foot skin temperatures were reduced with ATR ON, and presume that HF reduction is a result of helping to keep women within their TNZ for a longer period of time during sleep, individual TNZs were not assessed to confirm this hypothesis. Further research should explore the mechanism behind ATR-induced reductions in nocturnal HFs to confirm that indeed women are spending more sleep time in their TNZ. And if cooler T_C and foot skin temperatures are indeed the mechanism by which ATR reduces HFs, identifying each woman's unique TNZ would allow even more targeted ATR temperature adjustments throughout the night that might result in an even larger HF reduction. This study could be strengthened by excluding participants classified as postmenopausal whose measured hormone levels (estrogen, progesterone, follicle-stimulating hormone, and luteinizing hormone) did not align with a typical postmenopausal profile. Menopausal status was determined by self-report, and although hormone levels were collected for a subset of postmenopausal participants (n = 60), these data were not used to refine group classification. Furthermore, having the exact time of the HF occurrence (for all participants, not limited to the timestamp subset) during the night, alongside T_C and skin temperature measurements, would further elucidate the mechanisms behind ATR-induced nocturnal HF reductions. With the goal of minimizing awake time, the majority of women (n = 60) were not asked to report the exact time of each HF occurrence, but to simply record when one occurred. In the same vein, because participants were instructed to record their nocturnal HFs as they occurred, objective sleep metrics like awake time after sleep onset may have been artificially inflated and therefore minimized any positive sleep effects of ATR ON, even when nocturnal HFs were reduced. Future studies can be strengthened by using a device that automatically detects nocturnal HFs.

In conclusion, this is the first study we are aware of to demonstrate that sleeping on an active temperature-regulated mattress cover meaningfully reduces nocturnal HF in a short time period (1 week) and also improves menopausal symptom severity and overall sleep quality, regardless of HRT or menopausal status. This is also the first study to show that ATR likely reduces HFs via slightly, but significantly, lowering body core and foot skin temperatures, thus keeping women in the thermoneutral zone for longer periods of time during sleep. Since chronic sleep disruptions and menopausal HFs impair daytime functioning, work productivity, caregiving capacity, and quality of life[37] for an average of 7 years during the menopausal transition [38], sleeping on an actively temperature-regulated mattress cover, like the Eight Sleep Pod, should be recommended as a non-pharmacological menopausal treatment.

Methods

The main goal of this study was to assess how ATR use (ATR OFF vs. ON) impacts nocturnal HF frequency, menopausal symptoms, and perceived sleep quality in peri- and post-menopausal women, and the potential physiological mechanisms behind ATR-induced HF reduction. Outcomes were further evaluated based on HRT and menopausal status. To address these aims, 98 peri- and post-menopausal women were consented and completed a 14-night crossover study with two ATR conditions (ATR OFF vs. ON), for 7 nights each. Data were collected across two studies: Study 1 occurred

between January - February 2025 and assessed whether ATR (via the Eight Sleep Pod) reduced HFs in peri-and post-menopausal women. This study found that ATR significantly reduced nocturnal HFs (by 54% nightly), so Study 2, which occurred July - October 2025 was run to understand HF reduction in a larger study population, especially expanding each HRT status group. Study 2 also collected sleep metrics with a biometric smart ring core and skin temperature data to assess potential physiological mechanisms behind ATR-reduced HFs. Both studies evaluated how decreased nocturnal HFs impacted menopausal symptom burden and subjective sleep quality. Participants were located in the United States or Canada. The order of ATR was fixed in the first study (n = 38; ATR OFF → ON), but randomized for the second study (n = 60). During ATR OFF nights, the Eight Sleep Pod's temperature control was disabled by the research team to prevent inadvertent temperature events.

The testing protocol is outlined in Fig. 4. Participants slept on the Pod Cover each night and recorded any nocturnal HFs awakenings by either screenshotting their smartphone time or marking a bedside tally (pen on paper). Each morning, they completed a daily survey to report nocturnal HF frequency and sleep details. All participants reported the total number of nocturnal HFs.

The body-temperature subset (n = 60 postmenopausal women) swallowed a gastrointestinal pill on Night 3 to measure core body temperature and recorded skin temperature at three sites on Nights 2–4. In this same group of women who recorded core and skin temperatures, we also tracked their objective sleep metrics (i.e. sleep stages and total sleep time) each night with a wearable (smart) ring. To assess menopausal symptom severity and sleep quality, participants completed a survey on the final morning (after Night 7) of each ATR condition.

Participants Characteristics and Inclusion Criteria

All recruitment, enrollment, and consent procedures were reviewed and approved by Sterling Institutional Review Board in January and June 2025 (IRB #s: 12954, 14003), written informed consent was obtained from all participants prior to participation, and all methods were conducted in accordance with relevant guidelines and regulations, including the Declaration of Helsinki.

Eligibility was first assessed using a brief yes/no screening survey. Exclusion criteria included not owning or currently sleeping on an Eight Sleep Pod (version 3, 4, or 5), inability to complete two consecutive weeks of at-home testing, regularly sleeping < 4 hours on three or more nights per week, < 45 years of age, currently pregnant, or a diagnosis of polycystic ovarian syndrome, endometriosis, obstructive sleep apnea, narcolepsy, multiple sclerosis, or autonomic neuropathy. For study 2, women were also excluded if they had changed HRT dosage or status within the 3 months leading up to study start and for Study 1 and Study 2, women were excluded if they declined to have ATR OFF for 7 consecutive nights. For the body-temperature subset, additional exclusion criteria included body weight < 40 kg (88 lb), inability to swallow the gastrointestinal (T_C) pill, presence of implanted electronic medical devices, or contraindication to adhesive sensor use due to sensitive skin.

Eligible participants completed a medical history questionnaire to confirm menopausal and HRT status and to document age, health characteristics, and self-reported HF frequency. Based on information from the medical history questionnaire, participants were enrolled and classified into two primary comparison groups: 1) HRT status, categorized as either using combination estrogen and progesterone HRT for ≥ 3 months (n = 35) or not using HRT (n = 52) within the last 3 + months, and 2) menopausal status, categorized as perimenopausal (n = 15) or postmenopausal (n = 83) based on self-reported menstrual cycle history (Table 4). Participants (from study 2) who reported changing their HRT status in the three months leading up to study start were classified as "Change" HRT status (n = 6) and participants who did not report an HRT status were classified as "Unknown" (n = 5). On average, participants were 54.0 ± 6.7 years (mean ± SD) old and age was similar between HRT groups, but significantly different between menopausal statuses (perimenopausal: 46.3 ± 5.05 years; vs. postmenopausal: 55.5 ± 5.89 years; $p < 0.01$). Height, weight, and body mass index (BMI) were comparable across HRT and menopausal status groups (all $p > 0.05$; Table 4). Note that all participants were cis-gendered females. Between HRT status groups, estrogen, progesterone, luteinizing, and follicle stimulating hormones were all significantly different and pre-study MRS[39] and PSQI[40] scores were also significantly different between these groups.

Table 4
Participant characteristics and survey ratings at baseline, split by group

Group	Age: mean ± SD (years)	Height: mean ± SD (meters)	Weight: mean ± SD (kilograms)	BMI (kg/m^2)	Estrogen (ng/mL) (n = 60)	Progesterone (µg/mL) (n = 60)	Luteinizing Hormone (mIU/mL) (n = 60)	Follicle Stimulating Hormone (mIU/mL) (n = 60)	Baseline MRS (points out of 44)	Baseline PSQI (points out of 21)
All	54.1 ± 6.7 (n = 98)	1.7 ± 0.1 (n = 91)	67.9 ± 12.2 (n = 91)	24.8 ± 4.3 (n = 91)	–	–	–	–	14.3 ± 7.6 (n = 59)	7.3 ± 3.0 (n = 83)
HRT	54.1 ± 5.7 (n = 35)	1.7 ± 0.1 (n = 34)	67.6 ± 13.5 (n = 34)	24.5 ± 4.5 (n = 34)	129.6 ± 134.1 ** (n = 30)	25.6 ± 8.7 ** (n = 30)	9.6 ± 7.3 * (n = 30)	45.4 ± 31.8 ** (n = 30)	12.0 ± 6.6 ▯ (n = 30)	5.6 ± 2.6 ** (n = 32)
No HRT	55.3 ± 6.7 (n = 52)	1.7 ± 0.1 (n = 49)	69.2 ± 11.5 (n = 49)	25.3 ± 4.2 (n = 49)	58.5 ± 36.8 ** (n = 30)	1.4 ± 0.9 ** (n = 30)	16.6 ± 15.0 * (n = 30)	79.2 ± 52.8 ** (n = 30)	16.7 ± 8.0 ▯ (n = 30)	8.3 ± 2.8 ** (n = 52)
Perimenopausal	46.3 ± 5.1 ** (n = 15)	1.6 ± 0.1 (n = 12)	67.3 ± 10.3 (n = 12)	25.1 ± 3.9 (n = 12)	–	–	–	–	–	6.0 ± 1.3 (n = 6)
Postmenopausal	55.5 ± 5.9 ** (n = 83)	1.7 ± 0.1 (n = 79)	68.0 ± 12.5 (n = 79)	24.8 ± 4.3 (n = 79)	94.0 ± 104.1 (n = 60)	13.5 ± 13.6 (n = 60)	13.1 ± 12.2 (n = 60)	62.4 ± 46.7 (n = 60)	14.3 ± 7.6 (n = 59)	7.4 ± 3.1 (n = 77)

Note: Participant mean age by HRT and menopausal status and mean biometrics (height, weight, BMI), hormones, MRS, and PSQI at baseline for the body-temperature group (n = 60). The sample sizes are different per group per metric due to data filtering methods; only HRT or non-HRT status groups are displayed ("Change" and "Unknown" HRT statuses are included in "All" women group). Statistical significance is denoted as follows: ** indicates difference between the two indicated cells in the column with $p < 0.001$, * indicates $p < 0.01$, and ▯ indicates $p < 0.05$.

All HRT administration types were included, including oral, transdermal, injectable, vaginal, and topical. All participants (n = 98) were asked to report any additional hormone use; there were no reports of testosterone use among the test population. To be classified as postmenopausal, women needed to report a lack of menstrual cycle for 12 consecutive months[41].

Active Temperature Regulation: ATR OFF vs. ON

The Eight Sleep Pod is a temperature-regulated mattress cover that modulates bed surface temperature in real-time based on the biometric signals it captures throughout the night (e.g. heart rate, heart rate variability, sleep stages; ATR-detected sleep stage was used to identify sleep stages in which HFs occurred). The system consists of a Hub, positioned beside the bed, which has a water reservoir that heats and cools the temperature of the water flowing through the ATR cover. The temperature is controlled by the participant via the Eight Sleep app. Importantly, the Pod Cover allows independent temperature control for each side of the bed.

ATR allowed for three temperature set points across the night: Bedtime (from in-bed to 15 min after continuous sleep detection), Initial (first 4 hours of sleep), and Final (from the end of Initial to wake). Participants set and adjusted their temperature profiles via the mobile application throughout the ATR ON week and were instructed to use their typical temperature settings, as all participants were existing Eight Sleep Pod users (SI Table 2). Ambient room temperature was measured by a thermistor in the Hub and recorded during both ATR conditions.

During the ATR OFF condition, temperature regulation was disabled on the participant's side of the bed, preventing delivery of any overnight temperature adjustments even if programmed, while their partner's side of the bed (if applicable) continued to receive temperature regulation. Each morning, Pod temperature data were checked to ensure compliance to the assigned OFF/ON condition. Two participants repeated one night each due to the incorrect temperature condition (i.e. ATR OFF when it was supposed to be ON), repeat nights were consecutive throughout the testing protocol.

Physiological Measurements

In Study 2 (n = 60), overnight T_C and skin temperatures were assessed to understand the potential physiological mechanisms by which ATR reduced HFs in postmenopausal women. Six participants each repeated one T_C and/or skin temperature night due to missing data or device failures (k = 6 nights each of T_C and skin temperature were repeated). Again, repeat nights were consecutive to the night with missing data throughout the testing protocol.

Objective Sleep Metrics

Each night of the study, participants (n = 60, all postmenopausal) wore a wearable ring that collects biometric information including sleep stages (deep sleep, REM sleep, light sleep, and wake after sleep onset), along with total sleep time (Oura Ring, Generation 4 ring, Oura sleep staging algorithms 2.0; Oura Health, Oulu, Finland)[42]. Participants wore the ring on the finger where it fit most snugly, and were asked to wear the ring 24-hours per day except when charging the device.

Skin Temperature

On Nights 2–4, at least 30 minutes before going to sleep, participants taped one iButton[43] (Model DS1925L; Maxim Integrated, San Jose, CA, USA) to each of the following three sites: the middle of the forehead, the upper left chest, and dorsum of the left foot (see Fig. 5). Each morning, all iButtons were removed upon waking. Each iButton is a self-contained micro-thermistor (range = -40°C to + 85°C; accuracy = ± 0.5°C; resolution = 0.0625°C) configured to record at 5-minute intervals. Sensors were affixed using 3M Transpore™ medical tape. These sites were selected to continuously measure mean weighted skin temperature (MWST) during sleep[44]: MWST = [(0.4 * forehead skin temperature) + (0.4 * chest skin temperature) + (0.2 * foot skin temperature)]).

Body Core Temperature

At least four hours before sleep on Night 3 of each ATR condition, participants swallowed a gastrointestinal pill that transmits intestinal temperature (T_C)[45] via Bluetooth to an external monitor each minute (eCelcius Performance Pill; Saint-Clair, France). The capsule passed naturally within seven days for all participants (mean residence time 72 ± 48 h; n = 60). Data were stored on the monitor and subsequently downloaded for analysis using BodyCap's eCelcius software.

Urine-Based Hormones

To ensure women were indeed peri- or post-menopausal and taking or not taking HRT, participants collected their urinary hormone levels on the morning after Night 3 of each ATR condition. Participants used their first-morning urine samples to measure estrone-3-glucuronide (E3G), pregnanediol-3-glucuronide (PdG), luteinizing hormone (LH), and follicle-stimulating hormone (FSH; Mira Clarity hormone kit, Mira Care, San Francisco, U.S.A.)[46–48]. Results were automatically logged in the Mira application and also reported in the daily survey (Table 4).

Perceptual (Survey) Measurements

Each morning participants filled out a daily survey where they reported their sleep satisfaction, sleep quality, ease of falling asleep/waking, calmness during sleep, thermal sensation during sleep, and thermal comfort during sleep[49]. They also reported their nocturnal HFs. Nocturnal HFs were a key symptomatic endpoint, as they reflect acute thermoregulatory instability and are closely linked to perceived sleep disruption in peri- and postmenopausal populations[11,13]. To minimize recall bias, participants were instructed to record nocturnal HFs immediately upon waking during the night[50], using bedside smartphone screenshots or notecards, that were then reported in the daily survey each morning[51]. In Study 1, participants recorded the timestamps of their HFs (n = 38), but in Study 2 participants only recorded the total number of HFs experienced each night (n = 60).

After each ATR condition (ON and OFF), participants completed the MRS[39] and PSQI[40]. The MRS[39] is a validated 11-item self-assessment tool that measures menopausal symptom severity across three domains: somatic, psychological, and urogenital. Participants rate symptoms on a 5-point scale (0 = none to 4 = very severe); domain-specific subscores are calculated by summing responses within each domain and combined to generate a total MRS score (maximum scores: somatic = 16, psychological = 16, urogenital = 12; total = 44). Higher scores indicate greater menopausal symptom severity. The PSQI[40,52] is a validated 19-item questionnaire that captures seven sleep domains: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction over a 1-month timeframe. Each component was scored from 0 = no difficulty to 3 = severe difficulty. The sum of these domains yields an overall PSQI score (range 0–21), where higher scores indicate poorer sleep quality. The PSQI administered after each ATR condition (1 week) had questions with slightly altered wording ("past 1 week" vs. "past 1 month") to account for the different timeframe (1 week vs. 1 month).

Data Preprocessing & Filtering

Participants were considered temperature-compliant if they completed ≥ 5 out of 7 valid nights with each ATR condition, in the assigned testing order (i.e. 10 out of 14 total nights in the study). All data processing and validation were performed using Python (3.12.9 or 3.13.5) in Visual Studio Code (version 1.102.3).

Survey data (Studies 1 & 2)

HF data were analyzed from 1,219 nights across 98 participants. MRS and PSQI questionnaires completed > 48 hours after completion of either ATR condition were excluded (n = 4) and participants who did not complete the survey during one of the ATR conditions or did not complete both surveys were excluded from the analysis. After exclusion, for the total population and menopausal status analyses, n = 80 participants had survey data from each ATR condition. For the HRT status analysis, n = 73 participants had an HRT status and survey data from each ATR condition.

Objective sleep metrics (Study 2)

Sleep stage data were obtained nightly via a wearable (smart) ring and filtered to remove instances where total sleep time was < 4 or > 14 h. Nights were further removed if any sleep stage was ± 2.5 SDs, and wake after sleep onset was removed if it was − 2.5 SDs, from each individual's nightly mean across ATR conditions. Additionally, one outlier with increasing hot flashes during ATR ON (80% increase; see SI Increased hot flashes) was removed

from the correlative analysis between HF reduction (%) and objective sleep metric changes (%) so as not to artificially drive correlations. This participant was also removed from the objective sleep analysis between ATR OFF and ON for high (> 50% HF reduction) and low (≤ 50% HF reduction) HF reduction groups because they were an outlier within the low HF reduction group. Therefore, n = 59 participants with k = 803 nights were included in the analysis.

Body temperature data (Study 2)

Before analysis, T_C and skin temperature data were converted to each participant's local timezone and filtered to ensure validity (details in each respective section below). All physiological data were processed to remove invalid sleep sessions (according to pre-defined time requirements; see SI Additional Data Exclusion). Additional preprocessing and filtration steps are outlined below. Ambient bedroom temperature was analyzed to confirm that primary outcomes were not impacted by environmental changes between conditions; ambient temperature outliers (± 2.5 SD from the mean of ambient temperature differences; n = 2) were excluded prior to analysis for a total of n = 96 participants.

Body core temperature (T) (Study 2)

T_C data were sampled every minute and filtered to remove non-physiological periods (shipping and pre-ingestion), retain only stable physiological readings, remove beverage-related artifacts[45,53], and exclude nights with < 4 h of valid data. Manual review excluded nights with atypical circadian T_C profiles and nights with < 4 or > 14 h of sleep. T_C was averaged nightly, using ATR-estimated sleep onset/offset timestamps after filtration, and analyzed between ATR conditions for 59 participants over 302 nights.

Skin temperature (Study 2)

Skin temperature data were sampled every 5 minutes and filtered to remove nights indicative of sensor detachment, poor-quality recordings, or partial detachment episodes identified by rapid, non-physiological shifts[53] (with minor trimming where appropriate). Nights with < 4 or > 14 h of sleep were excluded. One participant was excluded due to failure to return sensors. Additional predefined and participant-specific exclusions were applied as needed (see SI Skin temperature data exclusion criteria). Nightly MWST (equation above) was calculated by getting the mean of the 5-min timepoints across ATR-detected sleep (onset to wake) for each participant on each night. All sleep stages, including wake episodes after sleep onset and events when participants exited the bed during the night were included. After filtration, the following data were analyzed: foot = 369 nights from 59 participants, chest = 369 nights from 59 participants, and forehead = 363 nights from 58 participants.

Statistical Analysis

An a priori power analysis informed by prior literature was conducted for the key outcomes of T_C and HFs. Based on previous studies, a sample size of n = 21 was required to detect meaningful differences (mean difference = 1.4°C) in T_C[54] at 80% power. Prior research also indicates that a minimum of n = 15[25] participants is sufficient to detect differences in reported nocturnal HFs. Thus our target sample size was at least n = 30 in each HRT status group, for a total of n = 60 for Study 2 with body temperature data.

Statistical analyses for all survey-based metrics were performed in Python (version 3.12.9) and T_C and skin temperature statistical analyses were performed using R in R Studio (version 2025.05.1 + 513). For all outcomes, an alpha of $p < 0.05$ defined significance.

HF counts, menopausal symptom severity (MRS)[39], and subjective sleep quality (PSQI)[40] were analyzed using the same statistical methods. For each ATR condition, a mean nightly HFs, HF total change, and percent change (Eq. 1) were calculated. Also for each ATR condition, MRS and PSQI scores, total change, and percent change (Eq. 1) were calculated. For all metrics, percent change was calculated as the mean of individual participant percent changes. Normality was assessed via visualization (histograms) to determine whether to select tests based on data parametricity. HF, menopausal symptoms, and sleep quality were compared between ATR conditions (paired t-tests or Wilcoxon signed-rank tests). Key outcome changes were further evaluated by menopausal (peri- vs. post-menopausal; independent t-tests or Mann-Whitney U tests) and HRT status (HRT vs. no HRT; independent t-tests or Mann-Whitney U tests). Women who did not provide an HRT status or changed their HRT use in the three months leading up to the study (n = 11) were excluded from any comparisons of ATR effects on HRT status, but these women were kept in the analyses for the effects of ATR on HFs, menopausal symptoms, and sleep quality independent of HRT status. Results are reported as means ± SD, and p-values were adjusted for multiple comparisons using the Benjamini-Hochberg false discovery rate.

Equation 1:

$$Percent\ Change\ =\ \frac{ATR\ ON\ metric\ -\ ATR\ OFF\ metric}{ATR\ OFF\ metric}\times\ 100$$

When analyzing the daily survey data, for each ATR condition, the average score of each subjective metric was calculated per participant. Each daily reported subjective metric was tested for normality (visual inspection). Then, a mixed ANOVA (between-within; 2 x ATR condition, 2 x HRT status)

assessed any interaction between ATR condition and HRT status. For any significant interaction effects, follow-up tests were conducted with Bonferroni correction.

To understand the physiological impact of ATR on HFs, HF frequency was modeled as a function of the percent of time spent with T_C<36.5°C. For each night, percent time was calculated as the proportion of valid data points meeting each threshold relative to total nightly data points during sleep, multiplied by 100. Data visualization of mean T_C (x-axis) and nocturnal HFs (y-axis) highlighted a pattern where T_C above 36.5°C showed increased HFs. Additionally, the average T_C with ATR ON was 36.5°C, ~ 0.16°C lower than T_C with ATR OFF, a small change in T_C which can often be the minimal amount required to trigger HFs[29]. Percent time with T_C<36.5°C was modeled using linear mixed-effects models with participant ID as a random intercept to predict nightly HF counts across experimental conditions; there were 147 values during ATR OFF and 157 values during ATR ON. Skin temperature (forehead, chest, and foot) was evaluated between ATR conditions using linear mixed-effects modeling with participant ID as a random intercept; there were 369 values for MWST, foot, and chest temperatures, and 363 values for forehead temperature. Skin temperatures presented in table format (Table 2) were the average skin temperature during sleep. Skin temperatures presented in plots (Fig. 2) as time-series data included a pre-sleep period to display skin temperature shifts from pre-sleep to sleep onset and sustained sleep. All LMMs used CR2-adjusted estimates to account for potential heteroscedasticity or influential individual participant data. Objective sleep metrics were evaluated via two different methods. First, the mean sleep metric was calculated during each ATR condition within the high-hot-flash reduction (> 50% nocturnal hot flash reduction with ATR ON) group. Then, after testing normality within each ATR condition, sleep metrics were compared between ATR conditions using paired t-tests. Second, percent change (Eq. 1) was calculated for each sleep metric and plotted against the percent change (Eq. 1) in nocturnal HFs between ATR OFF and ON (Spearman correlation coefficient). All data reported throughout the manuscript are means ± SD unless otherwise stated.

Declarations

Materials & Correspondence

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Data Availability

The datasets generated for this study are not publicly available due to proprietary restrictions.

Code Availability

The underlying code for this study is not publicly available for proprietary reasons but may be made available to qualified researchers on reasonable request from the corresponding author.

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Author Contributions

Conceptualization: M.L.H., S.S.J., D.D.H., N.E.M.; Data collection: M.L.H., E.R.C.; Data storage: E.R.C.; Data analysis and visualization: M.L.H., S.S.J.; Data interpretation: M.L.H., S.S.J., T.M., N.E.M.; Writing (original draft): M.L.H., S.S.J., E.R.C., B.C.W., D.D.H., T.M., N.E.M.

Competing Interests

The authors declare the following competing interests: M.L.H., S.S.J., E.R.C., B.C.W., D.D.H., and N.E.M. all receive financial compensation in the form of salary from Eight Sleep, Inc. and all own, have, or will have the option to own, equity in Eight Sleep, Inc. T.M. declares support from the Canada Research Chairs Program (CRC-2022-00245). All authors declare no non-financial competing interests.

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Figures

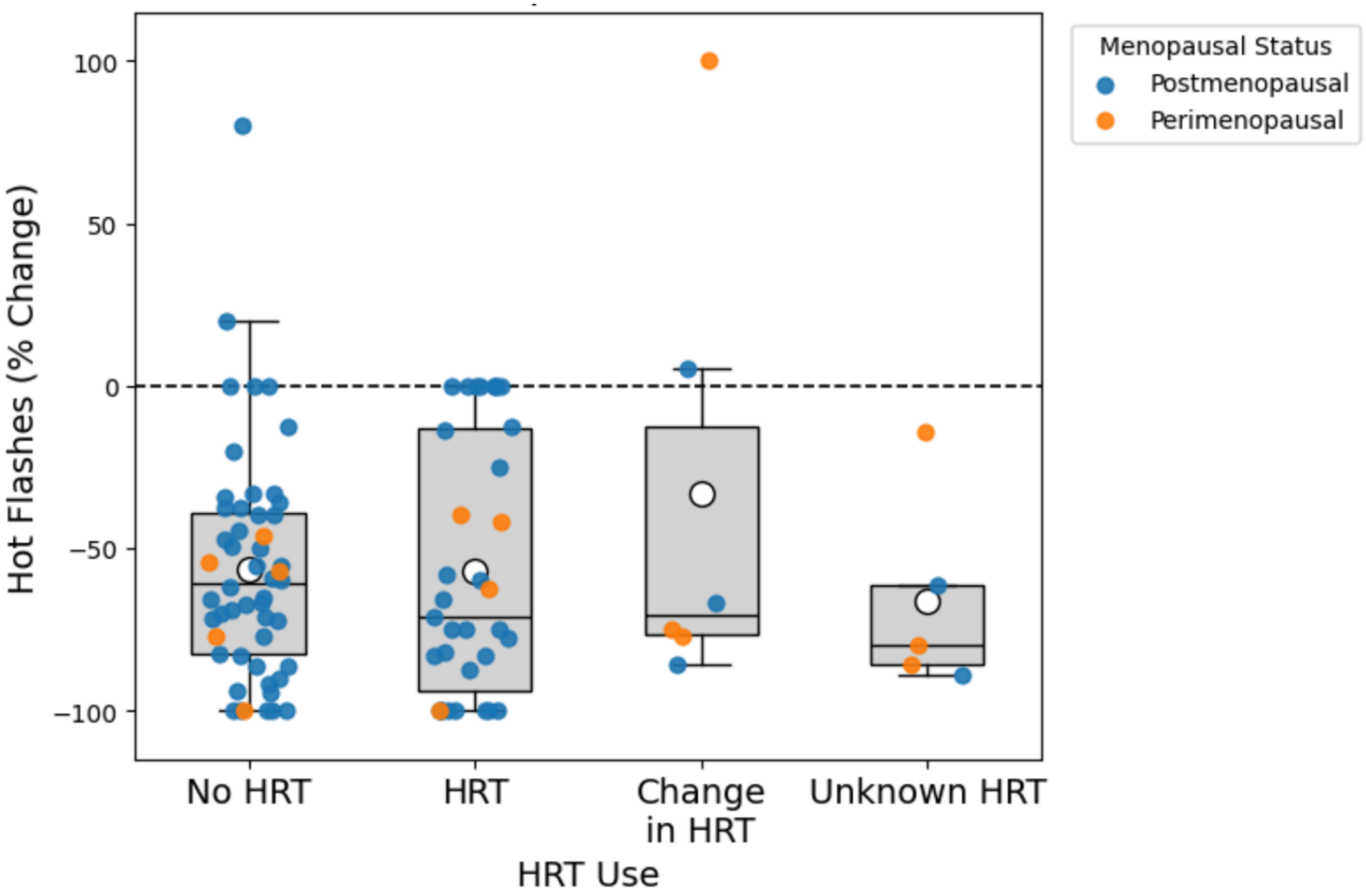


Figure 1

Nocturnal hot flash (HF) percent change with ATR OFF vs. ON by hormone replacement therapy (HRT) status. The boxplots depict the percent change (Equation 1) in nocturnal HF frequency from ATR OFF to ON conditions for peri- and post-menopausal women (orange vs. blue dots, respectively), split by HRT use (No HRT: n=52/98, HRT: n=35/98). Participants who reported changing their HRT status in the three months leading up to study start were classified as “Change” HRT status (n=6/98) and participants who did not report an HRT status were classified as “Unknown” (n=5/98) (see Methods Participants Characteristics and Inclusion Criteria for more information). Each data point represents 1 participant. The box indicates the interquartile range (IQR; 25th and 75th percentiles), with the horizontal line representing the median, and whiskers showing 1.5 × IQR. The white dot denotes the mean HF reduction (% change) from ATR OFF to ON (means ± SDs: No HRT = -57 ± 35%, HRT = -57 ± 39%, Change in HRT = -33 ± 73%, Unknown HRT = -66 ± 31%). The dashed horizontal line at 0% represents no change in HFs between ATR conditions.

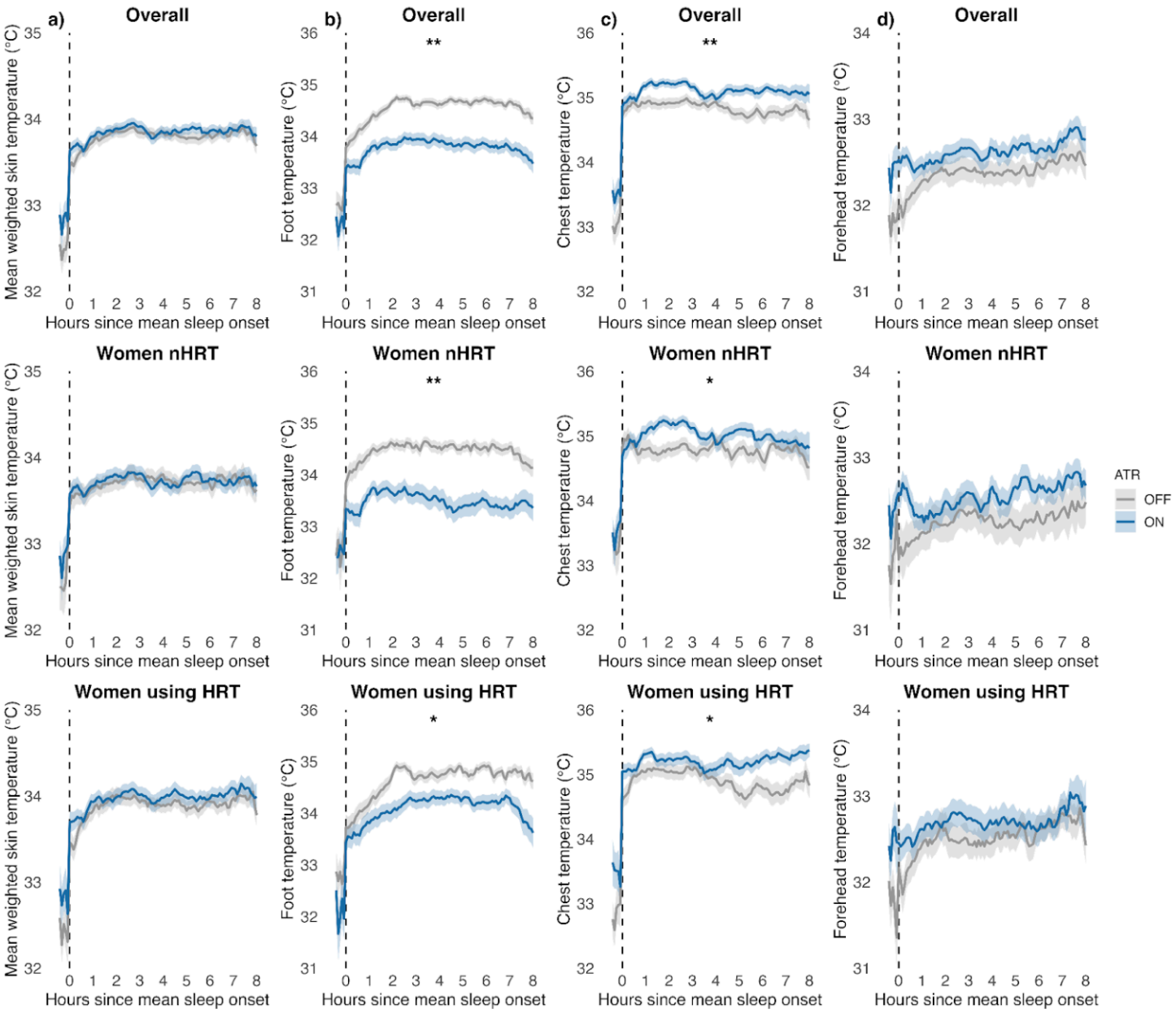


Figure 2

Time-series overnight skin temperatures with active temperature regulation (ATR) OFF versus ON. Mean ± SE skin temperatures throughout the night: (a) 3-site mean-weighted skin temperature (MWST), (b) foot temperature, (c) chest temperature, and (d) forehead temperature are shown for all participants (top row; n=59, k=369), women not using hormone replacement therapy (nHRT; middle row; n=29 k=180), and women using hormone replacement therapy (HRT; bottom row; n=30, k=189). The y-axis shows the skin temperature measurement and is aligned within each measurement type. The x-axis shows hours since sleep onset (vertical dashed line = 0 h). Blue lines represent ATR ON and gray lines represent ATR OFF. Shaded regions indicate ± standard error of the mean. On each subplot, * indicates significance at $p<0.01$ and ** indicates significance at $p<0.001$ (CR2-adjusted linear mixed-effects estimates).

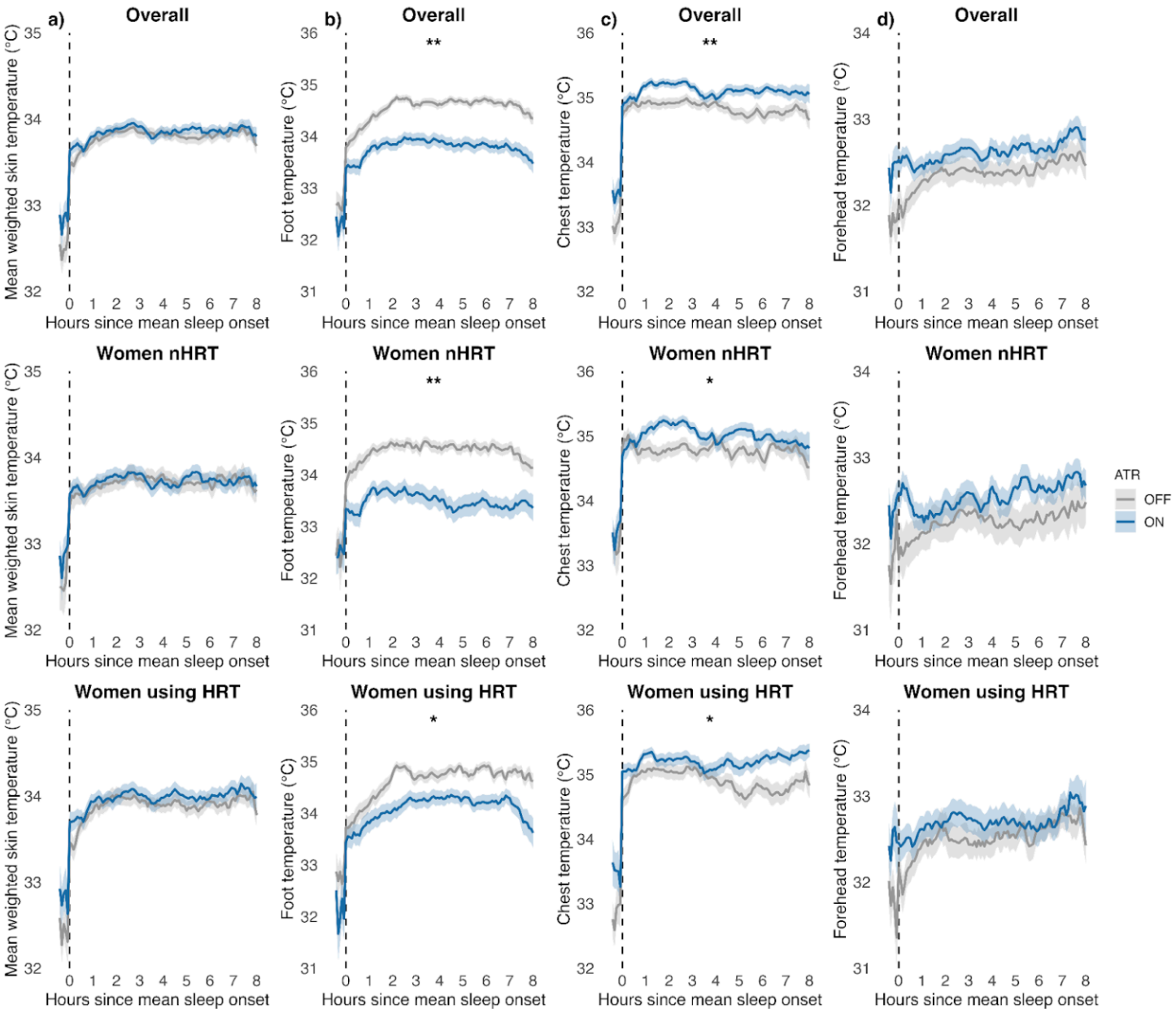


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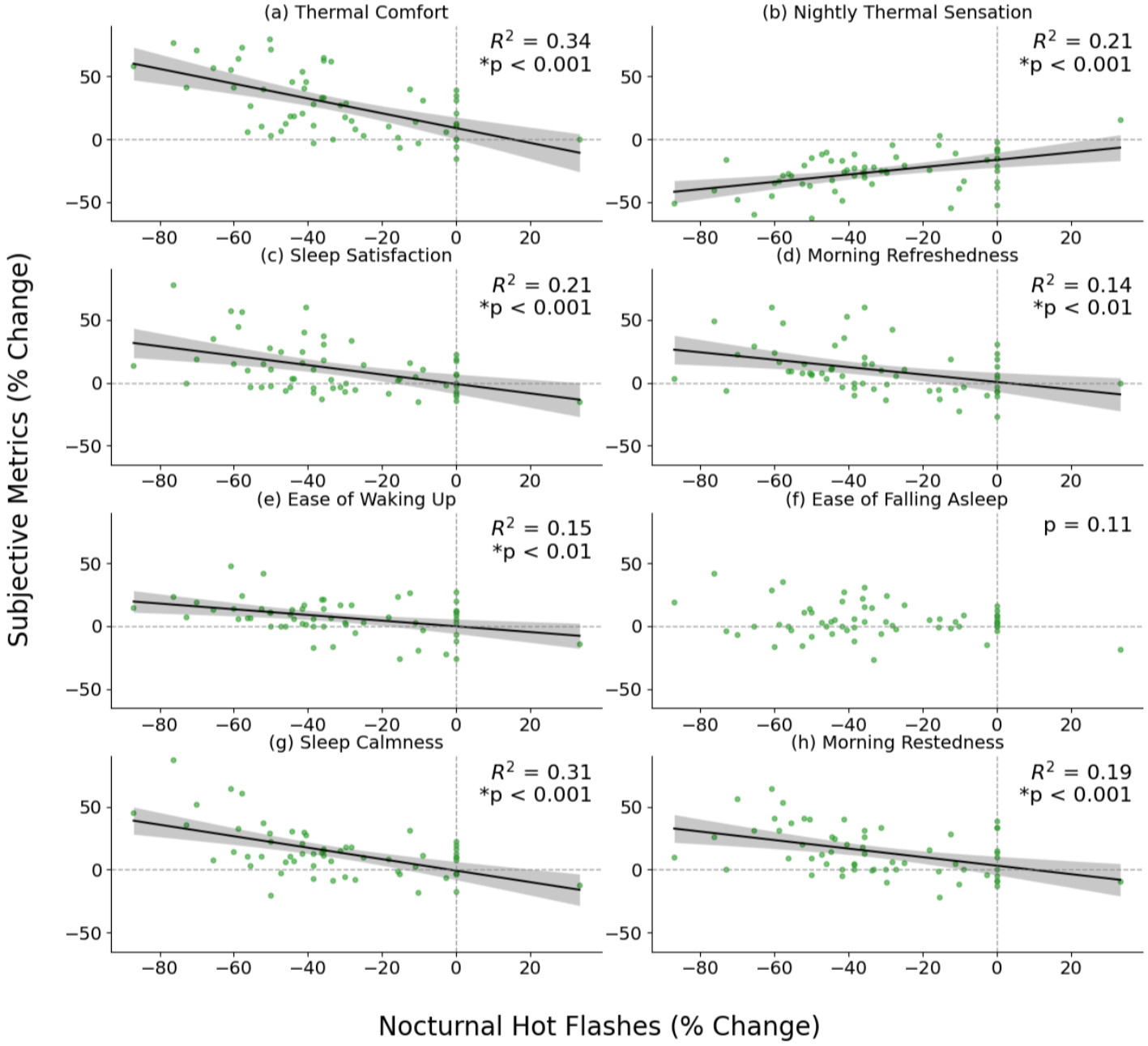


Figure 3

Percent change in nocturnal hot flashes (HFs) vs. percent change in subjective sleep metrics from ATR OFF vs. ON. Scatterplots illustrating the relationship between the percent change (Equation 1) in nocturnal HFs (x-axis) and the percent change in subjective measurements (y-axis) from ATR OFF to ON. Each subplot (panels a-h) displays individual participant data points (green dots) along with a fitted ordinary least squares (OLS) linear regression line in black and its corresponding 95% confidence interval shown in gray shading. OLS correlation coefficients (*R*2) and associated *p*-values are provided for each measurement; *p*-values below 0.01 are displayed as "*p*<0.01." All statistically significant *p*-values are indicated with an asterisk (*). For reference, vertical and horizontal dashed lines indicate where there would be no change in that variable from ATR OFF to ON. Reported OLS R^2 values correspond to Pearson correlation coefficients (r) reported in text.

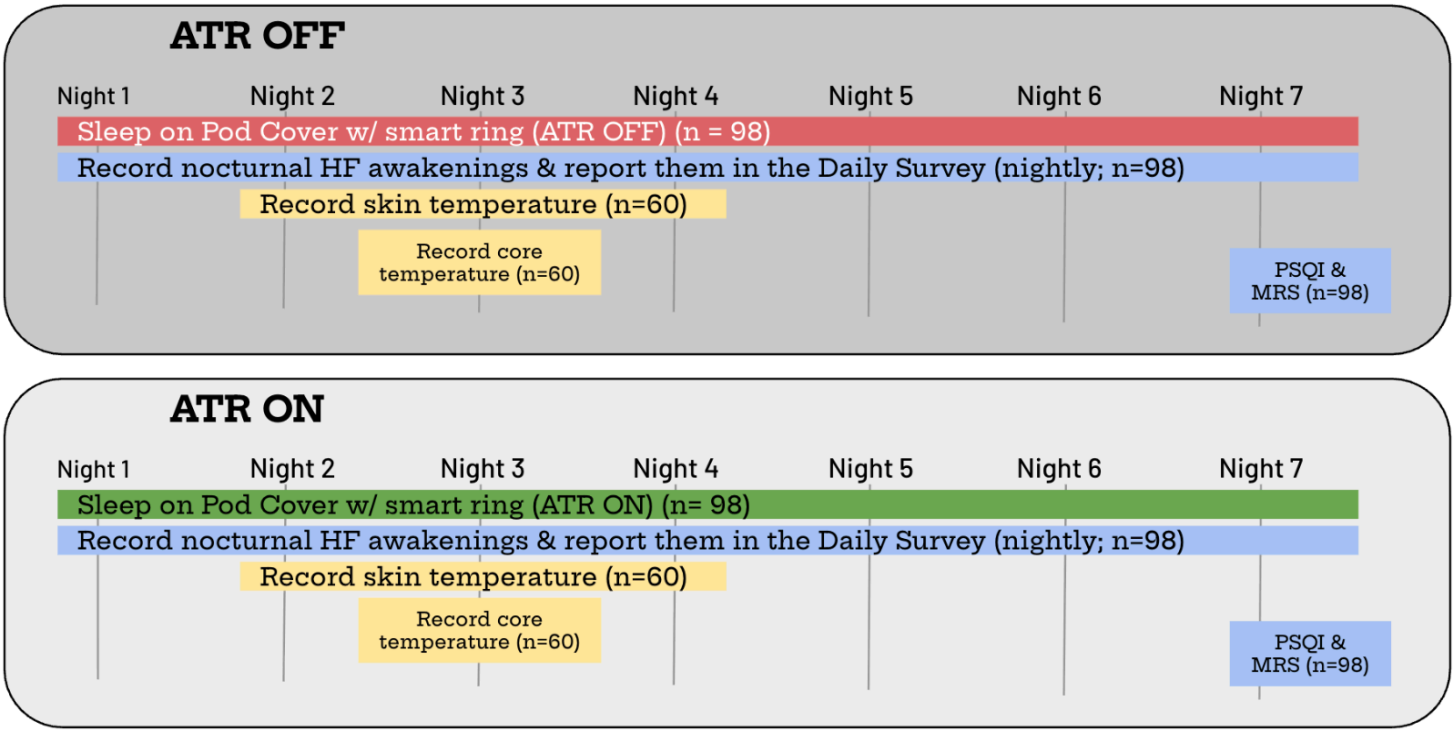


Figure 4

Schematic of the study protocol for ATR OFF and ON conditions. Each week, participants (n=98) completed the same tasks on the same days, the only variable that changed was ATR condition (ON or OFF) (randomized order for n=60, and fixed order for n=38). The red and green bars indicate the ATR condition, blue bars indicate nightly and daily tasks completed by all participants, and yellow bars and boxes indicate additional data collection by the body-temperature subset. The Pittsburgh Sleep Quality Index (PSQI)39 and Menopause Rating Scale (MRS)40 questionnaires were administered on the final morning (after Night 7) of each condition for all participants.

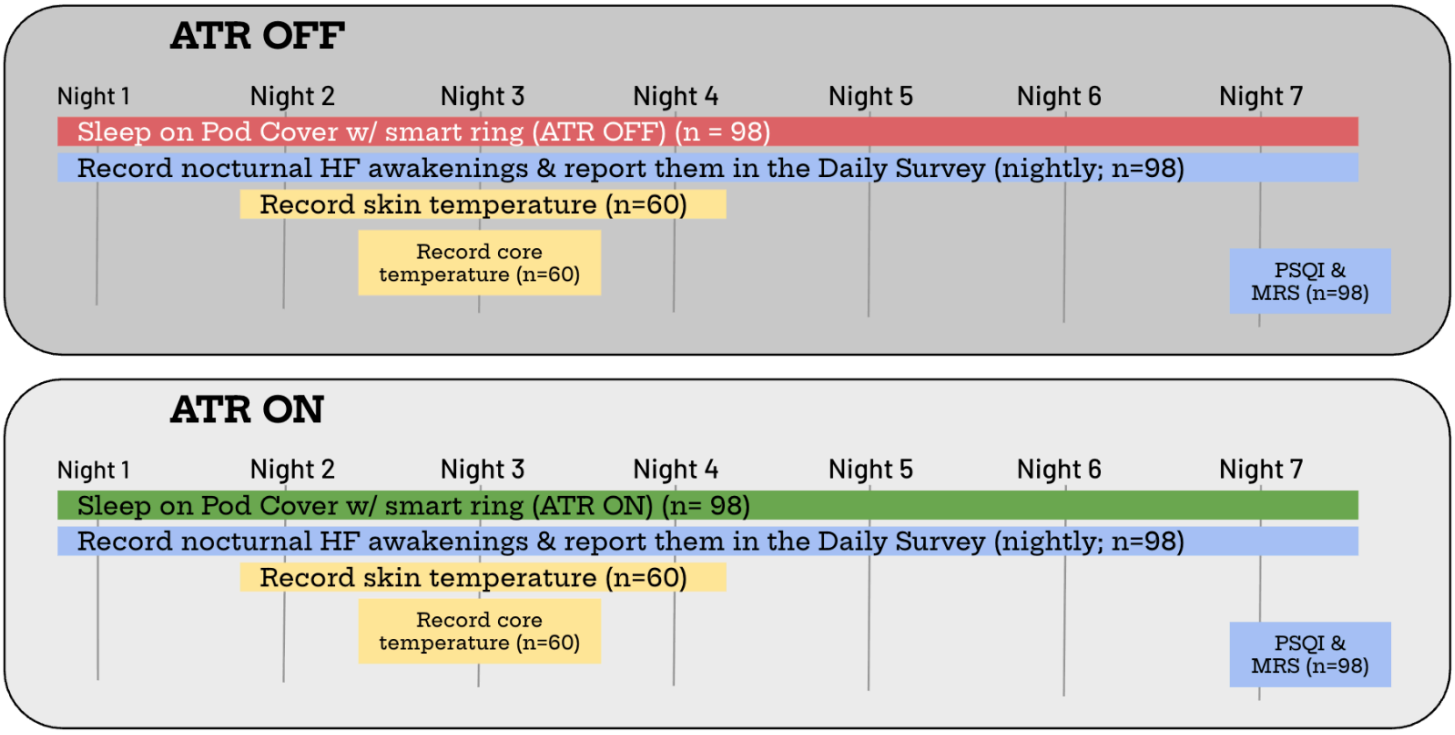


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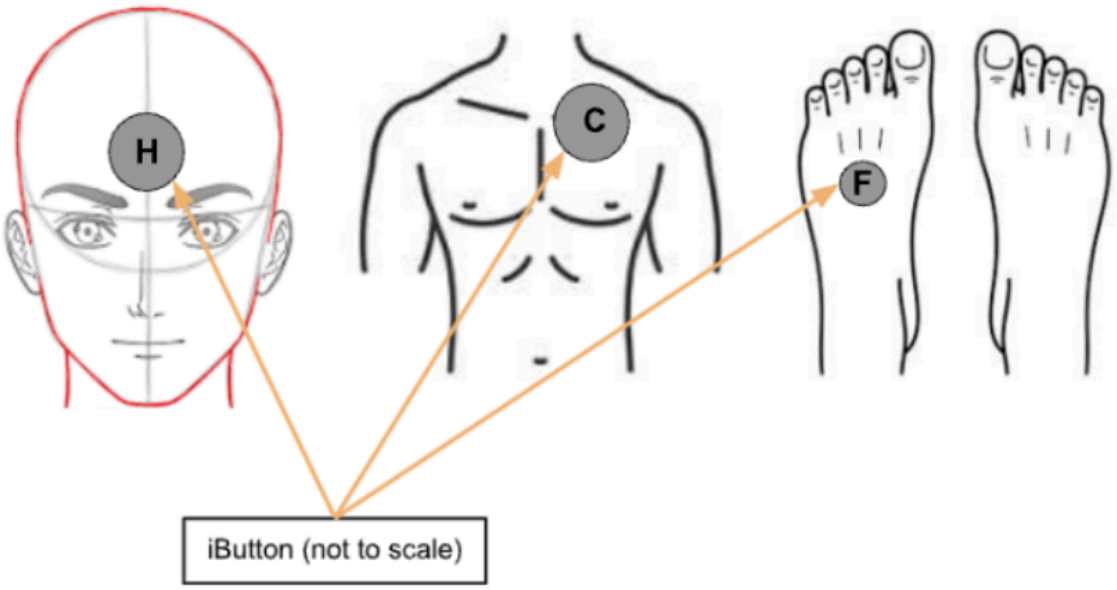


Figure 5

Pictorial representation of skin temperature sites. Skin temperature sensors (not to scale) were affixed to the forehead (H), left chest (C), and left foot (F) to capture cranial, proximal, and distal temperatures used to compute mean weighted skin temperature (MWST) during sleep. Skin temperature sensors were worn on Nights 2-4 of each ATR condition.

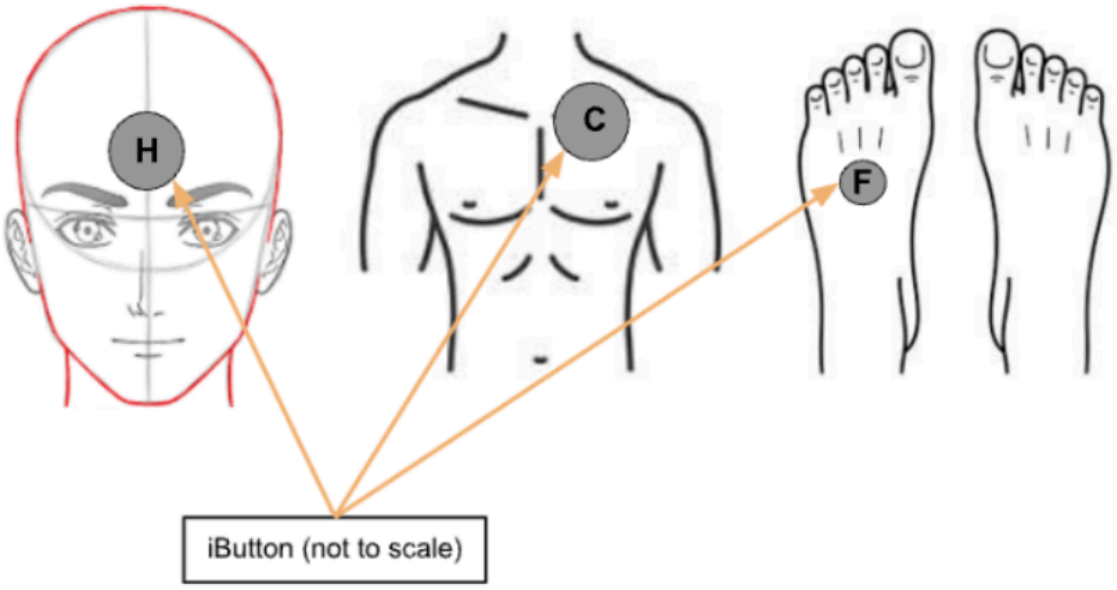


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Supplementary Files

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