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Original Article

Changes in sleep profile on exposure to sodium chloride and artificially carbonated springs: a pilot study

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Abstract. [Purpose] Herein, we aimed to investigate the effects of bathing in a sodium chloride spring and an artificially carbonated spring on core body temperature and electroencephalograms, to assess whether the springs facilitate sleep. [Participants and Methods] This randomized, controlled, crossover study evaluated the effects of a sodium chloride spring, an artificially carbonated spring, a plain hot bath, and no bath on sleep. The subjective evaluations and recording of temperature were performed before/after bathing at 40 °C for 15 min at 22:00 h, before nocturnal sleep (0:00–7:00 h), and after the participants (n=8) woke up in the morning. [Results] Bathing significantly increased the core body temperature, with significant subsequent declines observed until bedtime. Participants in the sodium chloride spring group had the highest average core body temperature, while participants in the no-bath group had the lowest average core body temperature before bedtime (23:00–0:00 h). During bedtime (1:00–2:00 h), the participants in the no bath group had the highest average core body temperature, while participants in the artificially carbonated spring group had the lowest average core body temperature. The amount of delta power/min in the first sleep cycle significantly increased in the bathing groups, with the highest value during bedtime being recorded in the artificially carbonated spring group, followed by the sodium chloride spring, plain hot bath, and no-bath groups. These sleep changes were associated with significant declines in the elevated core body temperature. Increased heat dissipation and decreased core body temperature were observed in the artificially carbonated spring and sodium chloride spring groups, which increased the delta power during the first sleep cycle compared with that observed in the plain hot bath group, followed by the no-bath group. [Conclusion] An artificially carbonated spring would be the most appropriate given each circumstance because it did not cause fatigue, as observed with the sodium chloride spring.
Key words: Sleep, Sodium chloride spring, Artificially carbonated spring

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INTRODUCTION

Insomnia has received global attention and occurs at a rate of 17–21% in Japan[1]. Work inefficiency owing to cognitive function decline and daytime sleepiness have negative financial impact and also increases morbidity associated with mental and physical disorders[2–4]. Although various studies have been conducted regarding increasing the quality of sleep, many home remedies have been overlooked. Of these remedies, bathing before bedtime has been demonstrated to facilitate sleep[5–7]. For centuries, bathing has been one of the most well-maintained traditions worldwide. Many health benefits of bathing in hot springs have been recognized since ancient times[8]. Generally, the effects can improve pain and peripheral circulation through thermal effects. In Japan, there are 110 volcanoes, and many naturally occurring hot springs can be found[9]. Due to the abundance of hot springs, bathing culture has developed to influence modern practices of not only bathing in plain hot water (PHB) but also in hot springs because of its strong influence on sleep and well-being[10, 11].

Many types of hot springs exist, including simple hot springs, sodium chloride, sulfate, carbon dioxide, and sulfur springs[12]. Generally, improvement in pain and peripheral circulation may be achieved through thermal effects. The Hot Spring Law of the Environment Agency includes a guideline that reflects mineral spring analysis methods that states that hot springs may provide beneficial or adverse effects[12].

Some researchers using electroencephalograms (EEGs) have observed that normal bathing in PHB affects core body temperature to increase slow-wave sleep (SWS)[13] and decrease sleep latency[6, 7]. However, reports on sleep changes and hot springs are very rare[14, 15], and whether there are benefits of hot springs over PHB on sleep requires further investigation.

Of the many parameters related to sleep, body temperature is closely associated[16, 17], as evidenced by reports that circadian rhythm disturbances cause insomnia[18–20]. The distal-proximal temperature gradient (DPG) indicates heat dissipates from the peripheral area of the skin[20]. Large declines in core body temperature resulting from heat dissipation after bathing. DPG has been reported to show a smooth time course throughout the experiment and exhibits high correlations with sleep-onset latency[21]. It has been postulated that heat dissipation decreases elevations in core body temperature to facilitate sleep[21, 22].

We examined sodium chloride spring (SCS), which is a common naturally occurring spring in Japan, and artificially carbonated spring (ACS) using an ACS device that has been recently developed. SCSs have a strong heat conservation effect owing to the sodium chloride that remains on the skin and maintains warmth after bathing[12, 23, 24]. ACSs also demonstrate a strong heat conservation effect due to peripheral circulation and increased blood flow[25, 26].

Research objectives were that we hypothesized that baths in SCS and ACS would facilitate and improve sleep by promoting heat dissipation and by decreasing core body temperature.

This is the first study to explore alterations in core body temperature and sleep parameters using EEG after SCS and ACS baths.

PARTICIPANTS AND METHODS

The participants underwent SCS, ACS, PHB, or no-bath (NB) at a local hotel with spas at one-week intervals. Participants and researchers were not blinded to the bath conditions since the participants would be able to distinguish the type of baths from the characteristics of the water.

The study protocol was approved by the Ethics Committee of Akita University (No. 663). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Eight healthy males (mean age: 20.1 years) were eligible for enrollment (Table 1). The participants agreed to avoid strenuous physical activity or that they were unaccustomed to during the study period. The participants were required to be healthy, as confirmed by their medical history and physical examination. The exclusion criteria were the use of hypnotics within the previous year and a history of drug or alcohol abuse. Females were excluded from the study because their body temperatures fluctuate according to their menstrual cycles. The participants were required to abstain from prescription and nonprescription

Table 1. Demographic data of participants

Characteristic	Average ± SD
Age (years)	21.0 ± 1.2
Gender (male)	8
Body Mass Index (kg/m^2)	20.0 ± 2.6
Exercise or sports	Up to 3 times/week
PSQI-J	3.5 ± 1.6
MEQ	49.8 ± 3.7

PSQI-J: Japanese version of the Pittsburgh Sleep Quality Index; MEQ: Morningness-Eveningness Questionnaire; SD: standard deviation.

drugs and supplements. Alcoholic beverages, caffeine, nicotine, and napping were prohibited 24 hours before and during each visit. From one week before to the end of this study, participants used a sleep diary, went to bed at 24:00 and woke up at 7:00 every day to maintain a constant circadian rhythm. They took baths as usual (participants took a shower every day) and exercised 3–4 times per week.

This study had a randomized, positively and negatively controlled, four-session crossover design. The participants were divided into four bathing treatment groups: sodium chloride spring (SCS, Akita Onsen Satomi; pH 8.5, Na 5,482 mg/kg, Ca 973 mg/kg, K 28 mg/kg, Cl 8,306 mg/kg, HCO_3 2,589 mg/kg); artificial carbonated spring (ACS, Carbonic, Cristal Corporation®, Japan, pH 4.8 [estimated CO_2 concentration: 1,000 ppm]); PHB (pH 7.4); and NB (control). The treatments were randomly assigned to each group every week. The participants took 15 min baths at 22:00, went to bed at 24:00 and awoke at 7:00 (Fig. 1).

The temperature of the bath water was set to 40 °C to mimic the temperature of the hot springs and maintain consistent conditions[9]. Participants were submerged in the bath at a level to enable their chests to touch the water. The room air temperature was 23 °C for ACS, PHB, and NB, but was 27 °C for SCS (we used a natural hot spring facility, and therefore the room air temperature could not be adjusted).

The participants then slept in a controlled environment. ACS and PHB were performed in a bathroom with a bedroom (temperature: 23 °C, humidity: 38%, illumination: 200–300 lux before bathing/bedtime). The temperature was adjusted to avoid large temperature differences between the outdoors and indoors. Participants were semi-supine on their bed until lights off (0:00) and instructed to sleep from 0:00 to 7:00. Participants were provided with the same supper (1,200 kcal), sleepwear, and bedding every evening. Under NB conditions at the time of bathing, the participants spent their time in the bedroom quietly engaged in an activity of choice. The experiments were conducted at Akita-Onsen Satomi, a local hotel with a spa.

From 21:00–21:30 and 23:00 to the next morning at 7:00, we measured the core body temperature (rectum), proximal skin temperature (lower part of the clavicle), and distal skin temperature (top side of the foot) each minute (Fig. 1). We used a Skin Temp & Humidity Logger LT8 (Gram Corporation®, Saitama, Japan) as a clinical thermometer (Fig. 2). The participants practiced inserting a thermometer into the anus to a depth of 7 cm under the supervision of a physician.

Before the experiments, we evaluated sleep based on the Japanese version of the Pittsburgh Sleep Quality Index (PSQI-J)[27, 28] and confirmed that the participants had no sleep disorders. We also evaluated their sleep schedule cycle and chose the intermediate type, based on the Morningness-Eveningness Questionnaire (MEQ)[29] that participants had completed in advance.

All participants underwent overnight EEG monitoring on experimental nights (Fig. 1) that was obtained using a single-channel EEG (MOOMIN-KEI; Sleep Well Co., Osaka, Japan) (Fig. 2), as previously described[30]. According to protocol[30], the recorded nights were divided into 30 s sequential periods and manually classified into rapid eye movement (REM) sleep and non-REM sleep, which were further classified into light (N1, N2) or slow wave (S3, S4=N3) sleep. The total sleep time (TST) was calculated as the total sleep period minus the wake time after sleep onset (WASO). Sleep onset was defined as the first occurrence of stage 2 sleep, followed by 5 min of continuous sleep comprising stages 1, 2, 3, and 4, or REM sleep. As a marker of deep sleep[31], we calculated the delta power. As previously described[32], EEG data underwent autoregressive high-pass filtering, a Hanning window was implemented, and data were subsequently decomposed into 30 s periods using fast Fourier transform into delta and other frequency bands. The power (μV^2) of the delta frequency band and the delta power per minute in the first sleep cycle ($\mu V^2/min$) were calculated. Because sleep has 3–4 cycles per night and the first cycle becomes the deepest sleep, we calculated delta power in the first sleep cycle independently.

We evaluated participants for sleepiness using the Stanford sleepiness scale (SSS)[33] and visual analog scale (VAS)[34] for alertness, mood, and fatigue. The evaluations were performed before and after bathing, before nocturnal sleep, and after the
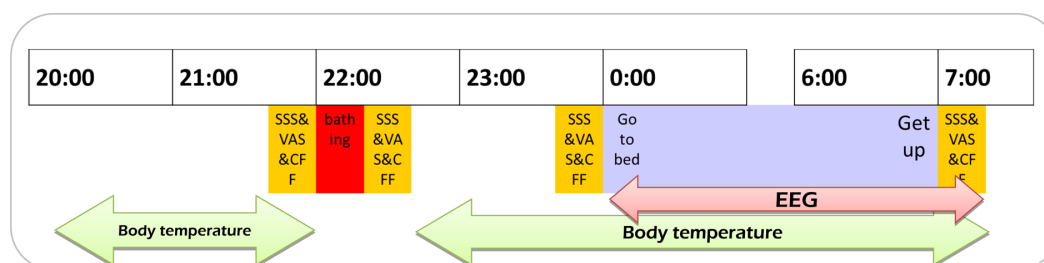
Fig. 1. Experimental schedule.
Bathing: from 22:00 for 15 min; Sleep: from 0:00 to 7:00. Recording core body, distal skin, and proximal skin temperatures between 21:00 and 22:00 and from 23:00 to the following morning at 7:00. EEG: from 23:00 to the following morning at 7:00. Subjective evaluation: Stanford sleepiness scale (SSS), visual analogue scales (VAS) of alertness, mood, and fatigue before/after bathing, before nocturnal sleep, and after participants awoke the following morning.
SSS: Stanford sleepiness scale; VAS: visual analogue scale; CFF: Critical Flicker Fusion.

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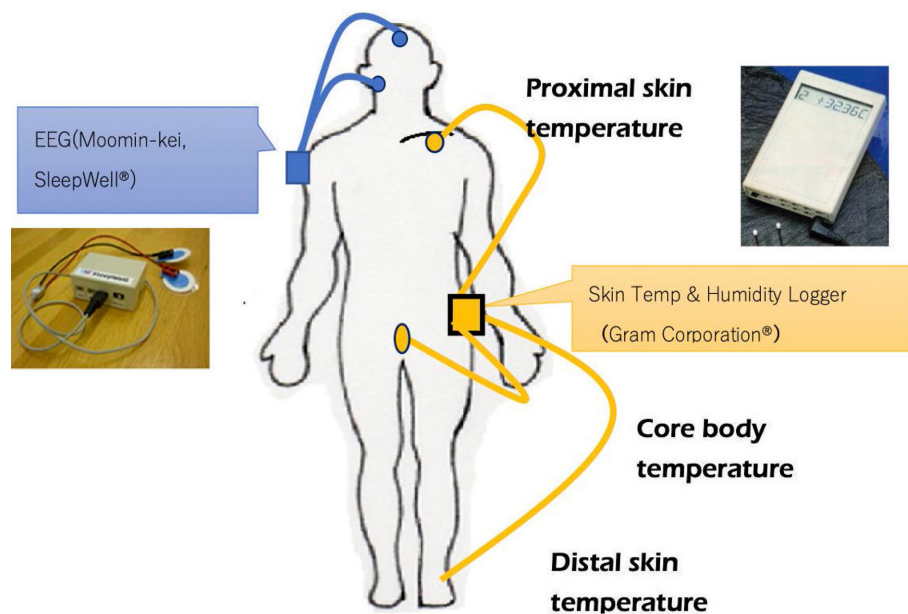
Fig. 2. Experimental equipment.
Core body temperature (rectum), proximal skin temperature (lower part of the clavicle), and distal skin temperature (top side of the foot) were measured using a clinical thermometer (Skin Temp & Humidity Logger LT8, Gram Corporation, Saitama, Japan). Electrodes of a single channel EEG monitor (Moomin-kei, Sleepwell Corportion., Osaka, Japan) were placed on the middle of the forehead and the mastoid. EEG: electroencephalogram.

participants woke up in the morning. For the SSS, smaller scores are better in terms of the functionality of the participant, whereas larger values are better for VAS.

Critical flicker fusion (CFF) test: This task is believed to assess the integrative capacity of the central nervous system. Individual thresholds were determined by the psychophysical method of limits on two ascending (flicker to fusion) and two descending (fusion to flicker) scales[35]. The mean of these two ascending and two descending presentations were used as the threshold frequency (Hz). A decreased threshold was indicative of impairment.

We compared the mean body temperatures between the four conditions (SCS, ACS, PHB, and NB) before and after sleep using repeated two-way ANOVA, with the types of bathing and times as factors every hour. After checking for interactions, we performed multiple comparisons using the Bonferroni correction for the main effects of bathing. Descriptions of the main effects of time have been omitted. With sleep latency, TST, stage 1–2 sleep, stage 3–4 sleep, REM sleep, WASO, sleep efficiency, and the amount of delta power per minute in the first sleep cycle, we used repeated one-way ANOVA and multiple comparisons using Bonferroni correction. For subjective evaluation and CFF, we used repeated two-way ANOVA with bathing type and time as factors. We conducted a post hoc power analysis and the effect size (η^2). The significance level was set at $p<0.05$. Statistical analyses were performed using SPSS version 26 (IBM Corp., Armonk, NY, USA) and R2.8.1.

RESULTS

The temperatures of the bathing groups showed initial increases right before bedtime that decreased more quickly than those of the non-bathing group during sleep.

A total of eight of ten participants (mean age: 20.1 years) completed the entire experiment. Two participants were excluded because of poor physical condition or a lack of data.

From 21:00–21:30 and 23:00 to the next morning at 7:00, we measured the core body, proximal skin, and distal skin temperatures every minute. Bathing significantly increased the core body temperature, and the largest subsequent declines were observed until participants went to bed (23:00–0:00) (Fig. 3).

The mean core body temperatures of the SCS, ACS, and PHB groups were significantly higher than that of the NB group before bedtime (23:00–0:00) (repeated 2-way ANOVA, $p<0.01$) (Table 2, Fig. 3). However, during bedtime, the lowest core body temperatures were indicated in the order of ACS, SCS, PHB, and NB groups, from 1:00 to 2:00 (repeated 2-way ANOVA, $p<0.01$) (Table 2, Fig. 3). Morning nadir core body temperatures were lowest in the order of SCS, ACS, PHB, and NB groups, but the difference was not statistically significant (Table 2, Fig. 3).

DPG similarly increased before sleep in the bathing groups, but declined during sleep.

After bathing, the mean DPG increased in the order of ACS, SCS, PHB, and NB groups (23:00–0:00) (repeated 2-way
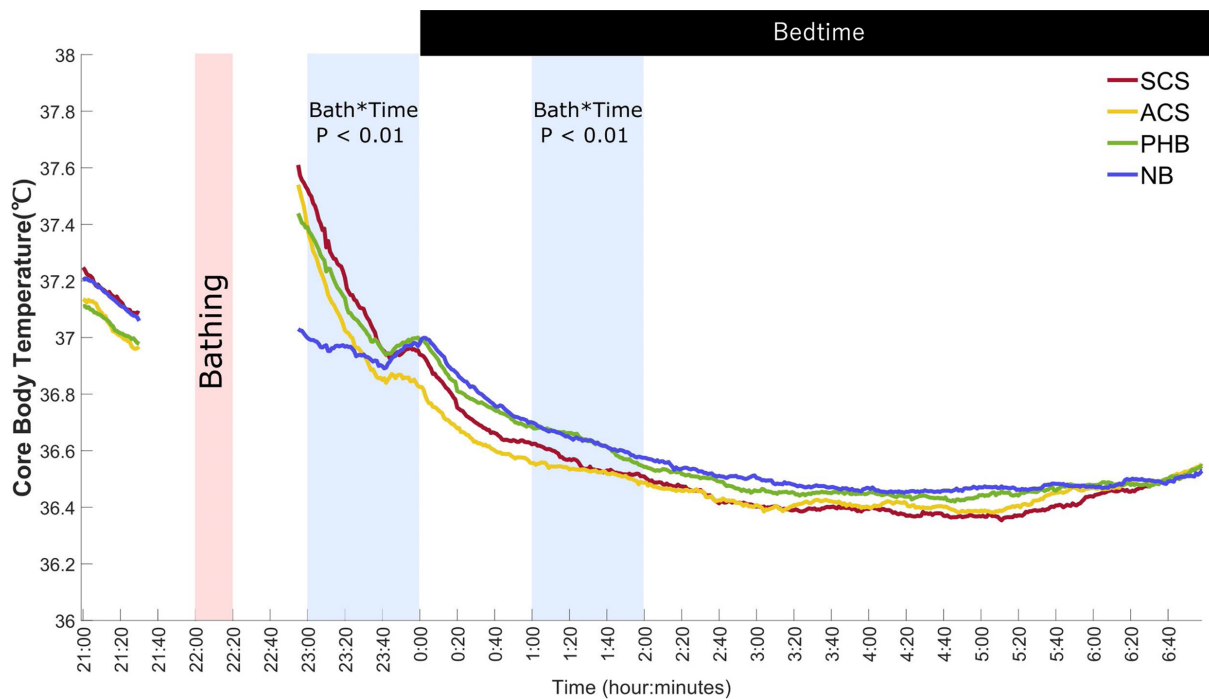
Fig. 3. Core body temperatures (°C).
Measured every minute from 21:00–21:30 and 23:00 to the following morning at 7:00 (repeated two-way ANOVA)
SCS: sodium chloride spring; ACS: artificially carbonated spring; PHB: plain hot bath; NB: no-bath; ANOVA: analysis of variance.

Table 2. Body temperatures of participants

|		SCS	ACS	PHB	NB	ANOVA	Effect size
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Interaction bath*time	η^2
Core body temperature 23:00–0:00	(°C)	37.1 ± 0.0	37.0 ± 0.0	37.1 ± 0.1	37.0 ± 0.1	**	1.2
Core body temperature 1:00–2:00	(°C)	36.6 ± 0.1	36.5 ± 0.1	36.6 ± 0.1	36.6 ± 0.1	**	0.5
Nadir of core body temperature 0:00–7:00	(°C)	36.3 ± 0.1	36.3 ± 0.1	36.3 ± 0.1	36.3 ± 0.1		
DPG 23:00–0:00	(°C)	−0.8 ± 0.1	−0.2 ± 0.1	−1.2 ± 0.1	−2.4 ± 0.1	*	0.5
DPG 5:00–6:00	(°C)	−0.9 ± 0.3	−0.3 ± 0.3	−0.4 ± 0.5	−0.2 ± 0.3	**	0.5

**p<0.01, *p<0.05.
SCS: sodium chloride spring; ACS: artificially carbonated spring; PHB: plain hot water; NB: no-bath; ANOVA: analysis of variance; DPG: distal-proximal temperature gradient; SE: standard error.

ANOVA, p<0.01) (Table 2, Fig. 4). Subsequently, the DPG declined by midnight, when the participants went to bed. During the first few hours of sleep, DPG increased and then decreased in the latter half of sleep (Fig. 4). In contrast, the DPG of the SCS was suppressed from 5:00 to 6:00 (repeated 2-way ANOVA, p<0.01) (Table 2, Fig. 4).

Bathing groups showed higher delta power during the first sleep cycle.

Sleep latency also decreased in the following order: SCS (5.6 min), PHB (6.1 min), NB (8.9 min), and ACS (10.5 min); however, the difference was not statistically significant (p=0.31; Table 3). The TST, stage 1–2 sleep, stage 3–4 sleep, REM sleep, WASO, sleep efficiency, and total amount of delta power did not significantly differ between groups (Table 3). However, the amount of delta power per min in the first sleep cycle significantly increased in the bathing groups (repeated 2 way-ANOVA, p<0.01), with the highest power observed in the ACS group (SCS; 20.4μV²/min, ACS; 20.7μV²/min, PHB; 18.1μV²/min, NB; 13.6μV²/min) (Table 3).

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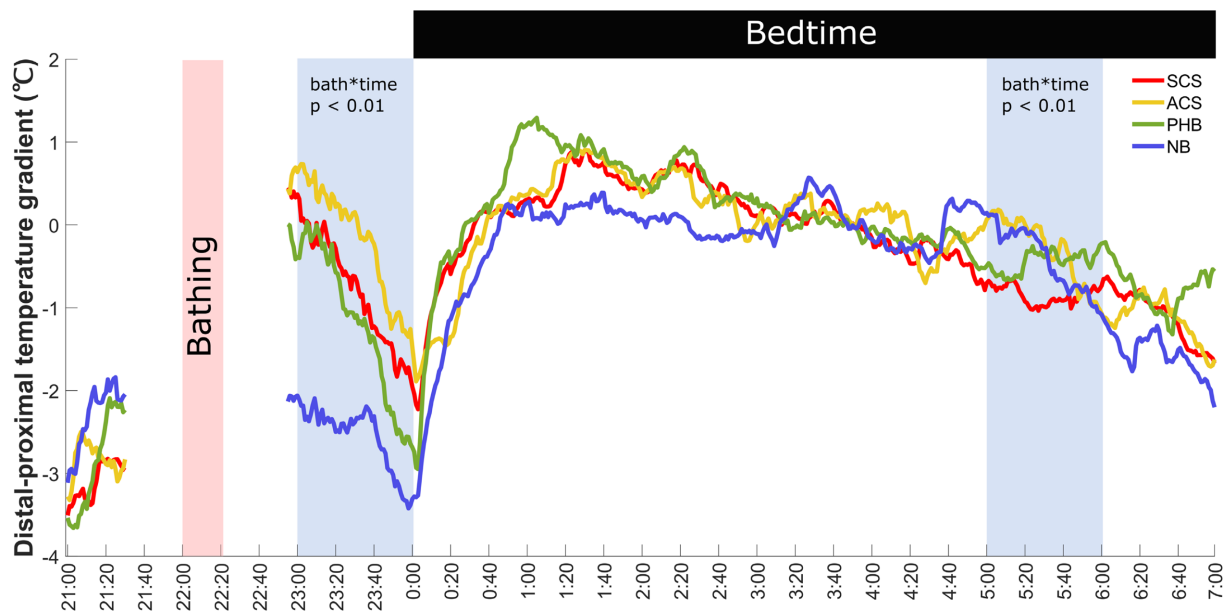
Fig. 4. Distal-proximal temperature gradient (°C).
Measured every minute from 21:00–21:30 and 23:00 to the following morning at 7:00 (repeated two-way ANOVA)
SCS: sodium chloride spring; ACS: artificially carbonated spring; PHB: plain hot bath; NB: no-bath; ANOVA: analysis of variance.

Table 3. Electroencephalogram data

		SCS	ACS	PHB	NB	ANOVA	Effect size
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	main effects (bath)	η^2
Sleep latency	min	5.6 ± 1.7	10.5 ± 4.5	6.1 ± 1.6	8.9 ± 2.4		
Total sleep time	min	390.8 ± 8.5	387.1 ± 6.6	401.7 ± 3.7	375.9 ± 13.2		
Stage 1–2 sleep	min	232.1 ± 19	232.0 ± 16.8	247.9 ± 7.2	218.8 ± 13.9		
Stage 3–4 sleep	min	63.0 ± 16.2	56.3 ± 10.7	50.1 ± 9.3	54.6 ± 16.1		
REM sleep	min	95.7 ± 9.6	98.8 ± 9.0	103.7 ± 4.1	93.6 ± 5.7		
WASO	min	20.8 ± 7.5	19.3 ± 4.1	9.5 ± 3.2	27.7 ± 11.5		
Sleep efficiency	%	93.1 ± 2.0	92.2 ± 1.6	95.6 ± 0.9	89.5 ± 3.1		
Total amount of delta power	μV^2	3,471.2 ± 612.7	3,289.9 ± 533.0	3,130.2 ± 436.2	3,202.8 ± 572.9		
Amount of delta power/min in the first sleep cycle	μV^2/min	20.4 ± 4.0	20.7 ± 3.8	18.1 ± 2.6	13.6 ± 2.8	**	0.9

**p<0.01, *p<0.05.
SCS: sodium chloride spring; ACS: artificially carbonated spring; PHB: plain hot water; NB: no-bath; ANOVA: analysis of variance; REM: rapid eye movement; WASO: wake time after sleep onset; SE: standard error.

The SCS group showed fatigue before bedtime. Among the subjective parameters before bedtime, significant differences in SCS-induced fatigue were found between the four groups (p<0.05, R-ANOVA) (Table 4). Other subjective parameters such as SSS, alertness, and mood did not differ. The objective parameter, CFF, did not exhibit any between-group differences (Table 4).

DISCUSSION

Many health benefits of bathing in hot springs have been recognized since ancient times[8]. Bathing, especially in hot springs with various mineral compositions, is known to facilitate and improve sleep by warming the body[11, 15, 36, 37, 38]. It is postulated that heat dissipation decreases the elevated core body temperature and facilitates sleep[39, 40]. However, there is limited scientific confirmation of these effects using EEG. Therefore, we investigated the effects of hot springs on core body

Table 4. Subjective evaluation & CFF

	SCS	ACS	PHB	NB	R-2 way ANOVA	Effect size
	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Interaction bath*time	η^2
SSS						
Before bathing	3.0 ± 0.4	2.6 ± 0.4	2.9 ± 0.3	2.8 ± 0.2		
After bathing	3.5 ± 0.4	3.0 ± 0.6	3.0 ± 0.5	2.8 ± 0.3		
Go to bed	4.6 ± 0.4	3.6 ± 0.5	4.0 ± 0.5	4.1 ± 0.7		
Get up	3.4 ± 0.4	3.6 ± 0.4	4.0 ± 0.4	3.5 ± 0.2		
Alertness						
Before bathing	52.0 ± 9.6	54.4 ± 9.0	58.0 ± 9.8	67.1 ± 7.4		
After bathing	57.5 ± 8.9	67.3 ± 10.6	66.6 ± 8.9	58.6 ± 9.5		
Go to bed	25.6 ± 5.5	38.9 ± 10.1	30.8 ± 5.7	37.0 ± 9.5		
Get up	53.8 ± 6.6	46.0 ± 7.5	54.1 ± 7.7	55.3 ± 7.5		
Mood						
Before bathing	67.8 ± 3.8	68.6 ± 7.0	66.3 ± 7.4	59.6 ± 5.7		
After bathing	42.8 ± 9.7	48.5 ± 8.0	60.1 ± 7.0	58.3 ± 7.0		
Go to bed	59.8 ± 8.1	67.5 ± 7.7	61.3 ± 8.3	52.9 ± 10.1		
Get up	56.8 ± 6.0	51.4 ± 7.0	54.0 ± 9.4	53.9 ± 6.9		
Fatigue						
Before bathing	48.9 ± 5.5	56.3 ± 8.2	58.3 ± 9.2	53.6 ± 6.9	*	
After bathing	24.4 ± 5.7	47.8 ± 10.7	48.3 ± 9.1	51.9 ± 6.8		0.65
Go to bed	33.8 ± 6.8	52.4 ± 7.9	34.8 ± 6.9	45.1 ± 6.1		
Get up	56.4 ± 7.9	57.6 ± 6.8	55.9 ± 10.2	53.1 ± 5.2		
CFF						
Before bathing	36.9 ± 3.2	35.7 ± 2.0	36.7 ± 3.1	36.4 ± 3.3		
After bathing	37.1 ± 3.6	37.3 ± 2.1	36.8 ± 3.4	36.0 ± 3.2		
Go to bed	35.7 ± 3.1	34.7 ± 2.9	35.8 ± 3.1	37.2 ± 0.9		
Get up	36.5 ± 3.2	35.6 ± 3.1	36.0 ± 3.2	36.9 ± 1.6		

**p<0.01, *p<0.05.
SCS: sodium chloride spring; ACS: artificially carbonated spring; PHB: plain hot water; NB: no-bath; ANOVA: analysis of variance; SSS: Stanford sleepiness scale; CFF: critical flicker fusion; SE: standard error.

temperature and EEG to confirm whether hot springs facilitate or improve sleep. However, sleep improvements with SCS and ACS were not significantly better than those with PHB, suggesting that PHB itself has a beneficial effect on sleep.

However, it is difficult to determine the medical effects of hot spring ingredients independently because the effects of hot springs involve complex biological interactions with multiple stimuli, such as hot spring temperature, physical action, and chemical composition[41].

In recent years, a meta-analysis of balneotherapy was performed by Kamioka et al., and the effectiveness of spa therapy was confirmed[42]. However, the effects of spring quality have not been studied extensively, owing to the limitations mentioned above. We compared the three types of bathing in a laboratory setting (i.e., in similar environments). Under SCS conditions, the participants bathed in a hot spring, but under ACS and PHB conditions, they used a bathtub inside the hotel room. It should be noted that masking was not possible.

The types of hot springs used in this study were the SCS and ACS. SCS is a very common spring in Japan, which has a strong heat conservation effect owing to the sodium chloride that remains on the skin and retains heat even after bathing[22, 24, 43]. Maeda reported the following effects of body heating by SCS at Yunohama Onsen (Na 1,236 mg/kg, K 629 mg/kg, Cl 2,589 mg/kg)[44]. A single bath increased body temperature, heat retention, and blood flow. After bathing for two days, a psychological relaxation effect was observed. The Akita Onsen Satomi used in this study was also an SCS, and a similar increase in body temperature was observed.

Naturally carbonated springs are rare in Japan; however, in recent years, ACS equipment has been developed for home use and has gained popularity. ACS also exhibits a strong heat conservation effect by enhancing peripheral circulation and increasing blood flow[12, 25]. It has been argued that for the mechanism of heat conservation, carbon dioxide is absorbed by the skin[45, 46]. ACS is widely used to treat vascular insufficiency[47, 48] and pressure sores[49] in patients with diabetes, in which case a footbath is often used. ACS is also used for rehabilitation and resistance training in athletes to improve muscle fatigue and performance[49–52].

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DPG shows a smooth time course throughout the experiment and exhibits the highest correlations with sleep-onset latency[21, 22, 53]. Bathing facilitates the increase in core body temperature, the subsequent decline in core body temperature, and DPG exceeding zero (23:00–0:00), due to an increase in peripheral heat dissipation. However, there were no significant differences in sleep-onset latencies among the four groups. Reports have shown that SCSs helps to maintain the body temperature; therefore, the DPG of SCS was suppressed from 5:00 to 6:00[23, 44].

Kraüchi et al.[21, 22] reported that DPG decreased due to increased heat dissipation and a decline in the core body temperature, and simultaneously, sleep was facilitated. However, sleep latency did not reach a significant level (Table 3). For TST, stage 1–2 sleep, stage 3–4 sleep, REM sleep, WASO, and sleep efficiency, no differences were found between the four groups (Table 3). We found that there was no differences in TST, stages 1–4, REM sleep, WASO, and sleep efficiency, indicating that the participants were healthy male participants without sleep problems.

Delta waves are high amplitude brain waves with an oscillation frequency between 1–4 Hz, are associated with the deep stage 3–4 of non-REM sleep, also known as SWS, and aid in characterizing the depth of sleep[54]. Delta power is a summation of the amplitude and duration of delta waves and reflects the number of delta waves and SWS[31]. The delta power of the first sleep cycle is known to be highest during nocturnal night sleep[55, 56]. The amount of delta power per minute in the first sleep cycle significantly increased in the bathing group, and the highest power was observed in the ACS group. This result indicates that bathing participants had deeper sleep in the first sleep cycle. Bathing groups exhibited increased heat dissipation and a decline in core body temperatures. As a result, the bathing groups would have deeper NREM sleep during the first sleep cycle than the NB group. Although different from full body bathing, Ichiba et al. recently reported an increase in delta power after periocular skin warming during the first sleep period of 30 min, showing a facilitation in better sleep via thermoregulation[53].

In the current study, we found that the major factors that change the sleep profile by bathing are temperature changes characterized by an increase in core body temperature associated with a decline in DPG, followed by large reductions in core body temperature at bedtime. Larger effects on temperature were observed with SCS and ACS compared to PHB. This may suggest that the mineral composition (i.e., sodium chloride) of SCS and CO_2 of ACS facilitate heat absorption and subsequent heat dissipation, as previously reported[25, 26, 44, 58].

Due to the increase and subsequent decrease of core body temperature, we deemed that the timing of bathing before sleep is important; we observed that it took about 90 min for the core body temperature to return to baseline after 15 min of bathing, and the core body temperature then declined to below the baseline (Fig. 3). According to Tai et al., bathing and showering at 40–42.5 °C reduced sleep latency by 10 min 1–2 hours before bedtime, improving self-assessed sleep quality and efficiency[59, 60]. These were considered to be consistent with the DPG achieved by increased peripheral hemoperfusion and the time of core body temperature decline due to body temperature dissipation. Our research results also generally support this timing and the hot water temperature. Therefore, 90 min before going to bed was the optimal time to facilitate sleep under the current experimental conditions.

Many factors, such as rejuvenation from cleansing of the body and mild fatigue caused by bathing, may benefit subsequent sleep. Among the subjective parameters, SCS caused fatigue after bathing, and significant differences were found in the interactions between the four groups ($p < 0.05$). Interestingly, ACS induced similar temperature changes to SCS, and both equally altered some sleep profile features; however, ACS did not cause fatigue after bathing. Although there is a possibility for the difference in fatigue for SCS to be due to different chemical compositions, we believe that the other factors were similar to other bathing conditions. Therefore, ACS would be more appropriate than SCS for the elderly or susceptible individuals. ACS is often used in rehabilitation practices because it suppresses tension and blood pressure, with parasympathetic dominance[40, 57].

The sample size of this pilot study was small, involving eight male participants (effect size: 0.45–1.2). This limitation is partially due to the main purpose of the study, which was to compare the effects of various bath components on body temperature and sleep. The participants and researchers were not completely blinded to the bath conditions, and the results were not explained to the participants. As we were unable to identify previous research on a similar topic, we were unable to calculate the statistical power before initiating the study. However, we confirmed that we had sufficient power and effect size for the analysis and therefore, we believe that the results are useful based on our analysis. We examined acute bathing effects but not chronic effects. We used a portable single-channel EEG device because of the experimental settings. Further blinded studies are required to include female participants, the elderly, and patients with insomnia (i.e., masking the participants and experimenters), with long-term observations of SCS and ACS bathing.

ACS and SCS increased heat dissipation and decreased core body temperature. They facilitated sleep better than NB, as previously reported, but did not promote sleep better than PHB. Bathing timing is important in terms of thermoregulatory physiology before and after bedtime. Since ACS does not cause fatigue, it would be more suitable than SCS. Bathing helped improve sleep profile features, which suggests that bathing provides a healthy alternative to medications for those who require better sleep.

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