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Infrared sauna as exercise-mimetic? Physiological responses to infrared sauna vs exercise in healthy women: A randomized controlled crossover trial

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ABSTRACT

Background: Passive heat therapies have been reported to have similar effects on the cardiovascular system as exercise. Studies supporting these findings in healthy populations have predominantly been done with men using warm water immersions or traditional saunas, rather than newer infrared-based saunas.
Objective: To explore short-term thermal and cardiovascular responses in women using an infrared sauna as compared to moderate-intensity exercise.
Study design: Randomized controlled crossover trial with balanced allocations.
Setting: Brisbane, Australia (August 2019 - March 2020)
Participants: Ten healthy women (36 ± 9 years)
Interventions: 45 min of resting, infrared sauna or indoor bicycling
Primary outcome measures: tympanic/skin temperatures; respiratory rate; blood pressure; arterial stiffness; heart rate variability
Results: Tympanic temperatures were elevated during infrared sauna as compared to both control (mean diff = +1.05 °C ± SEM 0.12 °C, 95% C.I.: 0.73 – 1.36, $p < 0.0005$) and exercise (mean diff = +0.79 °C ± SEM 0.12 °C, 95% C.I.: 0.49 – 1.08, $p < 0.0005$). Respiratory rates were higher during exercise as compared to both control (mean diff = +7.66 ± SEM 1.37, 95% C.I.: 4.09 – 11.23, $p < 0.0005$) and infrared sauna (mean diff = +6.66 ± SEM 1.33, 95% C.I.: 3.20 – 10.11, $p < 0.0005$). No significant differences in non-invasive measures of blood pressure, arterial stiffness or heart rate variability were detected between any of the interventions.
Conclusions: These findings suggest the physiological effects of infrared sauna bathing are underpinned by thermoregulatory-induced responses, more so than exercise-mimetic cardiorespiratory or cardiovascular activations.

1. Introduction

Habitual lifestyle practices involving whole-body heat exposures (saunas, steam rooms, hot springs, etc.) have been used for centuries to promote good health and feelings of wellbeing. Exercise is the lifestyle activity most endorsed by health authorities for preventive health and for its anti-inflammatory, anti-aging and disease-mitigating effects when performed regularly.[1–3] The most established clinical benefits of frequent sauna use, especially low humidity forms such as Finnish and/or infrared-based sauna, involve improvements in cardiovascular disease (CVD) outcomes.[4–6] The habit of Finnish sauna bathing at least 4 times weekly has been associated with reductions in sudden cardiac

Abbreviations: AIx75, augmentation index - adjusted to HR 75 bpm, measure of arterial stiffness; **ANS**, autonomic nervous system; AugPress,, central augmented pressure, measure of arterial stiffness; **CHF**, congestive heart failure; COVID-19,, coronavirus disease of 2019; **CVD**, cardiovascular disease; **HRV**, heart rate variability; LF/HF ratio,, low frequency-to-high frequency ratio, measure of HRV; **IR**, infrared sauna; PWA,, pulse wave analysis; RRMSD,, square root of mean squared differences in successive R wave-to-R wave intervals, measure of HRV; $\mathbf{T_{tymp}}$, tympanic body temperature; USG,, urine specific gravity.

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death by 63% and reduced all-cause mortality by 40% in men.[5] These findings are remarkably similar to the benefits demonstrated in large cohort studies, correlating habitual exercise with a 35% reduction in CVD and a 33% reduction in all-cause mortality.[7] Similar physiological mechanisms proposed to explain these long-term benefits for both activities include improvements in endothelium-dependent vascular dilatation, reduced arterial stiffness, modulations of the autonomic nervous system (ANS), changes in circulating inflammatory markers and lipid profiles, as well as lowering of blood pressure.[6,8–12]

Newer non-invasive measures of arterial stiffness and heart rate variability (HRV) have been gaining reliability as clinical indicators of CVD.[13,14] Arterial stiffness is a biomarker of vascular aging and is claimed to be a more dynamic measure of blood vessel alterations, more so than resting blood pressure (BP).[15,16] Heart rate variability (HRV), analyzed in both time and frequency domains, is interpreted as a cardiac barometer of the ANS.[14,17] Higher HRV is associated with a greater capacity of the cardiovascular system to respond to stressed conditions, both mental and physical.[18,19]

Several studies involving single and/or repeat sessions of thermal therapy have measured arterial stiffness responses of passive water-based heating (water perfusion suits or warm water immersions) as compared to exercise,[20–22] but fewer have focused on dry heat-based (sauna) interventions as compared to exercise.[23,24] HRV parameters have been measured after single and/or repeated sessions of sauna bathing (humid and dry forms), either as a sole intervention or pre/post-exercise, but predominantly in men.[25–35] Evidence in these

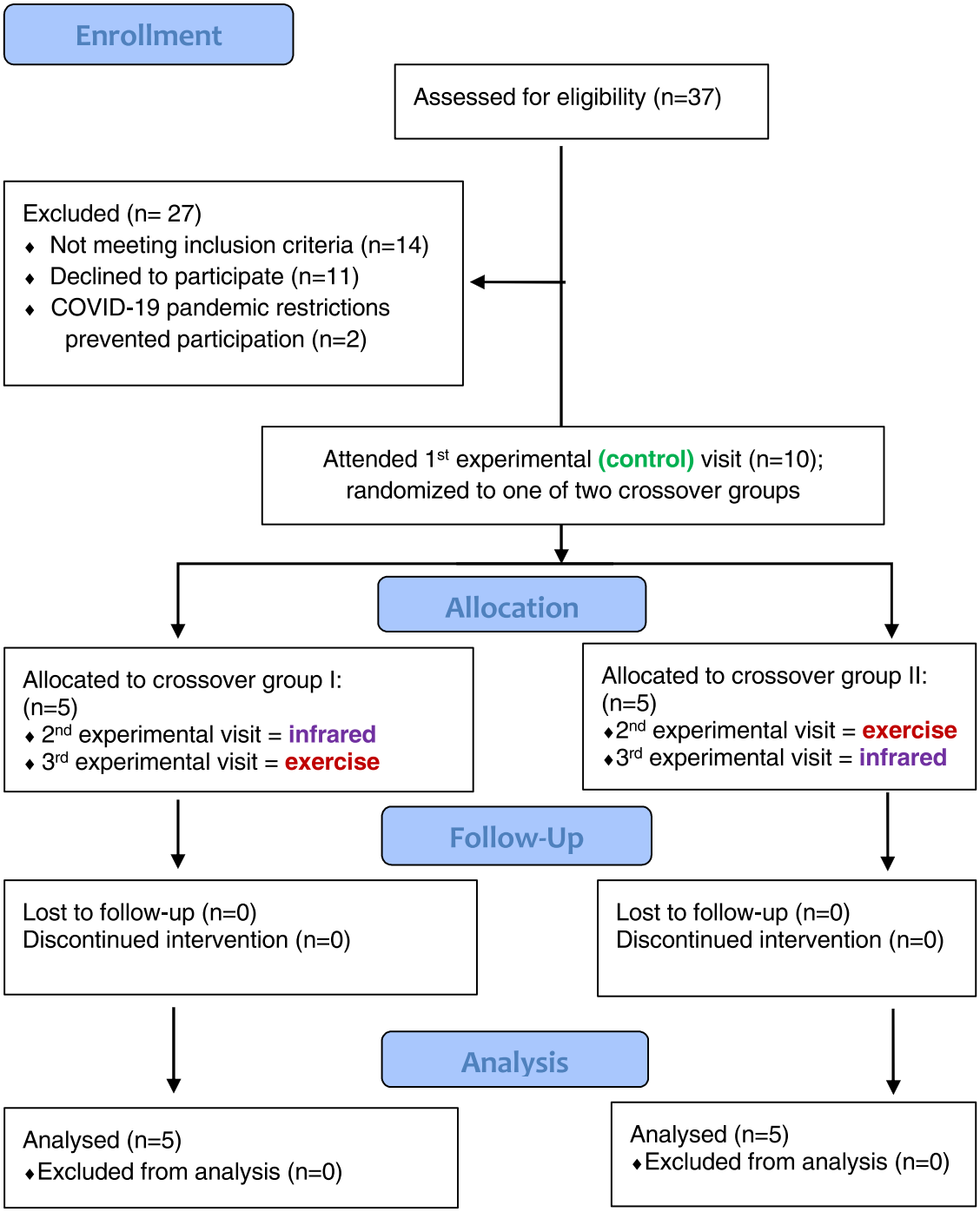

Fig. 1. CONSORT flow diagram.

studies could be improved firstly, by recruiting more female participants; secondly, by using a crossover design; thirdly, by including adequate washout periods; and finally, by incorporating control groups or interventions. These considerations were integrated into this study's design.

To further investigate the physiological effects of increasingly popular infrared sauna bathing,[36,37] inclusive of these newer clinical markers of CVD more thoroughly studied with exercise, a controlled crossover trial in women was conceived. The clinical protocol compared thermal responses, arterial stiffness and heart rate variability within premenopausal women before, during and after interventions of infrared sauna, exercise or controlled resting. It was hypothesized that similar thermal and cardiovascular-related responses would be seen for the sauna and exercise activities, both as compared to control.

2. Methods

2.1. Study design

This was a randomized, controlled crossover trial adhering to the Consolidated Standards of Reporting Trials (CONSORT) 2010 guidelines with extension for randomized crossover trials section, which was added in 2019.[38,39] (Fig. 1) The parameters of the three interventional visits (control, exercise and infrared sauna) were designed to enable comparisons with the duration and intensity of typical sauna bathing sessions.[4,36,40,41] All visits were conducted at least 48 h apart. The first visit for all participants was the control intervention, at which time they were randomly assigned by the same researcher (JH) to the exercise and sauna interventions (random draws.com/au/random-sequence-generator) to ensure balanced allocation of intervention order. Data were collected from August 2019 to March 2020, at the indoor research gym of the Queensland Academy of Sport in Brisbane, Australia. The COVID-19 pandemic restrictions instituted mid-March 2020 in Brisbane prematurely closed the clinical trial.

2.2. Participants, recruitment and inclusion/exclusion criteria

Participants were recruited from the general population using social media and various public advertisement postings. Prospective study participants were screened by the same researcher (JH) via telephone/email. All participants were assessed with pre-specified inclusion criteria to be premenopausal, non-pregnant women, ≥ 18 years old, non-smokers, regular exercisers (non-elite), non-frequent (< 6-monthly) sauna bathers, not diagnosed with any medical disorders, not taking any medications regularly (except hormonal contraceptives), and generally considered healthy, within normal BMI range (BMI < 30.0 and $\geq$18.5 kg/m^2). Anyone with a history of atrial fibrillation and/or Raynaud's syndrome (or phenomenon) were excluded due to contraindications with the pulse wave analysis testing. Baseline demographic and clinical characteristics of participants are presented in Table 1.

2.3. Ethics

All subjects provided written informed consent before participation. Study procedures were conducted in concordance with approval granted by the RMIT University Human Research Ethics Committee (no. 21191). This study was registered with the Australian New Zealand Clinical Trials Registry (ANZCTR no. 12618000679280).

2.4. Interventions

Each participant completed only one of three interventions at each designated visit, with the control intervention being the first visit for all participants. The control intervention involved resting for three 15-minute sessions. The room temperature (temp) was adjusted to participant comfort, at ~ 25 °C, for all the visits. In the exercise intervention, participants engaged in three sessions of moderate intensity aerobic exercise on a standard bicycle ergometer, with 5-min cool-down breaks at room temp between sessions. A finger pulsoximeter was worn during bicycling to help guide participants to maintain pulse rates associated with moderate intensity exercise (55–70% of maximal heart rate, HR_{max}).[42] HR_{max} was calculated for each participant based upon the equation: $HR_{max} = 220 - (\text{age in years})$.[42]

The sauna intervention utilized a full-spectrum infrared cabin (Clearlight Jacuzzi™ Sanctuary 2 Unit, Berkeley, CA, U.S.A.). The sauna was maintained at 60 °C, < 20% RH for the three sessions. The 5-min cool-downs were experienced at room temp.

2.5. Outcome measures

2.5.1. Vital signs and thermal measurements

Body weight was measured using medical-grade scales with ± 0.1 kg accuracy (Salter Kent, U.K.). Height was determined using a stadiometer (QuickMedical, Warwick, RI). Urine specific gravity (USG) was measured by manual reading of Roche™ Combur-10 Roche urinalysis test strips. Tympanic body temperatures (T_{tymp}) were assessed using a diagnostic-grade thermometer (Microlife Ear, Taipei, Taiwan) and skin temperatures were obtained at the forehead, back and both inner forearms using an infrared-based surface thermometer (Microlife Non-Contact, Taipei, Taiwan). Respiratory rate (RR) measurements involved counting the observations of chest movements timed over 1 min. O_2 saturations (O_2 sat) and pulse rates (PR) were measured using a medical pulsoximeter (NONIN 9590 Vantage, Heal Force Bio-Meditech Holdings Ltd, Shenzhen, China).

2.5.2. Blood Pressures and Pulse Wave Analysis (PWA)

Systolic/diastolic blood pressure (SBP/DBP), mean arterial pressure (MAP) as well as PWA-derived variables including central blood pressures and heart rate (HR) were obtained from participants sitting upright, using a brachial cuff-based electronic sphygmomanometer/ laser microprocessor - SphygmoCor XCEL (AtCor Medical Pty,Ltd, Sydney, NSW, Australia), as validated in prior studies.[13,43–45] (Table 2).

Table 1
Baseline demographic and clinical characteristics of participants by crossover sequence group and entire cohort (total).

Characteristic	Crossover Sequence for Experimental Visits						
	Group I: Control visit, followed by IR, then EX (n = 5)			Group II: Control visit, followed by EX, then IR (n = 5)			Total (n = 10)
Age, yrs	39.8 ± 8.7			33.0 ± 9.8			36.4 ± 9.4
Weight, kg	58.6 ± 9.9			53.8 ± 3.0			56.2 ± 7.3
Height, cm	167.1 ± 5.0			163.7 ± 3.7			165.4 ± 4.5
BMI, kg/m^2	21.1 ± 3.7			20.1 ± 1.8			20.6 ± 2.8
	C	**IR**	**Ex**	**C**	**Ex**	**IR**	
Washout time (range - no. of days after preceding interventional visit)	N/A	3–14	7–28	N/A	2–8	2–42	
Menstrual status (range - no. of days after LMP)	2–21	1–15	6–30	2–27	7–25	6–31	

Values are means ± SD. C = control; IR = infrared sauna; EX = exercise; LMP = last menstrual period; N/A = not applicable.

Table 2
SphygmoCor XCEL algorithm-generated PWA parameters with cardiovascular-related definitions/validations.

Parameter	Description	Cardiovascular-related definitions
AIx[a] (%)	Augmentation Index	The ratio of AP (central augmented pressure) to C-PP (central aortic pulse pressure[b]), indicating the combined influences of large artery pulse wave velocity, peripheral pulse wave reflection and inherent vascular function.[48]
AIx75[c] (%)	Augmentation Index, corrected to HR of 75 bpm	Since AIx (augmentation index) varies with heart rate, it is commonly adjusted to a standard heart rate of 75 bpm.[49]
AugPress[a](mmHg)	Central augmented pressure	The difference between two pressure peaks: the initial peak detected as central aortic systolic pressure and then a second peak as aortic central pressure reading increased by the pulse wave reflected back towards the heart from the periphery, which adds to (or 'augments') the central aortic pressure in late systole.[43]

[a] Both AIx and AugPress are validated measures that approximate 'arterial stiffness' for clinical settings.[13,43,44]
[b] Aortic pulse pressure > 50 mmHg has been independently associated with adverse cardiovascular outcomes.[50]
[c] AIx @HR 75 is a widely researched index of PWA, with several studies indicating that AIx is independently predictive of adverse cardiovascular events.[45,50]

2.5.3. Heart rate variability (HRV)

Continuous 10-min measurements of heart rate (ECG-based) and breathing rate (motion-based) were obtained from subjects resting and positioned supine on a massage table, using the Zephyr™ bioharness3 device (Medtronic, Boulder, CO, USA). HRV data was extracted using Zephyr™ software (Medtronic, Boulder, CO, USA), then filtered and analyzed in time and frequency domains with Kubios HRV Premium software (v3.3.1, University of Kuopio, Kuopio, Finland).[46] Table 3 summarizes the key HRV parameters used in this study.

Table 3
Summary of key HRV parameters and associated physiological origins.

HRV Parameter	Description	Associations with ANS Responses
Time-domain		
RRMSD (ms)	Square root of the mean squared differences between successive R wave-to-R wave intervals on ECG[a],[14]	Reflects vagal tone (parasympathetic nervous system activities)[51]
Frequency-domain		
LF power (ms^2)[b]	Signal energy filtered into ECG components of rhythms with oscillations between 0.04 and 0.15 Hz (low frequencies)[14]	Produced by both sympathetic and parasympathetic nervous system influences on primarily baroreflex activities[19,51]
HF power (ms^2)[b]	Signal energy filtered into ECG components of rhythms with oscillations between 0.15 and 0.40 Hz (high frequencies)[14]	Reflects primarily respiratory-mediated vagal influences (parasympathetic nervous system activities)[51,52]
LF/HF ratio	Ratio of LF power to HF power[14]	Estimates the mix of sympathetic and vagal (parasympathetic) activities[51,52]

ms = milliseconds; ECG = electrocardiogram, a recording of graphed voltage versus time electrical activity of the heart using electrodes placed on the skin; Hz = 1/s.
[a] Mean HR, Min HR and Max HR computed by Kubios HRV software using *N* beat moving average or default value of $N = 5$, with minimum 5 min segments[46].
[b] Power is the signal energy found within one frequency band. Fast Fourier transform (FFT) was utilized with our frequency-domain measurements, expressed as ms (milliseconds) squared divided by cycles per second (ms2 /Hz)[51]

2.6. Experimental protocol

For 24 h prior to each visit, participants abstained from using over-the-counter medicines or topical skin preparations. Each participant fasted overnight and remained fasting until the assigned interventional visit was complete. All experimental visits occurred in the mornings and were completed within 3 h.

Each study visit entailed outcome measures taken before (T0), during (T1, T2) and/or after (T3, T4) the interventions, as detailed in Table 4. Room temp and relative humidity (RH) were monitored throughout visits with an indoor hygrometer (ThermoPro, TP-50, Guangdong, China). Participants were encouraged to drink water ad libitum throughout experimental sessions.

For clinical safety and risk mitigation purposes, participants were visually monitored by a registered medical practitioner (JH) throughout all interventions. Additionally, participants were verbally polled with fit-for-purpose questionnaires after each 15-min interventional session and at the end of visits. These questionnaires assessed symptoms associated with dehydration and other commonly reported complications of sauna or exercise in clinical studies.[36,47]

2.7. Sample size

A power analysis for primary variables of interest (body temperatures, heart rate variability and pulse wave analysis), specifying repeated measures, using conventional $\alpha = 0.05$ and $\beta = 0.80$ (G*power software v.3.1.9.4[53]), determined a minimum sample size of 9 participants necessary to detect within-subject changes.

2.8. Statistical analyses

Data were compiled with Microsoft Excel (Office 365, 2019) and statistically analyzed using IBM SPSS Statistics 26.0 (SPSS, Chicago, IL). Datasets were assessed for normality using Kurtosis/Skewness values, Shapiro-Wilk testing and plotted histograms. Variance-covariance matrices were explored using principal components analysis to determine the variables suitable for MANOVA.

Data were expressed as mean with standard deviation (SD) or standard error or means (SEM), or as median with 25th-75th interquartile range (IQR), depending on the distribution of the data. One-way ANOVA/MANOVA repeated measures with the repeated factors of time (within subjects, 2–4 time points) were used to analyze measurements across the interventions. In the event of significant time-by-intervention interactions ($\alpha = 0.05$), *post-hoc* Bonferroni analyses were performed to report multiple pairwise differences.

Table 4
Time points of outcome measures.

Parameters	T0	I	Rest-T1	I	Rest-T2	I	T3	T4
Height & Age	√							
Body weight	√							√
Tympanic/Skin temps	√		√		√		√	
Respiratory rate	√		√		√		√	
Pulsoximetry	√		√		√		√	
Blood pressure	√						√	√
Pulse wave analysis	√						√	√
Heart rate variability	√						√	
Control or Exercise or Infrared sauna		√		√		√		
Time to sweat		√						
Urine samples	√							√

T0 = before intervention; T1 = post 15 min intervention; T2 = post 30 min intervention;T3 = post 45 min intervention; T4 = post 30 min recovery; I = intervention.

3. Results

Of 37 individuals assessed for eligibility, 10 women enrolled and completed the three interventional visits in their allocated order. There were no dropouts in the study. Adjusted indoor environmental settings were mean room temp 25.4 °C ± SD 0.9 °C and mean RH 50% ± SD 10%. The women presented and departed the study visits in states of adequate hydration (USG < 1.025[54]) with pre/post USG median (IQR) of crossover group I = 1.005 (0.005)/ 1.005 (0.005); and of crossover group II = 1.000 (0.000)/ 1.008 (0.008).

3.1. Thermal responses

Tympanic and skin temperatures were measured at T0 (baseline), T1 (15 min), T2 (30 min) and T3 (45 min). The first two participants, both by chance assigned to Crossover Group I, do not have control-T3 data, as this time point was not included in the original protocol. It was added by HREC amendment after these participants completed their 1st visit.

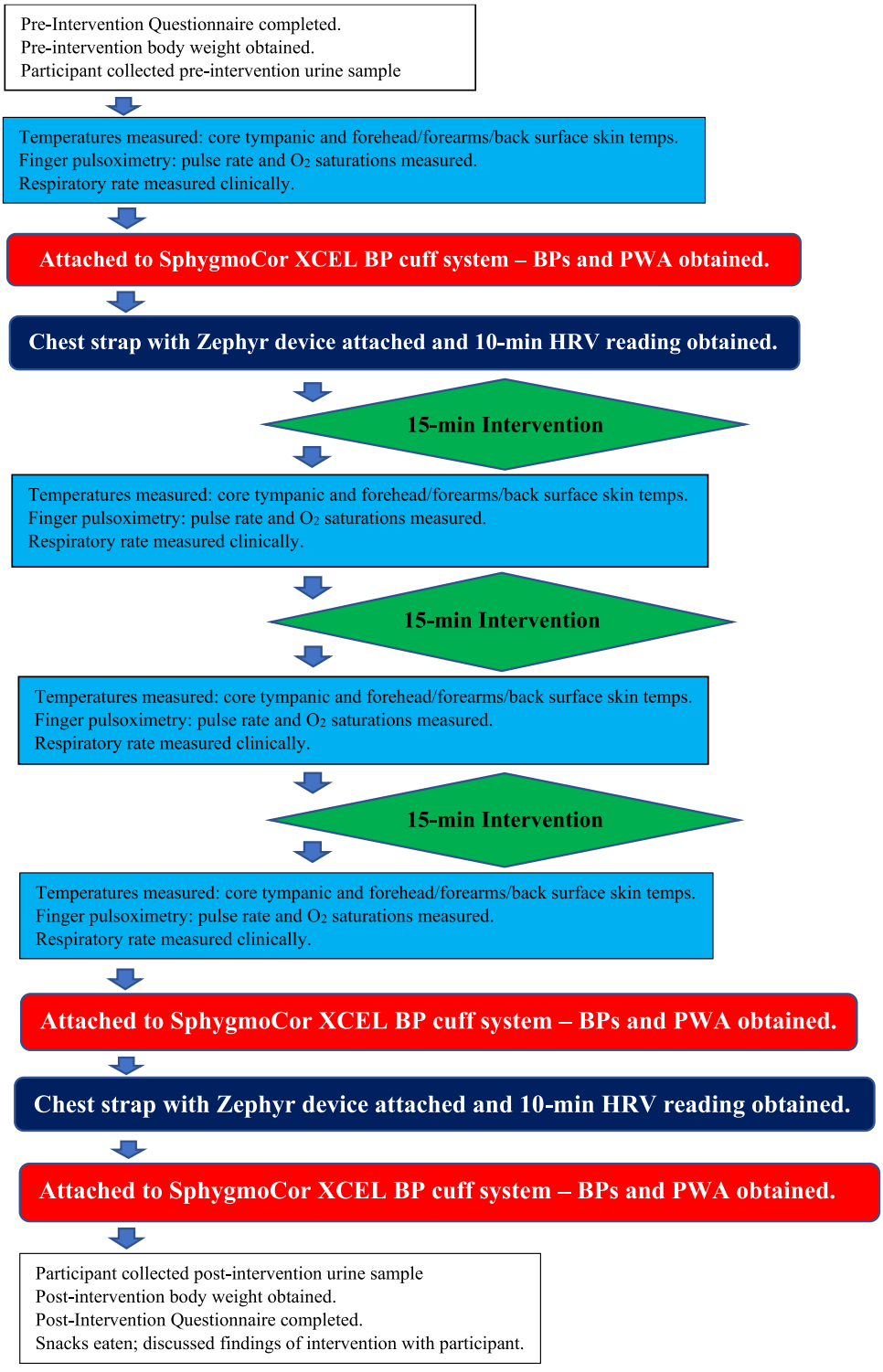

Fig. 2. Experimental protocol flow chart.

(Supplementary Tables 1 and 2).

Significant intervention-based effects with T_{tymp} were detected (Wilks' Lambda = 0.116, F(6,46) = 14.824, p < 0.0005, multivariate η^2 = 0.659). *Post-hoc* analysis revealed increases with sauna as compared to both control (mean diff = +1.05 °C ± SEM 0.12 °C, 95% C.I.: 0.73 – 1.36, p < 0.0005) and exercise (+0.79 ± 0.12 °C, 95% C.I.: 0.49 – 1.08, p < 0.0005), at 15 min, 30 min, 45 min (all p < 0.0005). A similar trend towards increased T_{tymp} with exercise as compared to control was noted but did not reach statistical significance (+0.26 ± 0.12 °C, 95% C.I.: - 0.05 – 0.58, p = 0.127). (Fig. 2).

Analysis of skin temperatures (forehead, wrist, back) measured at the same time points revealed the back temperatures showed the clearest differences across time/interventions (Wilks' Lambda = 0.399, F(6,46) = 4.470, p = 0.001, multivariate partial η^2 = 0.368). *Post-hoc* comparisons indicated both sauna- and exercise-related back temps were *lower* than respective control measures: mean diff ± SEM control/sauna (−0.48 ± 0.12 °C, 95% C.I.: - 0.17 to - 0.79, p = 0.002) at 30 min and 45 min; and greater differences comparing control/exercise (−0.84 ± 0.12 °C, 95% C.I.: - 0.53 to – 1.15, p < 0.001) at all time points. (Fig. 3) *Post-hoc* differences were also detected comparing sauna/exercise (- 0.36 ± 0.11 °C, 95% C.I.: - 0.07 to – 0.66, p = 0.012), with exercise back temps lower than sauna, but only at 15 min

3.2. Respiratory responses – RR and O_2sat

Respiratory rate (RR) and O_2 saturation (O_2 sat) measurements were obtained at time points (T0 – T3) as detailed above, with the same two participants missing control-T3 data. An additional participant is missing sauna-T2 data (Supplementary Table 3) due to equipment difficulties. Significant time-by-intervention differences were found with RR (Wilks' Lambda = 0.381, F(6,44) = 4.541, p = 0.001, multivariate partial η^2 = 0.382) but not with O_2 sat. *Post-hoc* comparisons revealed increased RR at 15 min, 30 min and 45 min with exercise as compared to both control (mean diff = +7.66 ± SEM 1.37 breaths/min, 95% C.I.: 4.09–11.23, p < 0.0005) and sauna (+6.66 ± 1.33 breaths/min, 95% C.I.: 3.2–10.11, p < 0.0005). No differences in RR were detected with sauna/control comparison (+1.01 ± 1.41 breaths/min, 95% C.I.: - 2.65 – 4.66, p = 1.000). (Fig. 4).

3.3. Basic cardiovascular responses: HR, SBP, DBP, MAP

Measurements of HR, SBP/DBP and MAP were obtained at baseline (T0), post intervention (T3), and during recovery (T4). Two participants are missing control-T4 data due to early adjustments made to the clinical protocol (Fig. 5).

Consistent with the study design, HR significantly changed over time-intervention: (Wilks' Lambda = 0.383, F(4,48) = 7.389, p < 0.0005, multivariate partial η^2 = 0.381). *Post-hoc* analysis indicated increased HR with exercise/control comparisons (mean diff = +17.5 bpm ± SEM 4.7 bpm, 95% C.I.: 5.5–29.4, p = 0.003) at post intervention and at recovery, but not with exercise/sauna (−7.9 ± 4.4 bpm, 95% C.I.: – 19.1 – 3.41, p = 0.257), nor with sauna/control (+9.6 ± 4.7 bpm, 95% C.I.: −2.4 to 21.6, p = 0.151).

Of the blood pressures, only systolic blood pressure (SBP) demonstrated a downwards trend over time with both sauna and exercise as compared to control (Wilks' Lambda = 0.635, F(4,48) = 3.060, p = 0.025, multivariate partial η^2 = 0.203). However, these trends were not demonstrated with *post-hoc* analysis at any of the three timepoints. (Supplementary Fig. 1).

3.4. Pulse wave analysis (PWA) responses

Both indices of arterial stiffness derived from the SphygmoCor XCEL PWA system - Central Augmented Pressure (AugPress) and Augmentation Index (AIx75) - were measured pre/post interventions (T0, T3) and during recovery (T4). Two participants are missing control-T4 data due to the early adjustments in the clinical protocol. Trends were detected across time/intervention in the repeated measures of AIx75 (Wilks' Lambda = 0.549, F(4,48) = 4.201, p = 0.005, multivariate partial η^2 = 0.259), however none were demonstrated statistically with *post-hoc* testing (mean diff ± SEM): − 4.5 ± 7.9%mmHg, 95% C.I.: – 24.7 – 15.7, p = 1.000 (exercise/control); − 6.7 ± 7.9%mmHg, 95% C.I.: – 26.9 – 13.6, p = 1.000 (sauna/control), and + 2.2 ± 7.4%mmHg, 95% C.I.: – 16.9 – 21.2, p = 1.000 (exercise/sauna). (Supplementary Fig. 2) Inspection of estimated marginal means plots (not shown) suggested higher arterial stiffness trended with exercise and sauna (both compared to control) at post intervention (T3) but resolved by recovery (T4). No differences were detected with repeated measures of AugPress: Wilks' Lambda = 0.728, F(4,48) = 2.068, p = 0.100, multivariate partial η^2 = 0.147). (Supplementary Fig. 2).

3.5. HRV responses

Two key indices of HRV, namely RRMSD and LF/HF ratio, were calculated pre (T0) and post (T3) intervention. Missing data included the control-T3-RRMSD value for participant 8 and the control- and sauna-T0-LF/HF values for participant 2 due to inadequate capture of data from the Zephyr™ device and/or difficulties transforming the data with the external software package. No differences in pre/post HRV responses between control, sauna and/or exercise were demonstrated (MANOVA - Wilks' Lambda = 0.793, F(4,22) = 0.678, p = 0.615, multivariate partial η^2 = 0.110). (Supplementary Fig. 3).

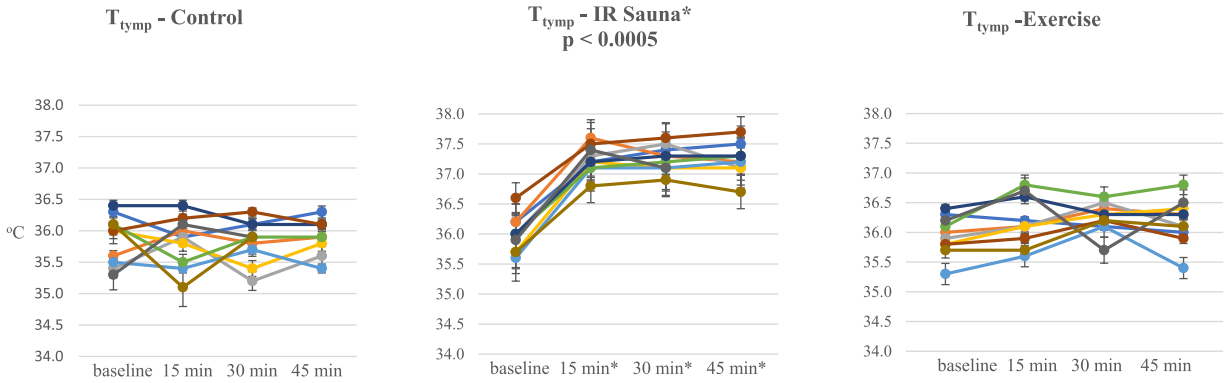

Fig. 3. Tympanic temperature measurements (°C). Measurements in subjects (n = 10) taken over time with control, infrared sauna and exercise interventions, color-coded by individual. Color-participant designations in Trellis graphs are maintained across all the figures. *Mean diff ± SEM were significant between **infrared sauna and control** = +1.05 °C ± 0.12 °C, 95% C.I.: 0.73 – 1.36, p < 0.0005) and between **infrared sauna and exercise** = +0.79 °C ± 0.12 °C, 95% C.I.: 0.49 – 1.08, p < 0.0005), at time points 15 min, 30 min, 45 min, but not between exercise and control.

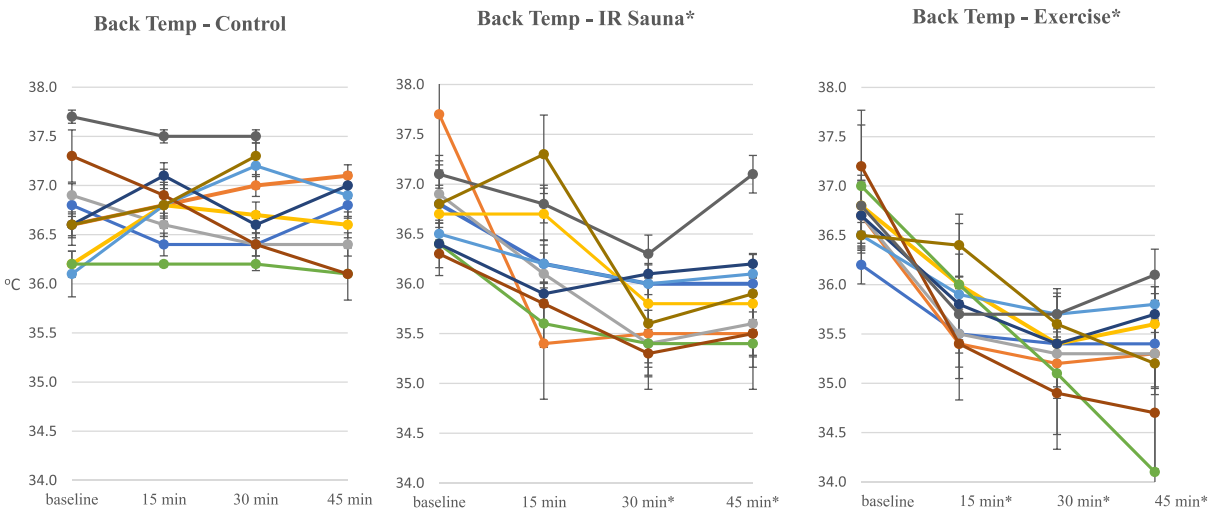

Fig. 4. Skin temperature measurements at the back (°C). Measurements taken at the back in subjects (n = 10) over time with control, infrared sauna and exercise interventions, color-coded by individual. * Mean differences ± SEM were significant between **exercise and control** (−0.84 °C ± 0.12 °C, 95% C.I.: - 0.53 to – 1.15, $p < 0.001$) and between **sauna and control** (−0.48 °C ± 0.12 °C, 95% C.I.: - 0.17 to - 0.79, $p = 0.002$) at indicated time points, as shown by an asterisk on the axis label. *Post-hoc* differences between **sauna and exercise** (- 0.36 °C ± 0.11 °C, 95% C.I.: - 0.07 to – 0.66, $p = 0.012$) were detected, but only at the 15-min time point.

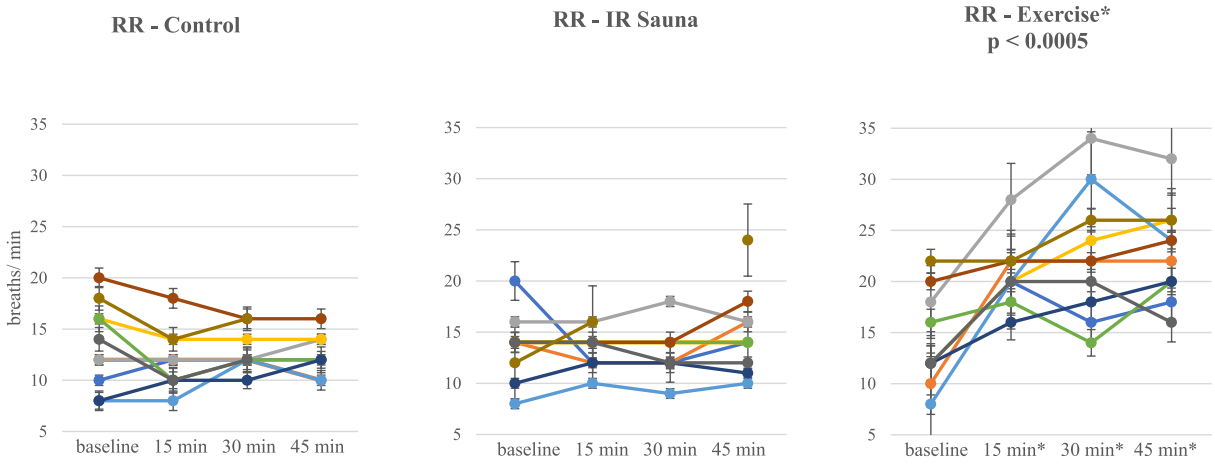

Fig. 5. Respiratory rate (RR) in breaths/min. Measurements taken in subjects (n = 10) over time points with control, infrared sauna and exercise interventions, color-coded by individual *Mean differences in RR were significant across time between **exercise and control** interventions (mean diff = +7.66 breaths/min ± SEM 1.37 breaths/min, 95% C.I.: 4.09 – 11.23, $p < 0.0005$) and between **exercise and infrared sauna** (+6.66 breaths/min ± 1.33 breaths/min, 95% C.I.: 3.20 – 10.11, $p < 0.0005$) at specified time points* .

3.6. Adverse events

Three participants experienced adverse events during the study sessions, none of whom required medical intervention. One participant experienced a brief episode of nausea and dizziness immediately following the exercise intervention. Another participant complained of bicycle seat irritation during the first 15 min of the exercise intervention, but this resolved promptly with adjustment of the bicycle seat. The third participant experienced mild dizziness after completing the infrared sauna intervention. At follow up, she reported developing a migraine headache later that same day, which resolved with rest and without the use of any medications.

4. Discussion

We report physiological findings whereby ten healthy women underwent sessions of infrared sauna (IR) as compared to moderate-intensity exercise and control resting sessions, utilizing a crossover design. Significantly higher T_{tymp} responses during and immediately after IR were experienced by the women, as compared to exercise and control. These women also responded with higher RR during and immediately after exercise as compared to IR and control. Contrary to our expectations, no significant differences in the measures of blood pressures, arterial stiffness or HRV were demonstrated.

The rise in T_{tymp} with IR vs control (+1.05 ± 0.12 °C, $p < 0.0005$) was expected. Other studies have demonstrated similarly elevated core body temperatures in both men and women with other forms of passive heating such as Finnish/traditional saunas (15–30 min exposures at 73–100 °C, 5–40% RH)[27,55–58] or warm water immersions (1-h exposures at 39–40 °C water).[59,60] Only studies involving healthy athletic men and/or participants with medical conditions (CHF, depression, fibromyalgia) have reported such findings with infrared sources of whole-body heat, which generally involve lower ambient temperatures than traditional Finnish saunas.[61–66] Our findings confirm these thermal relationships with infrared sauna use in healthy women, despite our participants being at various stages of their menstrual cycle during data

collections, as recorded in Table 1. This is noteworthy since premenopausal women are understood to have more variable body temperatures, depending upon their menstrual phase.[67–69] This also suggests infrared sauna and traditional Finnish sauna activities may involve similar hormesis-type physiological responses, crossing thermoregulatory thresholds at different points along a theorized U-shaped response pattern.[70]

In measures of surface skin temperatures, we found contrasting results (as compared to tympanic temperatures) of lower skin temperatures at the back (Fig. 4), wrists and forehead, most markedly with exercise. Participants were also noted to sweat more profusely during the sauna vs exercise interventions, and regionally more at the back compared to the forehead and wrists. The functional cooling effects of sweating plausibly explain these findings. These observations are consistent with studies of sweat distribution documented around exercise in both men and women.[71]

The higher sauna-associated T_{tymp} compared to matched levels of exercising ($+ 0.79 \pm 0.12$ °C, $p < 0.0005$) is intriguing. This concurs with findings of a study in male athletes that demonstrated higher core body temperatures with passive heating (infrared whole-body capsules at 65℃ - 80℃) as compared to a matched group engaging in similar timing of exercise (interval training).[62] This may have implications for better understanding sauna bathing's purported pain-relieving and anti-inflammatory effects, similar to exercise.

Recent discussions in the literature suggest the skeletal muscle 'heat' generated with exercise and the resultant thermoregulatory and immune-mediated responses via myokines might be responsible for its anti-inflammatory benefits.[60,72] Exercise-associated mechanisms proposed to support this hypothesis include the upregulation of heat shock proteins (i.e., HSP70, HSP72, HSP 90),[73] altered levels of various interleukins (IL-6, IL-10, IL-1 receptor antagonists)[72,74–76] and improvements in cutaneous microvascular function via increased nitric oxide-dependent vasodilation,[77–80] which have all been demonstrated to occur to the same degree or more with passive heat exposure.[9,81,82] Distinguishing the mechanisms during acute engagement (i.e., our study) versus adaptive responses of habitual exposures of either passive heat and/or exercise, complicates comparisons and requires further study.

The marked rise in participants' breathing rates with exercise compared to control ($+7.66 \pm 1.37$ breaths/min, $p < 0.0005$) was expected; however, absence of this during sauna compared to control ($+1.01 \pm 1.41$ breaths/min, $p = 1.000$) is worth highlighting. Given the rise in T_{tymp} with sauna vs control ($+1.05 \pm 0.12$ °C, $p < 0.0005$), it was expected that evidence of thermal-induced hyperpnea would be observed, as has been previously reported in the literature.[83] This increased respiratory drive with exercise but not sauna hints towards differences in not just thermoregulatory mechanisms but also differential O_2 metabolism perturbations on a cellular (mitochondrial) or more pleotropic level, potentially involving the greater production of damaging reactive oxygenated species (ROS) with exercise.[84–86]

Based on numerous prior studies, beneficial cardiovascular responses such as decreases in SBP/DBP and arterial stiffness were expected to be observed with the sauna and exercise activities.[32,40,55,87–89] Of note, these referenced studies were conducted predominantly with men and often involved CVD risk-afflicted populations.[32,40,55,87,88] Yet the blood pressure and arterial stiffness responses of our female participants were not significantly different across all three interventions, including control. However, we did not measure BPs *during* the interventions (only at baseline, immediately afterwards and post-recovery), unlike a recent study which tracked increases in HR and BP *during* a 25-min session of Finnish-style sauna (93 °C, 13% RH), followed by sustained decreases in BP afterwards.[40]

Several possibilities might explain the absence of BP and arterial stiffness differences in this study. Firstly, the intensities of both the infrared heat exposure and the bicycling may have been too mild to induce the necessary levels of physiological stress required to modulate arterial compliance. Many of the interventional studies reporting passive heat exposures reducing arterial stiffness (measured using multiple techniques which is a confounder) employed the use of traditional saunas, hot water immersions or water-immersion suits, representing higher thermoregulatory loads than infrared saunas.[10,21,23] Secondly, the control activity might have resulted in unintended beneficial modulations of arterial stiffness, similar in degree to the effects of the sauna and exercise. Thirdly, these results might reflect differences in study populations. The infrared sauna-based studies reporting vascular outcomes generally involved non-healthy populations and repeated treatments.[24,90–93] Likewise, the studies demonstrating exercise-induced changes in arterial compliance involved athletes or the opposite spectrum – metabolically challenged populations. This interrelates with findings of other studies suggesting the magnitude of heat-induced or exercise-induced improvements is mediated more by baseline stiffness measures (the higher the baseline arterial stiffness, the better the improvements) as opposed to the intensity level of heat/exercise.[94,95] These findings may also be influenced by gender, as indicated by a recent study demonstrating healthy young men display greater changes in arterial stiffness to aerobic exercise interventions than matched healthy young women.[96]

Similar explanations may apply to our study's unremarkable HRV findings. We found minimal change (in RRMSD) or confoundingly multidirectional changes (in LF/HF ratio) both intra- and inter-individually. (Supplementary Fig. 3) In the literature, episodic bouts of either aerobic exercise or intense heat in healthy individuals (mostly men) have been associated with decreased (↓) parasympathetic and increased (↑) sympathetic responses *during* the performance of these activities, as detected by HRV measurements and ANS-blocking drug studies.[97–99] When combined in a single session, exercise and heat stress can result in even greater vagal withdrawal (↓RRMSD).[100] What happens to HRV *after* these activities (single session or repeated) in the recovery period is more controversial: ↓LF/HF ratio *after* repeated Waon infrared therapy and predominantly in men[101,102]; ↑LF/HF ratio *during and after* Finnish sauna[29,30,33,103]; or ↑LF/HF/ ↓RRMSD *during* a Finnish sauna, followed by ↓LF/HF/ ↑RRMSD in the recovery[25]; or no changes in pre/post LF/HF ratio but ↑RRMSD after a combination sauna (Finnish, steam and warm water immersion).[32]

Results of other studies are difficult to compare to ours due to variations in sauna protocols (types/ temp/ humidity/ exposure times/ timing of outcome measures) and inconsistencies with the use of control groups. It can also be argued HRV may not be an accurate way to measure cardiac ANS responses due to its overly interdependent relationship with HR.[104]

4.1. Strengths and limitations

Despite the small sample size, prematurely limited by COVID-19 pandemic restrictions, the strength of this study was its robust crossover design with participants serving as their own controls in outcome comparisons. This is important since clinically validated 'normal range' values for the specialized outcome measures of arterial stiffness and HRV are still in development.

We acknowledge several study limitations. Conducting the crossover trial over 8 months presents the risk of overlooking seasonal effects, with outdoor temperatures in Brisbane ranging 13–27 °C over the study period. Indoor temperature settings were catered to the individual participant; however, humidity levels were not so easily manipulated (range: 30–75% RH) and could have impacted thermoregulatory responses. The minimum washout period of 48 h was sufficient to avoid crossover effects (by most of our statistical findings) yet the lack of a consistent washout period across all participants introduced potential time period differences. A circadian bias was associated with conducting the experimental procedures in the mornings. Although many people exercise first thing in the morning, fewer are known to typically engage in infrared sauna activities at this time of day.[36] Another limitation was

incorporating so few post-interventional time points for outcome assessment. On hindsight, such omission prevented capturing the full extent (i.e., estimated to be hours) of physiological end-effects resulting from various 'stress'-related gene expressions, as suggested by researchers studying the transcriptomic responses of blood-based mononuclear cells, obtained from healthy volunteers passively exposed to a 15-min Finnish sauna session.[82] Interestingly, the Saudi Arabian participants of this referenced study were reported as perceiving the sauna session as a nocebo intervention. Even though our study was conducted in a warm climate, all participants reported perceiving the sauna as a favorable activity, which may reflect cultural bias and placebo effects. As well, the same researcher collected all the data, which might have unintendingly incorporated bias.

4.2. Future considerations

The infrared sauna exposure of our study reproduced some of the thermoregulatory but not all the hemodynamic or ANS-associated results found with other passive heat studies. This highlights the need for a more nuanced approach to evaluating clinical studies of passive heat, by not assuming all forms of thermal heat therapy will have equivalent cardiovascular or metabolic effects, especially regarding women.[57,105] Measuring metabolic and enzymatic parameters along with sweating rate and other systemic physiological measurements in clinical studies will also guide further understanding of mechanistic differences. Clarifying such distinctions in the future will help to determine which passive heat activities are most beneficial for specific health-related outcomes, especially CVD-related outcomes.

4.3. Conclusions

The results of this study suggest the health effects of infrared sauna are driven by thermoregulatory adaptations, more so than exercise-mimetic hemodynamic, respiratory, or cardiac ANS responses.

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Author contributions

JH, MC and RG conceived and designed the study; JH recruited participants and collected/analyzed the data; JH, CJO, NM. and RG interpreted results of the experiments; JH drafted the original manuscript and prepared the tables/ figures; JH, MC, CJO, and RG edited and revised the manuscript.

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Conflict of interest

There is no conflict of interest with any of the authors.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ctim.2021.102798.

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