Sympathetic nerve activity and whole-body heat stress in humans

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Running Title: Hyperthermia and sympathoexcitation

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Abstract

We and others have shown that moderate passive whole-body heating (i.e., increased internal temperature ~0.7 °C) increases muscle (MSNA) and skin sympathetic nerve activity (SSNA). It is unknown, however, if MSNA and/or SSNA continue to increase with more severe passive whole-body heating or whether these responses plateau following moderate heating. The aim of this investigation was to test the hypothesis that MSNA and SSNA continue to increase from a moderate to a more severe heat stress.

Thirteen subjects, dressed in a water-perfused suit, underwent at least one passive heat stress that increased internal temperature ~1.3 °C, whilst either MSNA (N=8) or SSNA (N=8) was continuously recorded. Heat stress significantly increased mean skin temperature (Δ~5°C, P<0.001), internal temperature (Δ~1.3°C, P<0.001), mean body temperature (Δ~2.0°C, P<0.001), heart rate (Δ~40 beats•min⁻¹, P<0.001) and cutaneous vascular conductance (Δ~1.1 au•mmHg⁻¹, P<0.001). Mean arterial blood pressure was well maintained (P=0.52). Relative to baseline, MSNA increased midway through heat stress (Δ core temperature 0.63 ± 0.01°C) when expressed as burst frequency (26 ± 14 to 45 ± 16 bursts•min⁻¹, P=0.001), burst incidence (39 ± 13 to 48 ± 14 bursts•100 cardiac cyles⁻¹, P=0.03) or total activity (317 ± 170 to 489 ± 150 units•min⁻¹, P=0.02) and continued to increase until the end of heat stress (burst frequency: 61 ± 15 bursts•min⁻¹, P=0.01; burst incidence: 56 ± 11 bursts•100 cardiac cyles⁻¹, P=0.04; total activity: 648 ± 158 units•min⁻¹, P=0.01) relative to the mid-heating stage. Similarly, SSNA (total activity) increased midway through the heat stress (Normothermia; 1486 ± 472 to mid heat stress 6467 ± 5256 units•min⁻¹, P=0.03) and continued to increase until the end of heat stress (11,217 ± 6684 units•min⁻¹, P=0.002 vs mid-heat stress). These results indicate
that both MSNA and SSNA continue to increase as internal temperature is elevated above
previously reported values.
Introduction

Heat stress elicits a range of highly coordinated autonomic nervous system responses in order to maintain both internal temperature and blood pressure within safe limits (32). Heat stress-induced elevations in internal and skin temperatures profoundly increase skin blood flow and sweat rate, which are necessary for heat dissipation (18, 40). At the same time, elevations in cardiac output and vascular resistance of non-cutaneous beds ensure the maintenance of arterial blood pressure (34, 36). Appropriate adjustments of the autonomic nervous system are critical in mediating these cardiovascular and thermoregulatory responses to heat stress. Given that these neural responses are primarily governed by increases in sympathetic nervous system activity, heat stress has been referred to as a ‘hyperadrenergic’ state (33).

Whole-body heating causes pronounced increases in skin sympathetic nerve activity (SSNA), which is the neural signal responsible for increasing sudomotor and perhaps cutaneous active vasodilator activity during this exposure (16, 30). Similarly, heat stress elevates sympathetic nerve activity to muscle, i.e., muscle sympathetic nerve activity (MSNA). We and others have previously shown that moderate passive whole-body heating in humans (i.e., increased internal temperature ~0.7 °C) increases MSNA and SSNA (1, 6-8, 29, 46). We are unaware of any studies in which MSNA or SSNA responses to more severe heat stress were evaluated. It is unknown, therefore, if MSNA and/or SSNA continue to increase with further increases in internal temperature, when even greater demands are placed on the thermoregulatory and cardiovascular systems, or whether these responses plateau following moderate increases in internal temperature.
Progressive increases in renal, lumbar and splanchnic sympathetic nerve activity during passive heat stress in rats have been recorded over the course of 3 °C elevations in core temperature (20, 21, 23). Based upon these observations, it may be that in humans SSNA and MSNA would continue to rise beyond previously reported elevations in core temperature of ~0.7 °C. Similarly, sympathoexcitation to non heat-stress interventions, such as hypoxia and exercise, increase in proportion to graded levels of that intervention (37, 39), further supporting the hypothesis of a continued increase in sympathetic nerve activity with increasing severity of a sympathoexcitatory stimulus, as may be the case with passive heating.

Changes in skin blood flow and sweat rate are closely coupled to alterations in internal temperature (18, 40). The skin blood flow/sweat rate to internal temperature relationship is generally not linear throughout heat stress, as the slope of these relationships is often reduced or tends to plateau with further elevations in internal temperature greater than ~0.7 °C (17, 40). It is thus possible that SSNA plateaus, or continues to increase, albeit at a reduced rate, beyond relatively minor elevations in internal temperature. In addition, total peripheral resistance and blood flows to renal and splanchnic vascular beds tend decrease at a lower rate as internal temperature further increases beyond moderate levels of passive heating (28, 35). If MSNA is reflective of sympathetic activity to these regions, these findings suggest that relatively minor increases in MSNA would occur beyond moderate levels of passive heating. To address these questions, the aim of this investigation was to test the hypothesis that during passive heating MSNA and SSNA
continue to increase while individuals progress from a moderate to a more severe level of heat stress.
Methodology

Subjects

A total of 13 healthy subjects (8 males, 5 females; mean ± SD; age 35 ± 9 yrs, height 175 ± 10 cm and weight 78 ± 10 kg) underwent 1 or 2 passive heat stresses during which successful MSNA (N=8; 5 males) or SSNA (N=8; 4 males) recordings were obtained throughout the heat stress. Three subjects participated in both MSNA and SSNA trials, but on different days. MSNA and SSNA recordings from male and female subjects were not separately analyzed given the low numbers in each group and sex differences not being the primary objective of the evaluation. Subjects were free from cardiovascular, neurological or metabolic diseases. Subjects were asked to refrain from alcohol and exercise 24 h and caffeine 12 h before the study. Written, informed consent was obtained from all participants before they enrolled in the study. All procedures and the consent form were approved by the University of Texas Southwestern Medical Center at Dallas and Texas Health Presbyterian Hospital Dallas.

Instrumentation and Measurements

Each subject was placed in a tube-lined suit (Med-Eng, Ottawa, Canada) that permitted the control of skin temperature by changing the temperature of the water perfusing the suit. The suit covered the entire body surface with the exception of the head, one forearm, the hands, the lower leg from which sympathetic recordings were obtained, and the feet. Mean skin temperature was measured via the electrical integration of six thermocouples attached to the skin on the lateral gastrocnemius, anterior quadriceps, lower and upper back, abdomen and upper chest regions (42). Core temperature was measured from an
ingestible telemetry pill (HTI Technologies, Palmetto, FL) that was swallowed at least 2 h before data collection began. Heart rate was obtained from an electrocardiogram (SpaceLabs, Redmond, WA) interfaced with a cardiotachometer (CWE, Ardmore, PA). Intermittent arterial blood pressure was measured from the brachial artery by electrosphygmanometry (SunTech, Raleigh, NC). Cutaneous blood flow was indexed using a multifiber laser-Doppler probe (Perimed, North Royalton, OH) placed on a dorsal forearm not covered by the suit.

Multifiber recordings of MSNA and SSNA were obtained using a tungsten microelectrode positioned in the common peroneal nerve. A reference electrode was placed subcutaneously ~2–3 cm from the recording electrode. The position of the recording electrode was adjusted until a site was attained in which bursts of MSNA or SSNA were identified using previously established criteria (13, 43). The main criteria for the identification and differentiation of MSNA relative to SSNA recordings were 1) synchronicity of discharges with pulse rate, 2) increases in (or lack of) activity during inspiratory apnea, and 3) responsiveness to mental or somatosensory stimulation (e.g., loud sound and light stroking of the innervated region). Needle adjustments were made for recordings that contained evidence of both MSNA and SSNA, until just MSNA or just SSNA recordings were evident. Nerve signals were amplified, passed through a bandpass filter with a band width of 700–2000 Hz and integrated with a time constant of 0.1 s (Iowa Bioengineering, Iowa City, IA, USA). Mean voltage neurograms were displayed on a chart recorder. Nerve signals were also routed to an oscilloscope and a loudspeaker for monitoring throughout the study. If evidence of a position change in the
recording electrode was identified, which occurred in a few subjects, the protocol was immediately ended and these data were not analyzed. Subjects in whom this occurred are not included in the aforementioned subject numbers.

Experimental Protocols

Experiments were performed in a temperature controlled laboratory (26 ± 1 °C) in the morning or early afternoon at least 2 h postprandial. After instrumentation, subjects rested in the supine position while 34 °C water was perfused through the tube-lined suit for ~15 min. Thereafter, subjects were heat stressed by perfusing 48 °C water through the suit. Subjects were also covered with blankets during this heating protocol. The heat stress ended once subjects had reached the target internal temperature increase (~1.3-1.5 °C). This temperature was chosen given our experience that at temperatures much past this level subjects are often agitated making it difficult to maintain sympathetic nerve recordings.

Data Analysis

Data were sampled at 200 Hz via a data-acquisition system (Biopac System, Santa Barbara, CA) and analyzed using a statistical software package (SPSS v17, Chicago, IL). Mean arterial blood pressure (MAP) was calculated as one third pulse pressure + diastolic blood pressure. Cutaneous vascular conductance (CVC) was calculated from the ratio of skin blood flux to MAP. Mean body temperature (Tb) was calculated as (0.9 x Tc) + (0.1 x Ts). MSNA data were evaluated using LabView software (National Instruments, Austin, TX, USA) that identified bursts on a beat-by-beat basis from the integrated
neurogram established by fixed criteria, including an appropriate latency after the R-wave of the ECG and signal-to-noise ratio (7, 10). MSNA was expressed as burst frequency (bursts per min), burst incidence (number of bursts per 100 cardiac cycles) and total activity (identified from burst area of the integrated neurogram). To assess SSNA (expressed as total activity), a period of normothermic baseline in the absence of SSNA bursts was identified. The area of the integrated bursts above this baseline was measured at each stage of the heat stress. This approach was required given that for some subjects during more severe heating sequential SSNA bursts did not consistently return to baseline, and thus the area of individual bursts could not be identified. Segments of the digitized MSNA and SSNA records from normothermia (4-6 min), from the middle level (2-3 min) of heating and the end of the heat stress (2-3 min) were selected for analysis. A shorter duration was used for heat stress periods to avoid substantial increases in $T_c$ over the evaluation period. MSNA data were expressed relative to the increase in $T_c$ whereas the SSNA data were expressed relative to the increases in mean $T_b$ and $T_c$, given the recognized influence of skin temperature on cutaneous vasodilator and sudomotor responses (44, 46). For the MSNA recordings, the middle of heat stress was defined as half of the magnitude of the increase in $T_c$. For SSNA recordings, the middle of the heat stress was defined as half of the magnitude of the increase in both $T_c$ and $T_b$.

Thermoregulatory, MSNA and SSNA responses during normothermia, at the mid-point of the heat stress, and the end of heat stress were statistically compared using a 1-way repeated measures analyses of variance (ANOVA) followed by post-hoc comparisons, where necessary. All values are reported as means ± SD unless otherwise indicated. $P$ values of < 0.05 were considered statistically significant.
Results

Thermoregulatory and cardiovascular responses to heat stress

Thermoregulatory and cardiovascular responses to passive heating, during the periods when SSNA and MSNA were analyzed, are summarized in Tables 1 and 2, respectively. Heat stress significantly increased $T_c$, $T_{sk}$ and $T_b$ at the middle level and at the end of heating. Similarly, heart rate and cutaneous vascular conductance increased at both stages of heating (both $P<0.05$). Mean arterial blood pressure was maintained throughout heating ($P>0.05$).

SSNA responses to heat stress (N=8)

Compared to normothermia, when expressed against mean body temperature, SSNA increased midway through the heat stress ($\Delta T_b$ 1.01 ± 0.10°C; Baseline; 1486 ± 472 to mid heat stress 6467 ± 5256 units•min⁻¹, $P=0.03$, Figure 1A) and continued to increase until the end of heating ($\Delta T_b$ 1.95 ± 0.19°C, 11217 ± 6684 units•min⁻¹, $P=0.01$ vs baseline and $P=0.002$ vs mid-heat stress). Similar responses were identified when changes in SSNA were expressed against the elevation in $T_c$ (Figure 1B). The change in SSNA for the latter half of heating (e.g., moderate to severe heating) was not different from the first half of heating (e.g., normothermia to moderate heating; 4795 ± 4435 vs 5075 ± 2476 units•min⁻¹•°C⁻¹, $P>0.05$).

MSNA responses to heat stress (N=8)

Relative to normothermic conditions, MSNA increased midway through the heat stress ($\Delta T_c$ 0.63 ± 0.05°C, see Figure 2) when expressed as burst frequency (26 ± 14 to 45 ± 16...
bursts•min⁻¹, P=0.001), burst incidence (39 ± 13 to 48 ± 14 bursts•100 cardiac cycles⁻¹, P=0.03) or total activity (317 ± 170 to 489 ± 150 units•min⁻¹, P=0.02). Relative to mid-
heat stress, MSNA was further elevated at the end of heating when expressed as burst
frequency (61 ± 15 bursts•min⁻¹, P=0.01), burst incidence (56 ± 11 bursts•100 cardiac
cycles⁻¹, P=0.04) and total activity (648 ± 158 units•min⁻¹, P=0.01). The change in MSNA
for the latter half of heating (e.g., moderate to severe heating) was not different from the
first half of heating (e.g., normothermia to moderate heating) regardless of the expression
of MSNA, e.g., frequency (30 ± 12 vs 19 ± 21 bursts•min⁻¹•°C⁻¹, P>0.05), incidence (14 ±
15 vs 10 ± 19 bursts•100 cardiac cycles⁻¹•°C⁻¹, P>0.05) or total activity (276 ± 210 vs 202
± 217 units•min⁻¹•°C⁻¹, P>0.05).
Discussion

The aim of this investigation was to test the hypothesis that MSNA and SSNA continue to increase during more severe passive heating relative to that employed in previous studies. MSNA or SSNA were continuously recorded whilst subjects, dressed in a water-perfused suit, underwent whole-body heating that increased internal temperature ~1.3 °C. The main findings of this study are that, relative to the mid-point of heating (e.g., moderate passive heating), MSNA (regardless of whether it was expressed as frequency, incidence or total activity) and SSNA, continued to increase with further heating. These results indicate that MSNA and SSNA do not plateau after an elevation of internal temperature of ~0.7 °C, but continue to increase as internal/mean body temperature increase above these previously reported values. These findings are consistent with progressive elevations in sympathetic nerve activity across a wider range of increases in core temperature during passive heating in the rodent model (20, 21, 23).

Appropriate alterations in sympathetic nerve activity are vital for the effective regulation of internal body temperature. Whole-body heating causes pronounced increases in SSNA, which presumably causes elevations in skin blood flow and sweating to facilitate heat dissipation (16, 18, 30, 40). The neural signal contained within the SSNA signal includes both vasoconstrictor and vasodilator components (43). Transitioning from normothermic conditions to slight heating initially withdraws vasoconstrictor activity, which is evident by reductions in SSNA (1). More pronounced heating increases the sudomotor, and perhaps the vasodilator component, considerably resulting in large increases in SSNA that are well above normothermic baseline. Consistent with these changes, in previous
studies, which increased internal temperature by no more than ~0.7 °C, we and others have shown that this moderate level of passive whole-body heating increases SSNA (1, 6-8, 29, 46). The relationship between skin blood flow/sweat rate and internal temperature is not generally linear during heat stress, as the rate of increase in skin blood flow and sweat rate are often attenuated with further elevations in internal temperature beyond ~0.7 °C (17, 40). It therefore seemed reasonable that SSNA responses may likewise be attenuated during more severe passive heating.

In the present study, more severe passive whole-body heating was utilized to almost double the internal temperature increase previously employed, resulting in further increases in SSNA above the mid-point of heating (i.e., increased internal temperature of ~0.7 °C; Figure 1B). This finding indicates that SSNA continues to increase with more severe whole-body heating relative to that previously reported and likely mediates continued elevations in sweat rate and skin blood flow with increasing internal temperature. SSNA, as well as skin blood flow and sweat rate, are very sensitive to changes in mean skin temperature (44, 46). In the present study, there was a significant increase in mean skin temperature between mid- and final heating stages. To account for these changes in mean skin temperature, SSNA responses were also evaluated against mean body temperature (Figure 1B), which resulted in similar findings relative to that observed when analyzed against intestinal temperature (Figure 1A).

One could speculate that cardiopulmonary baroreceptor unloading coincident with passive heating, which attenuates heat-stress induced elevations in skin blood flow (5),
may alter the elevation in SSNA during both moderate and more severe heat stress. If this were the case, then such unloading would limit the extent to which SSNA increases during heat stress. However, prior findings strongly suggest that baroreceptor unloading with lower body negative pressure or upright tilt does not alter SSNA in heat stressed humans (9, 46). That said, it remains unknown whether preventing the reduction in cardiopulmonary baroreceptor unloading during passive heating would augment SSNA responses to that heat stress.

Others have shown a reduced rate in the decrease in splanchnic and renal blood flows, as well as total peripheral resistance, as passive heat stress progressed from moderate to more severe heating (28, 35). Based upon these observations, it may be that the increase in MSNA upon progressing from moderate to more severe heat stress would likewise be attenuated; recognizing the limitation that MSNA responses are not necessarily representative of the sympathetic response to splanchnic and renal vascular beds. Counter to that hypothesis, MSNA responses continued to increase throughout the heat stress at a rate comparable to the early phase of the heat stress. The specific mechanism(s) responsible for increases in MSNA during heat stress are unclear. MSNA can be modulated by baroreceptor loading status, where baroreceptor unloading increases MSNA and baroreceptor loading reduces MSNA. Previously we showed that during moderate heat stress reductions in central venous pressure, and presumably cardiopulmonary baroreceptor unloading, were not responsible for accompanying increases in MSNA (4). However, in the cited study the elevation in internal temperature was moderate and thus it remains unknown whether cardiopulmonary baroreceptor
unloading contributes to the elevations in MSNA during more severe heat stress. In contrast, sympathetically mediated elevations in splanchnic vascular resistance during whole-body heat stress are not caused by baroreceptor unloading (36), and increases in splanchnic sympathetic nerve activity in hyperthermic rats occur in both baroreceptor-denervated conditions (20). Furthermore, arterial baroreceptor modulation of MSNA remains intact during heat stress (3, 19), suggesting a preserved coupling of arterial baroreceptor control of MSNA.

Heat stress induced elevations in core temperature cause increases in ventilation that may aid in heat loss (45). Sympathetic nerve activity is subject to respiratory modulation through a within-breath pattern as a result of an inhibitory pulmonary stretch reflex (14, 38) and central (medullary) respiratory oscillators, e.g., central respiratory drive (11) suggesting that thermal hyperpnea could contribute to heat-stress induced sympathoexcitation. There are, however, a number of factors that do not support this hypothesis. Firstly, the profile of the change in respiratory rate with heating does not match the temporal profile of the MSNA response. The change in ventilation during hyperthermia displays an exponential increase in which the majority of the elevation in ventilation occurs later during heat stress; i.e., after a core temperature increase of ~1 °C (45) and well after large increases in MSNA have occurred (see Figure 2). Secondly, although the within-breath pattern of MSNA is potentiated during hyperpneic conditions (38) and is reflected in a reduction in MSNA during inspiration and an increase in MSNA during expiration, increases in tidal volume produce no or small decreases in steady-state total MSNA (38, 41). Although ventilation was not measured in the present study, it is...
unlikely that relatively subtle changes in ventilation in the progression from moderate to more severe heat is responsible for further increases in MSNA. Finally, interventions that exclusively manipulated central respiratory drive (i.e., those that do not induce chemoreceptor activation) do not change MSNA (14, 38). These data suggest that even if central respiratory drive increased with heating at and above elevations in core temperature of ~1 °C, this response is unlikely to contribute to the elevation in MSNA.

One hypothesis for heat stress-induced elevations in MSNA, and likely SSNA, is a central activation of the sympathetic nervous system. Central regulation of sympathetic outflow occurs primarily within the brainstem (medulla), pons and hypothalamus, which integrate inputs from many different peripheral and central sources and provides major sources of supraspinal sympathoexcitatory outflow to sympathetic pre-ganglionic neurons in the intermediolateral cell column of the spinal cord (12). The role of the central nervous system in mediating sympathetic nerve responses to heat stress is complex. Previous studies in rodents suggest that hypothalamic, brainstem, and spinal cord sites are involved (22-25). In those models sympathoexcitation is not specifically dependent on intact neural connections between the forebrain and brainstem, while brainstem neural circuits play a key role (25), in particular the rostral ventral lateral medulla (24). Nevertheless, the mechanism(s) that might contribute to the heat stress-related sympathetic activation in the human are unclear.

A central mechanism that may contribute to sympathoexcitation associated with heat stress in humans might revolve around changes in body water content. Sweating is a
critical heat loss mechanism during hyperthermic conditions, but it is accompanied with
dehydration (40). Dehydration increases MSNA without alterations in blood pressure,
presumably via activation of the renin-angiotensin system (31), which plays an important
role in blood pressure and body fluid homeostasis. Increases in renin and angiotensin II
occur during whole-body hyperthermia (15, 26), supporting the possibility that factors
associated with dehydration and the renin-angiotensin system could explain heat-stress
induced sympathoexcitation. In support of this hypothesis, blockade of central
angiotensin II mediated neurotransmission attenuates heat-stress induced elevations in
splanchnic sympathetic nerve activity and reductions in renal blood flow in rats (2, 27).
Further research is warranted to investigate this hypothesis.

Limitations
In the present study, heat stress induced an average increase in internal temperature of
~1.3 °C, which was approximately double that of previous studies that have assessed
sympathetic nerve activity responses to this challenge. Despite this extension of previous
investigations, the findings of the present study are only applicable to the temperature
range studied. It is thus unknown if MSNA and SNNA would continue to increase or
plateau beyond the internal temperature studied in the present investigation.

Vasoconstrictor, sudomotor, and perhaps vasodilator components are contained within
the SSNA signal, and it is not possible to separate primary sources of elevations in SSNA
amongst these components. The primary responses observed in the integrative SSNA
recording is likely related to the neural signal that is closest, and has the greatest neural
fiber recruitment, relative to the recording electrode. It is therefore possible that the
magnitude of the elevation in SSNA to the heat stress at a site (i.e., in a given subject) that primarily records from sudomotor fibers may be different from a site whose recording has significant contributions from cutaneous vasoconstrictor fibers. This would result in an increased variability in the elevation in integrative SSNA between subjects during the heat stress. However, every subject increased SSNA from normothermic to moderate heat stress as well as from moderate to severe heat stress as sudomotor and perhaps vasodilator fibers were activated.

In conclusion, relative to a moderate level of passive heating, MSNA and SSNA continue to increase during more profound passive heat stress sufficient to elevate internal temperature ~1.3 °C. These results indicate that MSNA and SSNA do not plateau but continue to increase as internal/mean body temperatures increase above previously reported values. The mechanisms causing heat-stress induced elevations in MSNA and SSNA remain to be determined.
Acknowledgements

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Table 1. Mean (± SD) thermoregulatory and cardiovascular responses to normothermia and heat stress when SSNA was recorded (N=8).

<table>
<thead>
<tr>
<th></th>
<th>Normothermia</th>
<th>Mid Heat Stress (Tb)</th>
<th>Mid Heat Stress (Tc)</th>
<th>End Heat Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Temperature (°C)</td>
<td>37.10 ± 0.18</td>
<td>37.37 ± 0.29*</td>
<td>37.70 ± 0.22*^</td>
<td>38.35 ± 0.30*#</td>
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<tr>
<td>Mean Skin Temperature (°C)</td>
<td>34.6 ± 0.7</td>
<td>38.5 ± 0.5*</td>
<td>38.7 ± 0.6*</td>
<td>39.3 ± 0.5*^</td>
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<tr>
<td>Mean Body Temperature (°C)</td>
<td>36.6 ± 0.2</td>
<td>37.6 ± 0.2*</td>
<td>37.9 ± 0.2*</td>
<td>38.6 ± 0.3*#</td>
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<tr>
<td>Heart Rate (beats•min⁻¹)</td>
<td>55 ± 10</td>
<td>73 ± 14*</td>
<td>80 ± 13*</td>
<td>94 ± 16*#</td>
</tr>
<tr>
<td>Systolic Blood Pressure (mm Hg)</td>
<td>112 ± 14</td>
<td>114 ± 11</td>
<td>115 ± 10</td>
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<td>Diastolic Blood Pressure (mm Hg)</td>
<td>68 ± 6</td>
<td>65 ± 4</td>
<td>65 ± 6</td>
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<td>Mean Arterial Blood Pressure (mm Hg)</td>
<td>82 ± 8</td>
<td>81 ± 5</td>
<td>81 ± 6</td>
<td>84 ±11</td>
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<td>Forearm CVC (au•mm Hg⁻¹)</td>
<td>0.41 ± 0.35</td>
<td>1.05 ± 0.67*</td>
<td>1.19 ± 0.61*</td>
<td>1.51 ± 0.59*^</td>
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</table>

Tb: Mean body temperature; Tc: Mean core temperature; CVC: cutaneous vascular conductance. *P < 0.05 vs Normothermia, #P<0.05 vs mid heat stress (Tb and Tc), ^P<0.05 vs mid heat stress (Tb only).
Table 2. Mean (± SD) thermoregulatory and cardiovascular responses to normothermia and heat stress when MSNA was recorded (N=8).

<table>
<thead>
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<th></th>
<th>Normothermia</th>
<th>Mid Heat Stress</th>
<th>End Heat Stress</th>
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<tbody>
<tr>
<td>Core Temperature (°C)</td>
<td>37.01 ± 0.22</td>
<td>37.64 ± 0.22*</td>
<td>38.37±0.22*#</td>
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<td>Mean Skin Temperature (°C)</td>
<td>34.6 ± 0.6</td>
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<td>Mean Body Temperature (°C)</td>
<td>36.6 ± 0.2</td>
<td>37.9 ± 0.2*</td>
<td>38.6 ± 0.2*#</td>
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<tr>
<td>Heart Rate (beats•min⁻¹)</td>
<td>63 ± 11</td>
<td>92 ± 11*</td>
<td>105±10*#</td>
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<td>Systolic Blood Pressure (mm Hg)</td>
<td>122 ± 16</td>
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<td>130 ± 14</td>
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<td>Diastolic Blood Pressure (mm Hg)</td>
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<td>Forearm CVC (au•mm Hg⁻¹)</td>
<td>0.34 ± 0.40</td>
<td>1.45 ± 0.66*</td>
<td>1.52±0.69*</td>
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</table>

CVC; cutaneous vascular conductance

*P < 0.05 vs Normothermia, #P<0.05 vs mid heat stress.
Figure Legends

Figure 1. Group (±SD) averaged skin sympathetic nerve activity (SSNA) data during normothermia, mid and end of heat stress, expressed as total activity (arbitrary units) against increases in mean body temperature ($T_b$; panel A) or increases in core temperature ($T_c$; panel B). Regardless of how it is expressed, SSNA continues to increase throughout heat stress with no evidence of a plateau following the mid-level of heating. *$P < 0.05$ vs normothermia, #$P < 0.05$ vs mid heat stress (N=8).

Figure 2. Group (±SD) averaged muscle sympathetic nerve activity (MSNA) data, expressed as burst incidence (panel A), bursts per 100 cardiac cycles (panel B) and total activity (panel C), during normothermia (first data point) and at mid (2nd data point) and end (last data point) of heat stress. Regardless of how it is expressed, MSNA continues to increase throughout heat stress with no evidence of a plateau following the mid-level of heating. Delta $T_c$: Increase in core temperature measured from telemetry pill in the intestines. *$P < 0.05$ vs normothermia, #$P < 0.05$ vs mid heat stress (N=8).
References


