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ORIGINAL ARTICLE

Wearing graduated compression stockings augments cutaneous vasodilation in heat-stressed resting humans

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Abstract

Purpose We investigated whether graduated compression induced by stockings enhances cutaneous vasodilation in passively heated resting humans.

Methods Nine habitually active young men were heated at rest using water-perfusable suits, resulting in a 1.0 °C increase in body core temperature. Heating was repeated twice on separate occasions while wearing either (1) stockings that cause graduated compression (pressures of 26.4 ± 5.3, 17.5 ± 4.4, and 6.1 ± 2.0 mmHg at the ankle, calf, and thigh, respectively), or (2) loose-fitting stockings without causing compression (Control). Forearm vascular conductance during heating was evaluated by forearm blood flow (venous occlusion plethysmography) divided by mean arterial pressure to estimate heat-induced cutaneous vasodilation. Body core (esophageal), skin, and mean body temperatures were measured continuously.

Results Compared to the Control, forearm vascular conductance during heating was higher with graduated compression stockings (e.g., 23.2 ± 5.5 vs. 28.6 ± 5.8 units at 45 min into heating, $P = 0.001$). In line with this, graduated compression stockings resulted in a greater sensitivity (27.5 ± 8.3 vs. 34.0 ± 9.4 units $°C^{-1}$, $P = 0.02$) and peak level (25.5 ± 5.8 vs. 29.7 ± 5.8 units, $P = 0.004$) of cutaneous vasodilation as evaluated from the relationship between forearm vascular conductance with mean body temperature. In contrast, the mean body temperature threshold for increases in forearm vascular conductance did not differ between the Control and graduated compression stockings (36.5 ± 0.1 vs. 36.5 ± 0.2 °C, $P = 0.85$).

Conclusions Our results show that graduated compression associated with the use of stockings augments cutaneous vasodilation by modulating sensitivity and peak level of cutaneous vasodilation in relation to mean body temperature. However, the effect of these changes on whole-body heat loss remains unclear.

Keywords Central blood volume · Thermoregulation · Heat stroke · Baroreceptors · Compression garments

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Introduction

Appling pressure to the lower extremities has been shown to increase venous return and/or reduce venous pooling, modulating cardiovascular responses in particular in the upright posture (Nishiyasu et al. 2007, 1998). In real-life conditions, a similar effect can be achieved by wearing graduated compression stockings that are widely used in the treatment or prevention of chronic venous disease such as venous thrombosis and varicose veins. More recently, these stockings are gaining popularity in various sporting events for the purposes of improving exercise performance and/or recovery processes after exercise (Ali et al. 2007; Bovenschen et al. 2013; Goh et al. 2011; Priego et al. 2015). As a consequence, graduated compression stockings are commonly used under conditions eliciting elevated body temperatures (e.g., exercise in the heat) (Goh et al. 2011; Houghton et al. 2009). Furthermore, it is well established that the body temperature remains elevated above baseline resting for a prolonged period (60–90 min) following cessation of exercise; a response attributed to postexercise reduction in mean arterial pressure (Kenny and Jay 2013). To date, although some studies evaluated the influence of graduated compression stockings on body temperatures (Barwood et al. 2013; Duffield et al. 2008; Goh et al. 2011; Houghton et al. 2009; MacRae et al. 2012; Noonan and Stachenfeld 2012), to the best of our knowledge, none have examined their effects on heat loss responses (i.e., cutaneous vasodilation and sweating).

Reports have shown that during heat exposure, enhanced venous return or increased central blood volume augments heat loss response of cutaneous vasodilation (Crandall et al. 1999; Gonzalez-Alonso et al. 1999; Nagashima et al. 1998; Nielsen et al. 1984; Nose et al. 1990; Paull et al. 2016; Schlader et al. 2015) presumably by loading baroreceptors. Although baroreceptors may modulate heat loss response of sweating especially during (Mack et al. 2001) and following (Gagnon et al. 2008) prolonged exercise, recent studies have reported that increase in venous return thereby loading baroreceptors does not augment sweating during heat stress (McGinn et al. 2014; Paull et al. 2016; Schlader et al. 2015). Hence, graduated compression stockings may augment cutaneous vasodilation during heat stress by increasing venous return and central blood volume. In line with this, a recent report demonstrated that wearing graduated compression stockings (below-knee stockings) during postexercise hyperthermia increased skin temperature in areas of the body (i.e., thighs) not directly covered by the garment (Quesada et al. 2015). These findings may indicate an increase in distribution/transfer of warm blood to skin due to greater cutaneous vasodilation induced by the compression stockings. However, it should be noted that changes in skin temperature are not limited to the influences of skin blood flow alone and can be mediated by increases in heat exchange associated with convective, radiative, and evaporative (i.e., evaporation of sweating) heat transfer which may confound our interpretation of these responses. Therefore, direct assessment of skin blood flow is required to conclude if the increased skin temperature was due to augmented cutaneous vasodilation. Therefore, the following study was conducted to examine the effect of graduated compression stockings on cutaneous vasodilation during heat stress at rest. We assessed our hypothesis that stocking-mediated graduated compression augments cutaneous vasodilation occurring under passively heated resting states.

Methods

Ethical approval

The current study was approved by the Human Subjects Committee of the University of Tsukuba in accordance with the Declaration of Helsinki. Written informed consent was obtained from all subjects before their participation.

Subjects

Nine young males volunteered for this study. None of subjects reported having a chronic disease condition, or taking prescription medication, and none were smokers. The subjects' age, height, and body mass, in mean ± standard deviation, were 23.7 ± 2.0 years, 1.72 ± 0.03 m, and 65.7 ± 3.8 kg, respectively.

Pressure measurement session

This session preceded the main session (i.e., heat stress session, see below for details) to evaluate pressures under the graduated compression stockings that were provided by ALCARE Limited (REGUARD CG Tights EX33, ALCARE, Tokyo, Japan). The stockings are a pantyhose type, covering the lower limbs including the feet with the exception of toes and heels which remain exposed. Pressure sensors (AMI3037-10, AMI Techno, Tokyo, Japan) were attached underneath the stockings on the right side of the ankle (upper part of lateral malleolus), calf (head of fibula), and thigh (mid point of vastus lateralis), respectively. As a control, the same pressure measurement was conducted using the same stockings without causing graduated compression (the stockings were cut and loosened). These measurements were done during rest in a room maintained at 30 °C and 50% relative humidity (Fuji Medical Science Co., Ltd, Chiba, Japan) without heat stress. Figure 1 presents the actual recorded pressures.

Heat-stress session

The heat-stress session consisted of two trials in which the subjects were heated while wearing: (1) graduated compression stockings (defined as Graduated compression trial), or (2) no compression stockings (defined as Control trial). Each trial was separated by >5 days and completed in a counter-balanced manner. All subjects were instructed to abstain from taking over-the-counter medications for at least 48 h prior to the experimental

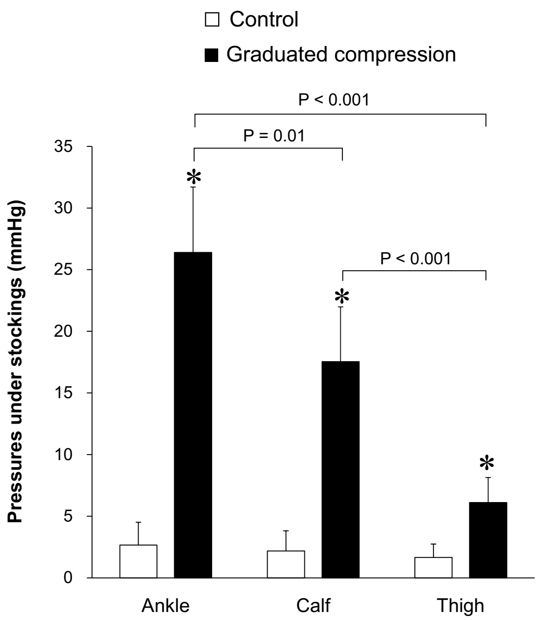

Fig. 1 Pressure measured under stockings. *, vs. Control ($P < 0.001$); data are mean ± standard deviation

session, as well as alcohol and caffeine consumption at least 12 h prior. Subjects also refrained from performing intense exercise the day prior to the study.

Upon arrival to the laboratory at 8:00 am, the subjects voided their bladder; thereafter, body mass was measured using a weight scale platform. Thereafter, they donned either graduated compression stockings or no compression stockings while wearing shorts only, and entered the environmental chamber regulated to 30 °C and relative humidity of 50% (Fuji Medical Science Co., Ltd). They rested in an upright-seated position in the chamber for 60 min during which time they were instrumented. They were then outfitted with water-perfusable suits that covered their upper and lower bodies with the exception of the left upper limb (for the forearm blood flow measurement), hands, head, and feet. The participant's feet were immersed to just below the lateral malleolus (ankle level) in temperate water maintained at 35 °C in a foot bath. The same water temperature in a small water bath was used to perfuse the water-perfusable suit.

After the participant was fully instrumented, a 5 min baseline resting measurement was obtained during which time the water temperature for both the water-perfused suits and foot bath was maintained at 35 °C. This baseline measurement was immediately followed by a heating protocol, wherein the temperature of water for both the water-perfused suits and foot bath was elevated and maintained at 47 and 42 °C, respectively. This heating continued until esophageal temperature had increased by 1.0 °C. The participant's body mass was measured following the completion of the trial.

Measurements

Esophageal and skin temperatures were obtained every 1 s using self-made cooper constantan thermocouples, the information of which was stored in a computer through data logger system (WE7000, Yokogawa, Tokyo, Japan). To obtain esophageal temperature, the temperature probe was inserted via nostril and positioned in the esophagus at a depth equivalent to one quarter of the subject's height. Skin temperature was measured at six sites (chest, abdomen, upper back, lower back, thigh, and calf), and mean skin temperature was evaluated as weighted mean value as follows: 22% chest, 14% abdomen, 21% upper back, 19% lower back, 14% thigh, and 11% calf (Taylor et al. 1984). Mean body temperature was calculated as 0.9 × esophageal temperature + 0.1 × mean skin temperature (Stolwijk and Hardy 1966).

Left forearm blood flow was evaluated every 30 s using venous occlusion plethysmography with the aid of a mercury-silastic strain gauge (Whitney 1953). Increases in forearm blood flow in response to heat stress have been shown to reflect increases in skin blood flow, since forearm muscle blood flow remains unchanged during heating (Detry et al. 1972). The forearm was supported and elevated approximately 0.1 m above the heart level by slings to maintain venous return. Pressure in the venous occlusion cuff was maintained at ~45 mmHg, while the circulation to the hand was restricted using a wrist cuff inflated to 220–230 mmHg. The wrist cuff was released periodically so as not to cause undue physical discomfort to the participant. Forearm blood flow was recorded twice each minute for a minimum of 10–20 s after the upper arm cuff was inflated. To account for the influence of changes in perfusion pressure on blood flow, forearm vascular conductance was evaluated as the forearm blood flow divided by mean arterial pressure (diastolic arterial pressure plus the one-third of the pulse pressure). Arterial blood pressures were measured from the right arm every 1 min via an automated sphygmomanometer (STBP-780; Nippon Colin, Tokyo, Japan). The sensor for measuring blood pressure was attached underneath the water-perfused suit which covered the right arm. Heart rate was recorded every 5 s via a heart rate monitor (HR monitor Vantage NV, POLAR, Kempele, Finland).

Data analyses

All data used for time-dependent data analysis (including Figs. 2, 3) were averaged at each 5 min interval. Forearm vascular conductance, heart rate, and mean arterial pressure were determined at mean body temperatures of

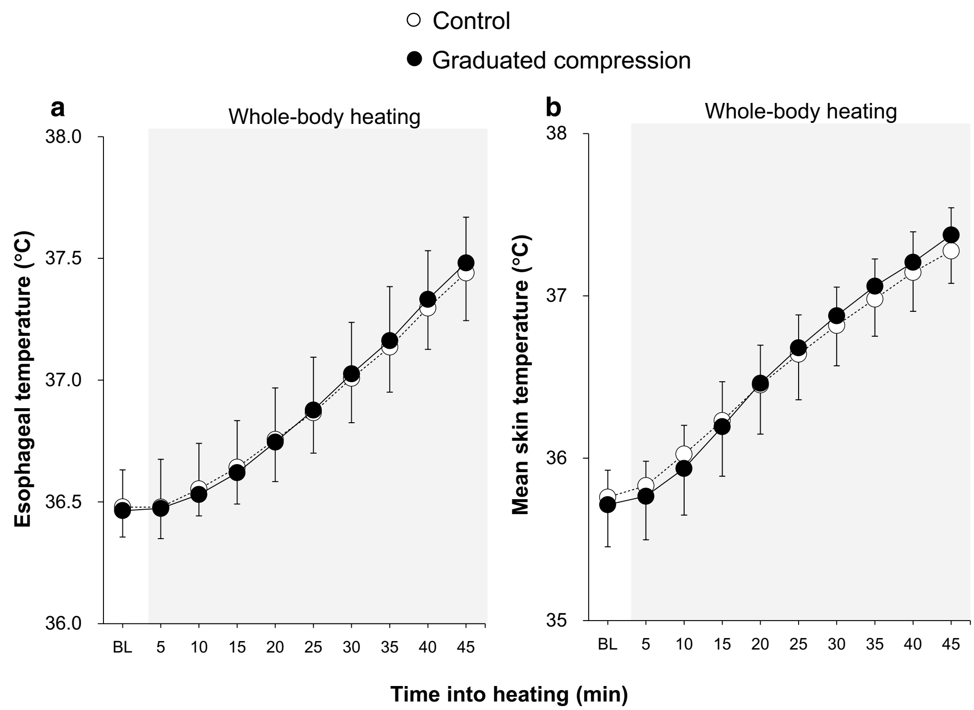

Fig. 2 Time-course changes in esophageal (**a**) and mean skin (**b**) temperatures evaluated during baseline (BL, before heating) and whole-body heating. Values did not differ between trials (all $P > 0.05$). Data are mean ± standard deviation

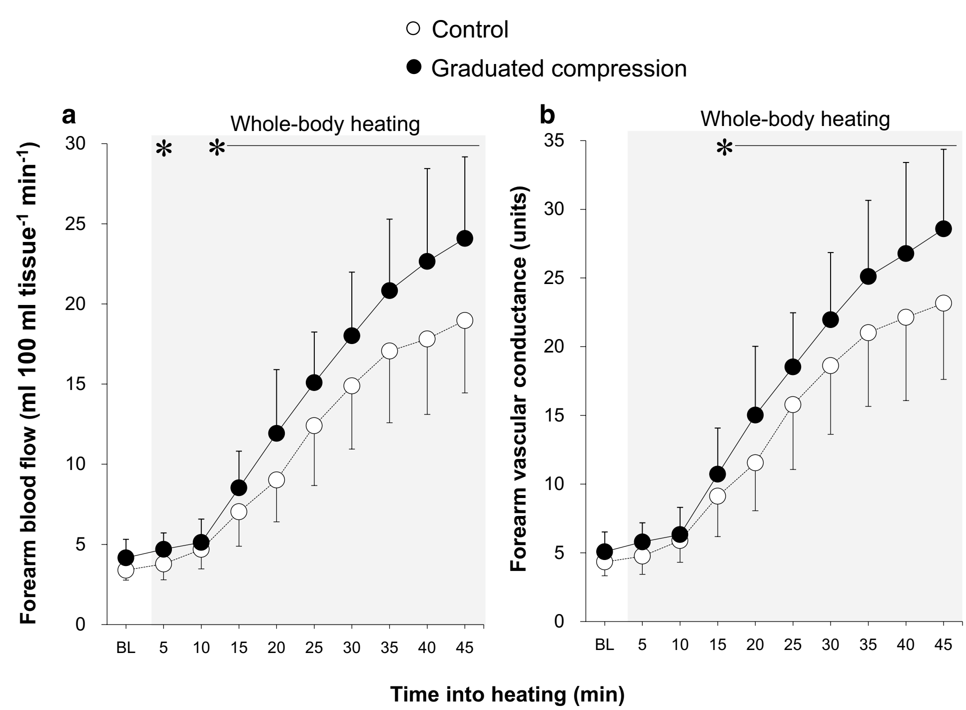

Fig. 3 Time-course changes in forearm blood flow (**a**) and vascular conductance (**b**) evaluated during baseline (BL, before heating) and whole-body heating. *, between trials ($P < 0.05$). Data are mean ± standard deviation. Units for forearm vascular conductance are ml 100 ml tissue^{-1} min^{-1} mm Hg × 100

36.4, 36.7, 36.9, 37.1, 37.3, and 37.5 °C. As described in our previous work (Fujii et al. 2012), the baseline horizontal line and the regression line were derived from the relationship between mean body temperature and forearm vascular conductance using 30 s averaged data. The slope of the regression line was used to determine the sensitivity of cutaneous vasodilation. A threshold for cutaneous vasodilation was evaluated by the mean body temperature at which the onset of cutaneous vasodilation occurred as determined by the point at which the regression line crossed the baseline horizontal line. Peak value of cutaneous vasodilation was assessed by averaging values over the last 5 min of heating.

Statistical analyses

Data are presented as mean ± standard deviation. Pressure values recorded from the stockings were analyzed with a two-way repeated-measures analysis of variance with two factors of trial (Control and Graduated compression) and skin site (ankle, calf, and thigh). Time-dependent data were analyzed using a two-way repeated-measures analysis of variance with two factors of trial (Control and Graduated compression) and time (baseline and every 5 min during heating). For the time-dependent analysis, we used data recorded until 45 min of heating in which all subjects remained. Forearm vascular conductance, heart rate, and mean arterial pressure measured at a given mean body temperature were analyzed by a two-way repeated-measures analysis of variance with factors of trial (Control and Graduated compression) and level of hyperthermia (mean body temperatures of 36.4, 36.7, 36.9, 37.1, 37.3, and 37.5 °C). When a main effect or an interaction was detected, *post-hoc* comparisons were performed using two-tailed paired t tests, with P value adjusted by Holm-Bonferroni's correction. Two-tailed paired t tests were also used to compare variables between trials where applicable. Value of $P<0.05$ was considered statistically significant. Statistical analyses were performed using the software package SPSS 24 (IBM, Armonk, NY, USA).

Results

Pressures under stockings

Compression stockings induced a graduated pressure on the skin from the ankle to the thigh, whereas the stockings under the Control conditions had a negligible effect in terms of the pressure exerted on the respective skin sites (all $P<0.01$ for main effects of trial and skin sites and their interaction, all $P<0.05$ for the posthoc comparisons, Fig. 1).

Physiological responses during heating

Total heating time required to increase esophageal temperature by 1.0 °C did not differ between the Control and Graduated compression trials (52.2 ± 3.6 vs. 51.1 ± 4.9 min, $P=0.51$). In line with this, esophageal temperature increased similarly during heating in both trials (both $P>0.64$ for a main effect of trial and an interaction between trial and time, Fig. 2a). In addition, mean skin temperature in both the Control and Graduated compression trials increased to a similar extent ($P=0.83$ for a main effect of trial, $P<0.01$ for an interaction between trial and time, all $P>0.07$ for the posthoc comparisons, Fig. 2b). Thigh and calf skin temperatures measured under the stockings did not differ between trials (both $P>0.12$ for a main effect and an interaction between trial and time).

The mean body temperature threshold at which an increase in forearm vascular conductance was measured was similar between trials (Fig. 4b). However, forearm blood flow (at 5 and 15–45 min of heating) and forearm vascular conductance (at and after 20 min of heating) were greater in the Graduated compression relative to Control trials (both $P<0.01$ for a main effect of trial and an interaction between trial and time, all $P<0.05$ for the posthoc comparisons, Fig. 3). Similarly, forearm vascular conductance assessed at increasing levels of hyperthermia (i.e., 36.9, 37.1, 37.3, and 37.5 °C of mean body temperature) was greater in the Graduated compression in comparison to the Control trials ($P<0.01$ for a main effect of trial, $P=0.28$ for an interaction between trial and level of hyperthermia, all $P<0.05$ for the posthoc comparisons, Fig. 4a). The increased forearm vascular conductance was paralleled by a concomitant increase in both the sensitivity and peak value measured for cutaneous vasodilation (both $P<0.05$, Fig. 4c, d).

Heart rate and mean arterial pressure plotted against mean body temperature were similar between trials (both $P>0.24$ for a main effect of trial and an interaction between trial and time, Fig. 5).

As compared to the Control trial, a reduction in body weight following heating tended to be greater in the Graduated compression trial (Control: 1.1 ± 0.5 kg; Graduated compression: 1.2 ± 0.4 kg, $P=0.07$).

Discussion

We demonstrated for the first time that graduated compression associated with wearing stockings during a heat stress induced marked increases in cutaneous vasodilation. This was evidenced by our observation that the sensitivity and peak level of the cutaneous vasodilation response were increased in the Graduated compression relative to the Control trials, such that a greater increase in forearm blood flow was observed with a progressive increase in mean body temperature.

Cutaneous vascular response

Lower body positive pressure has been shown to increase venous return and/or reduce venous pooling as demonstrated by increases in stroke volume and cardiac output when upright (Nishiyasu et al. 2007, 1998). Similarly, compression stockings can improve venous return and decrease venous pooling (Liu et al. 2008). Studies showed that graduated compression from 8 to 18 mmHg

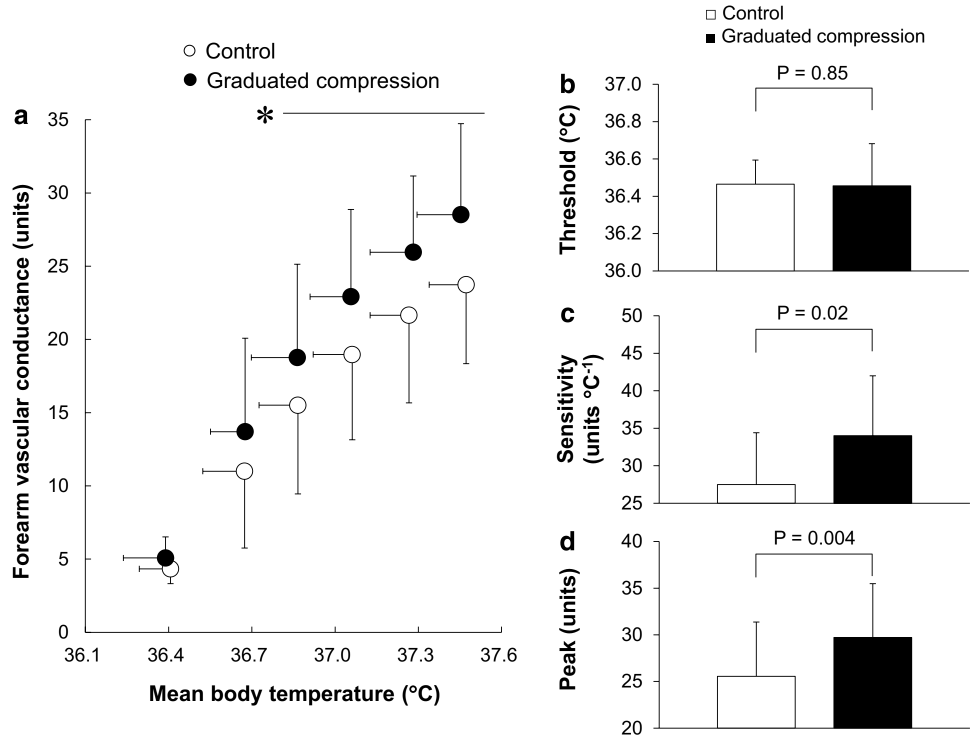

Fig. 4 Forearm vascular conductance plotted against mean body temperature (**a**). Averaged mean body temperature threshold (**b**), sensitivity (**c**), and peak (**d**) for cutaneous vasodilation are also presented. Data are mean ± standard deviation. Units for forearm vascular conductance are ml 100 ml tissue^{-1} min^{-1} mm Hg × 100

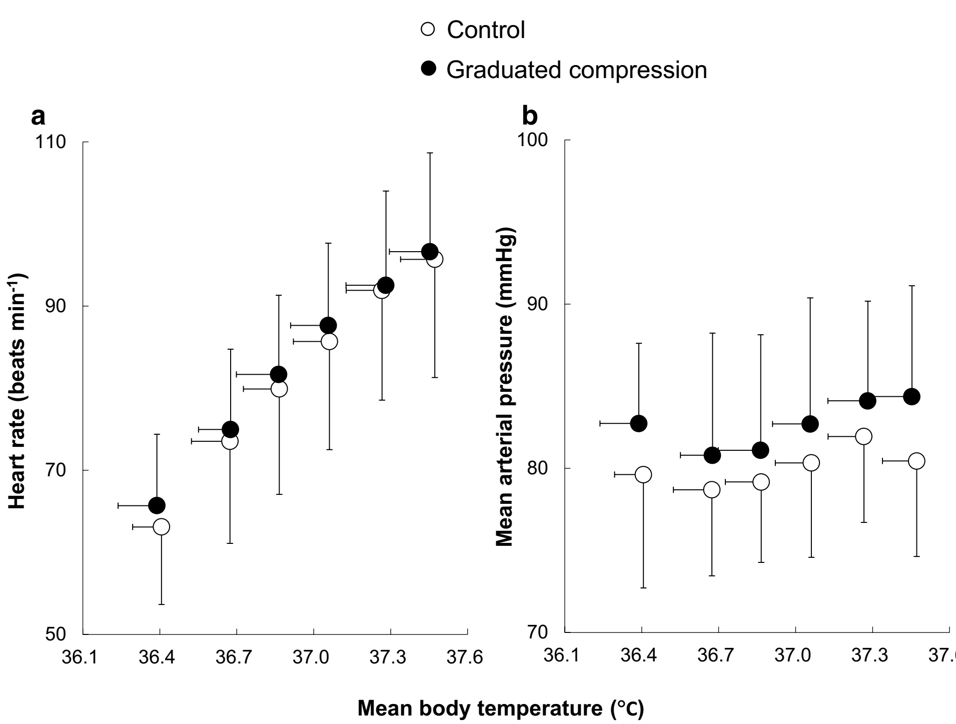

Fig. 5 Mean body temperature-dependent changes in heart rate (**a**) and mean arterial pressure (**b**) evaluated during baseline (BL, before heating) and whole-body heating. There were no between-trial differences in either heart rate or mean arterial pressure throughout (both $P > 0.24$ for a main effect of trial and an interaction between trial and time). Data are mean ± standard deviation

is effective in enhancing venous return (Lawrence and Kakkar 1980; Sigel et al. 1975). Graduated compression stockings used in the current study have a similar, but slightly higher pressure profile (pressures of 26.4 ± 5.3, 17.5 ± 4.4, and 6.1 ± 2.0 mmHg at the ankle, calf, and thigh, respectively, Fig. 1). It appears that increased venous return and central blood volume during baseline and heating was achieved by wearing graduated compression stockings in the current study.

To the best of our knowledge, this is the first study to report the effect of graduated compression associated with wearing stockings on cutaneous vasodilation during heat stress. We show that the graduated compression stockings enhance cutaneous perfusion with increases in level of heat stress relative to the Control (Fig. 3). Specifically, we showed that the sensitivity of the response increased, such that a greater change in cutaneous vasodilation occurred for a given change in mean body temperature (Fig. 4a, c) despite the fact that the onset threshold for cutaneous vasodilation was similar between trials (Fig. 4b). Furthermore, we showed that the peak response for cutaneous vasodilation was greater with the graduated compression for a given change in mean body temperature (Fig. 4d). Taken together, our findings demonstrate that the thermoeffector response of cutaneous vasodilation is enhanced with the use of compression stockings.

Given that a well-established link has been established between baroreceptors and cutaneous vascular response during heat stress (Kenny and Journeay 2010; Mack et al. 1988, 2001), it is plausible that baroreceptor loading due to compression-induced increases in venous return and central blood volume underlies the greater cutaneous vasodilation. In support of this possibility, several studies have demonstrated that increases in venous return and central blood volume augment cutaneous vasodilation during heat stress induced by postural [e.g., upright to supine (Gonzalez-Alonso et al. 1999; Johnson et al. 1974)] or mechanical manipulation (i.e., application of positive pressure to the lower limbs [McGinn et al. 2014; Paull et al. 2016]), infusion of saline (Crandall et al. 1999; Nose et al. 1990; Schlader et al. 2015), head-up water immersion (Nielsen et al. 1984), and continuous negative-pressure breathing (Nagashima et al. 1998).

Heart rate and mean arterial pressure

We observed a similar response in heart rate and mean arterial pressure between trials throughout the experiment (Fig. 5). This is consistent with the previous reports that showed no effect of compression garments on heart rate and mean arterial pressure during rest, exercise and/or subsequent recovery (Houghton et al. 2009; Iwama 1995; Lucas et al. 2012; Morrison et al. 2014; Quesada et al. 2015; Rimaud et al. 2010). One noteworthy exception was the observation by Morrison et al. (2014), who reported a reduction in mean arterial pressure during heat stress under resting conditions only. We showed that mean arterial pressure remained unchanged with graduated compression stockings despite greater cutaneous vasodilation. This is particularly noteworthy given that a greater cutaneous vasodilation can lead to lower total peripheral resistance, thereby reducing mean arterial pressure. It is possible, therefore, that blood pressure was maintained by an increase in cardiac output associated with an increase in venous return independent of a change in heart rate. This response would, therefore, counteract a reduction in total peripheral resistance associated with greater cutaneous vasodilation. Further studies using graduated stockings are required to elucidate the mechanisms underpinning this response.

Perspectives and significance

Our results show that graduated compression stockings augment cutaneous vasodilation during heat stress at rest, though the extent to which this augmentation increases heat loss cannot be fully elucidated from the current findings. When ambient temperatures exceed mean skin temperature (~34 °C), evaporation of sweat is the main avenue for heat loss and dry heat loss associated with increased cutaneous perfusion has a minor role in dissipating heat (Gisolfi and Wenger 1984). Along these lines, a recent study reported that a reduction in cutaneous vasodilation did not exacerbate increases in body core temperature during an ambient heat exposure of 41 °C (Cramer et al. 2017). Hence, increased dry heat loss due to the augmented cutaneous vasodilation in the present study may be negligible in context of its influence on body core temperature. In terms of evaporative heat loss, sweating in the current study might have been augmented with graduated compression stockings based on our observation that reduction in body weight following heating tended to be greater with graduated compression stockings. Further work is required to directly assess the extent to which augmented cutaneous vasodilation and possibly sweating elicited by wearing graduated compression stockings may affect whole-body heat dissipation and, therefore, body core temperature.

It should be noted that wearing the compression stockings *per se* can insulate the skin, thereby attenuating heat loss (Born et al. 2013; Doan et al. 2003; Engel et al. 2016). In the present study, to isolate an effect of graduated compression, comparisons were made between loose-fitting vs. graduated compression stockings. However, this comparison eliminated the influence of an increased insulation associated with wearing stockings. To account for the insulative effect, responses need to be compared between no stockings vs. graduated compression stockings. It may be that any increase in whole-body heat loss achieved by graduated compression stockings is negated by the reduced heat loss of the insulated limbs resulting in little to no change in body core temperature during heat stress. In line with this, the previous studies failed to see the effect of compression garments on body core temperature during exercise in ambient temperatures of between 10 and 35 °C (Barwood et al. 2013; Duffield et al. 2008; Goh et al. 2011; Houghton et al. 2009; MacRae et al. 2012; Noonan and Stachenfeld 2012). Graduated compression stockings that use materials with low insulative properties may be required to maximize heat loss associated with graduated compression.

Conclusions

Our results suggest that graduated compression achieved by wearing compression stockings augments cutaneous vasodilation under resting conditions by increasing the sensitivity and peak level of the response, such that a greater change in cutaneous vasodilation occurs for a given change in mean body temperature. However, the extent to which this augmentation increases whole-body heat dissipation cannot be fully elucidated from the current findings. Future studies are required to examine how the insulative properties of the stockings may be altered and or improved to enhance local heat transfer.

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Compliance with ethical standards

Conflict of interest None.

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