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Indirect hand and forearm vasomotion: Regional variations in cutaneous thermosensitivity during normothermia and mild hyperthermia

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ABSTRACT

In this experiment, hand and forearm vasomotor activity was investigated during localised, but stable heating and cooling of the face, hand and thigh, under open-loop (clamped) conditions. It was hypothesised that facial stimulation would provoke the most potent vascular changes. Nine individuals participated in two normothermic trials (mean body temperature clamp: 36.6 °C; water-perfused suit and climate chamber) and two mildly hyperthermic trials (37.9 °C). Localised heating (+5 °C) and cooling (−5 °C) stimuli were applied to equal surface areas of the face, hand and thigh (perfusion patches: 15 min), while contralateral forearm or hand blood flows (venous-occlusion plethysmography) were measured (separate trials). Thermal sensation and discomfort votes were recorded before and during each thermal stimulation. When hyperthermic, local heating induced more sensitive vascular responses, with the combined thermosensitivity of both limb segments averaging 0.011 mL·100 mL^{-1}·min^{-1}·mmHg^{-1}·°C^{-1}, and 0.005 mL·100 mL^{-1}·min^{-1}·mmHg^{-1}·°C^{-1} during localised cooling ($P < 0.05$). Inter-site comparisons among the stimulated sites yielded minimal evidence of variations in local thermal sensation, and no differences were observed for vascular conductance ($P > 0.05$). Therefore, regional differences in vasomotor and sensory sensitivity appeared not to exist. When combined with previous observations of sudomotor sensitivity, it seems that, during mild heating and cooling, regional representations within the somatosensory cortex may not translate into meaningful differences in thermal sensation or the central integration of thermoafferent signals. It was concluded that inter-site variations in the cutaneous thermosensitivity of these thermolytic effectors have minimal physiological significance over the ranges investigated thus far.

1. Introduction

The indirect thermal modulation of vasomotor function was first described by Tholozan and Brown-Séquard (1858), who observed that the cooling of one skin region modified blood flow within other tissues. Following innumerable subsequent contributions, we now have extensive knowledge concerning both the direct and indirect thermal mechanisms that control skin blood flow (Johnson et al., 2014). Most such research has, however, emphasised the impact of changes in deep-body temperature, the effects of thermal stimuli applied to large skin surfaces or their interactive influences (Barcroft and Edholm, 1943; Wyss et al., 1974; Proppe et al., 1976; Taylor et al., 1984; Pérgola et al., 1993). A significant piece missing from that complex puzzle is an understanding of the affect that temperature manipulations applied to small, remote skin surfaces might have upon indirect (reflex) vasomotion, and so the purpose of this investigation was to explore that interaction.

By investigating the indirect responsiveness of the vasomotor, sudomotor and thermogenic effectors to thermal stimuli applied to discrete skin locations, one can evaluate regional differences in cutaneous temperature sensitivity (Libert et al., 1984; Heising and Werner, 1987; Burke and Mekjavic, 1991; Patterson et al., 1998; Cotter and Taylor, 2005). The resulting thermosensitivity variations might reflect differences in thermoreceptor density, thermoafferent convergence or a differential central weighting of that feedback. There is ample evidence for the third possibility, with disproportionately larger somatosensory representations described for the face, hands and feet (Penfield and Boldrey, 1937). Nevertheless, variations in the representation of peripheral thermoreceptor feedback appear not to have been explored with respect to vasomotion, although a greater thermal awareness has been reported for facial stimulation (Hardy and Oppel, 1937). The face also has a greater thermoreceptor density with minimal apparent convergence (Poulos and Molt, 1976; Hensel, 1981). Accordingly, evidence was sought, particularly with respect to the face, that such mechanisms might participate in the indirect thermal control of skin blood flow.

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Experiments designed to isolate and evaluate the impact of localised thermoafferent flow from cutaneous tissues on autonomic function are technically difficult. For example, localised heating of the thermosensitive tissues of pre-heated individuals stimulates whole-body thermolysis, with the resulting cooling modifying thermal feedback from all of the affected receptive fields, even those beyond the treated tissues. In turn, the overall thermoefferent flow is reduced, resulting in a masking of the autonomic impact of the original treatment. To reveal regional differences in cutaneous thermosensitivity, feedback arms of the thermal control loops need to be opened, and the interactive feedback from the untreated tissues minimised, if not eliminated. That experimental requirement has not always been recognised (Nadel et al., 1973; Crawshaw et al., 1975; Libert et al., 1984). However, it can be achieved through thermal clamping of the unstimulated tissues (Jessen, 1981; Gordon et al., 2004), and an open-loop capacity for human research has been developed within the current laboratory (Patterson et al., 1998; Cotter and Taylor, 2005; Caldwell et al., 2014, 2016). Using those methods, Patterson et al. (1998) found that inter-site variations in cutaneous sudomotor sensitivity during mild heating and cooling were not evident over the temperature range they investigated. Cotter and Taylor (2005) supported that outcome, increasing the number of treated skin sites from four to ten, although they found facial skin to be more thermosensitive than that of the forearm, thigh, leg and foot during more powerful cooling.

In the current experiment, those open-loop methods were replicated to again evaluate regional variations in cutaneous thermosensitivity, but now with a thermoeffector that participates across all thermoregulatory zones (Mekjavic and Eiken, 2006; Werner et al., 2008); cutaneous blood flow. Since vasomotor control varies among skin regions (Johnson et al., 2014), that necessitated evaluating both glabrous (*e.g.*, palm) and non-glabrous skin (*e.g.*, dorsal hand and forearm). In addition, a method was developed that permitted concurrent thermal clamping of the skin at the sites of blood-flow measurement (water-displacement plethysmography: Caldwell and Taylor, 2014). These combined approaches were used to clamp the temperatures of the unstimulated tissues whilst those of three remote skin surfaces of equal size (face, hand and thigh) were independently modified. This clamping fixed the impact of the local tissue temperature on the dimensions of blood vessels within those tissues, permitting differences in the impact of the remote thermal treatments to be evaluated from reflex changes in the vascular conductance of the forearm and the entire hand (cutaneous thermosensitivity). It was hypothesised that the face would display the greatest sensitivity, with its stimulation eliciting the most powerful vascular responses.

2. Methods

2.1. Subjects

Physically active and healthy males (N=5) and females (N=4) provided written, informed consent before participating in four trials (age 28.3 y [standard deviation (SD) 6.9], body mass 67.8 kg [SD 8.6], height 170.1 cm [SD 4.4 cm], skin surface area 1.78 m^2 [SD 0.12]). Since gender-dependent differences in the cutaneous vascular responses were not anticipated, a mixed-gender sample was recruited and between-gender differences were not investigated. Power analysis for this experiment revealed that a sample size of 7–8 individuals was required to detect a change in local vasomotor sensitivity of 0.001 mL·100 mL^{-1}·min^{-1}·$mmHg^{-1}$·$^oC^{-1}$ when vasomotor conductance was in the range 0.004–0.007 mL·100 mL^{-1}·min^{-1}·$mmHg^{-1}$ (SD 0.004). No participant was taking medication, nor did any have a history of cardiovascular or thermal illness, and the women were tested during the luteal phase of their menstrual cycles. All procedures were approved by the Human Research Ethics Committee (University of Wollongong) in accordance with the regulations of the National Health and Medical Research Council (Australia), and in compliance with the Declaration of Helsinki.

2.2. Experimental procedures

2.2.1. Procedural overview

This experiment involved four trials, with all individuals participating in every trial (repeated-measures design). The aim was to investigate two clamped, whole-body thermal states with a mean body temperature (weighted sum of deep-body and mean skin temperatures) separation of approximately 1 °C: normothermia (~37 °C) and mild hyperthermia (~38 °C). Those conditions were first induced using whole-body water immersion, after which thermal clamping (water-perfusion garment, perfusion patches, temperature-regulated plethysmographs and climate chamber) enabled both the deep-body and mean skin temperatures to be sustained throughout every trial. Localised thermal stimuli were then applied to equal surface areas of skin on the face, left hand and left thigh. Those locations were chosen due to the greater sudomotor sensitivity observed for the face during moderate cooling (Cotter and Taylor, 2005), inter-site variations in thermoreceptor density (Hensel, 1981; Pierau, 1996) and differences in their representation within the somatosensory cortex (Penfield and Boldrey, 1937). Local stimulations involved either heating or cooling, such that skin temperatures were modified by about 5 °C. During each thermal stimulation, blood flows to either the right forearm or the entire right hand were measured (venous-occlusion, water-displacement plethysmography), with inter-site differences taken to reflect regional variations in cutaneous thermosensitivity. Since the control of blood flow varies between the glabrous and non-glabrous skin regions, those measurement sites provided sensitivity evaluations for both skin types. Due to the method of blood-flow measurement, however, those sites could not be investigated simultaneously, and that limitation necessitated the completion of two trials within each thermal state. Therefore, trials differed in two ways: whole-body thermal state (normothermia and mild hyperthermia) and the region of segmental blood-flow measurement (hand and forearm).

2.2.2. Pre-experimental standardisation

Subjects acted as their own controls with the treatment order balanced across individuals, with trials occurring at the same time of day within participants and with consecutive trials separated by at least seven days. Before each trial, subjects were instructed to drink fluids equating with at least 15 mL kg^{-1} of body mass, and to refrain from strenuous exercise and alcohol consumption on the preceding day, and from caffeine on the day of testing. Participants were requested to consume an additional 500 mL of liquid in the morning. Urine specific gravity was measured on presentation (Clinical Refractometer, Model 140, Shibuya Optical, Tokyo, Japan), yielding thermal state baselines averaging 1.018 (SD 0.01: normothermia) and 1.021 (SD 0.01: mild hyperthermia). Individuals with values > 1.029 immediately consumed additional water (10 mL kg^{-1}). To minimise dehydration effects, subjects consumed (*ad libitum*) an iso-osmotic drink on the first trial within each thermal state (1 L tap water with 40 g raw sugar and 0.5 g of table salt). For subsequent trials, each individual drank an matching, thermal state-specific fluid volume.

2.2.3. Experimental routine

The timing for every trial was identical (Fig. 1), with each trial lasting approximately 4 h. Following the hydration status check, the experimental routine included an initial instrumentation (A) and baseline data-collection phase (20–30 min), whole-body water immersion to stabilise and manipulate the pre-experimental thermal state (30–35 min), and transfer to a climate-controlled chamber for additional instrumentation (B), thermal clamping and pre-treatment baseline data collection (20–30 min). The experimental phase followed, with both thermal clamps sustained throughout testing (~180 min),

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