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The effects of facial fanning on thermal comfort sensation during hyperthermia

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Abstract We studied how facial fanning during hyperthermia improves the thermal comfort sensation. Experiments were carried out on ten male subjects. They were immersed in hot water at 40°C for 45 min. At 20 min and 35 min, fanning (1 m·s⁻¹) was applied to their faces for 5 min. Core temperature (T_c) measured as esophageal temperature (T_{es}) and tympanic temperature (T_{ty}) continued to rise during the immersion, but temporarily decreased during fanning with a delay of 2 or 3 min. Skin temperatures (T_s) on the forehead and cheek continued to increase slightly during immersion, but decreased immediately after the start of fanning. During immersion before face fanning, the time trend of thermal sensation towards the warm level was similar to that of skin temperature on the face, whereas the time trend of thermal comfort ratings towards the uncomfortable level was similar to that of T_c . The scores of both thermal sensation and thermal comfort were reduced significantly immediately after the start of fanning, and their time courses were different to those of T_s and T_{ty} . These results support previous reports that thermal sensation depends on skin temperature, and that thermal comfort depends on both the skin and core temperatures. Moreover, they indicate that both thermal sensation and comfort ratings are affected by the dynamic responses of the cutaneous thermoreceptors when fanning is applied to the face during hyperthermia.

Keywords Cutaneous thermoreceptor · Dynamic response · Face fanning · Hyperthermia · Skin temperature · Thermal comfort · Thermal sensation · Tympanic temperature

Introduction

Thermal sensation and thermal comfort have been distinguished in a number of studies concerning thermoreception or behavioral temperature regulation [11, 14, 17]. Thermal sensation is the perception dominated by cutaneous thermoreceptor input, and is expressed as “hot” or “cold”. Comfort sensation depends on the integrated input of the internal and peripheral thermoreceptors, expressed more subjectively as “comfortable” or “uncomfortable” [17].

A number of studies have reported that brain temperature predominantly determines thermal comfort [2, 5]. Most studies have adopted tympanic temperature (T_{ty}) as an index of the brain temperature. The validity of T_{ty} has been supported by Brinnet and Cabanac [1]. Brinnet et al. [2] investigated the correlation between T_{ty} and thermal comfort in hyperthermic subjects to demonstrate the possibility of selective brain cooling. In contrast, Marks and Gonzalez [24] studied thermal comfort when the local skin temperature was altered by radiant thermal stimulation to the forehead at a constant T_{ty} , and showed that thermal comfort could be rated only according to the input from cutaneous thermoreceptors. Recently, Frank et al. [13] and Bulcao et al. [4] have indicated that the mean skin temperature and core temperature contribute equally to thermal comfort.

The improvement in thermal comfort induced by an abrupt change in thermal conditions is experienced frequently in daily life [23]. For example, we actually feel more comfortable when the face is exposed to a breeze in a hot bath. We induced rapid temporary cooling of local head skin areas by face fanning, resulting in delayed changes of esophageal temperature (T_{es}) and T_{ty} , and investigated the effects on thermal sensation and thermal comfort in hyperthermic subjects.

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Materials and methods

Protocol

We studied seven healthy male subjects (21.0 ± 0.6 years, mean \pm SE), who entered a climate chamber at 23°C with 45% (relative humidity, rh) wearing only swimming trunks. After a baseline measurement of 20 min, they were immersed up to their necks in a hot bath for 45 min. The temperature of the water was controlled thermostatically at 40°C while stirring. Their left arm and head were placed outside the bathtub for the measurements. At 20 min and 35 min after the start of the immersion, an electric fan was used to blow their faces for 5 min with a wind velocity of $1 \text{ m}\cdot\text{s}^{-1}$.

The control experiments were carried out on seven healthy male subjects (21.3 ± 1.3 years), who were immersed in a hot bath (40°C) for 45 min under the same conditions without the fanning.

All the subjects provided informed consent for this experiment. Each experiment was performed at the same time of day in August 1997 and July 1998, thus avoiding the effects of circadian rhythm.

Measurement

T_{ty} and T_{es} were measured continuously as core temperatures (T_{c}) using thermistors. A T_{ty} thermistor probe designed by Masuda and Uchino [25] was attached to the tympanic membrane accurately [1]. The auditory canal was filled with absorbent cotton and the pinnae were covered with ear-muffs with a special filter to suppress air convection; only water vapor could pass through. A T_{es} thermistor was inserted 40–50 cm into the esophagus through the nose [6]. In one subject, we measured the rectal temperature (T_{re}) instead of T_{es} . In this case, the thermistor was inserted 12 cm into the rectum.

The skin temperature was continuously measured with thermistors at the forehead ($T_{\text{s-forehead}}$), left cheek ($T_{\text{s-cheek}}$) and left forearm ($T_{\text{s-forearm}}$) sites. As these sites were kept away from water, the measured temperatures were completely independent of water temperature.

Heart rate and subjective sensations were obtained every 5 min during the immersion and every 2 min during fanning. Questionnaires on subjective sensation consisted of the thermal sensation and the thermal comfort according to Hardy [14].

Analysis

All data were presented as mean values and standard errors. Differences of the time courses of T_{c} between the control and the fanning experiments were assessed by the interaction effects of ANOVA. Moreover, a paired Student's *t*-test and Friedman's non-parametric test were conducted, too. $P < 0.05$ was identified as a significant difference.

Results

Figure 1 shows the averaged time courses of the core temperatures. During the baseline measurement before the immersion, T_{ty} was higher than, or nearly the same as T_{es} in all the subjects. After 5 min of immersion, T_{ty} and T_{es} began to rise after the initial transient reduction, and then increased progressively in all the subjects. The increase of T_{ty} was suppressed by fanning with a delay of 2–3 min. After the fanning was stopped, the suppression continued for 5 min. Subsequently, T_{ty} started to increase again. Although T_{es} was also influenced by fanning in a similar manner, the rate of suppression was less in T_{es} than in T_{ty} and occurred with a larger delay. The T_{re} mea-

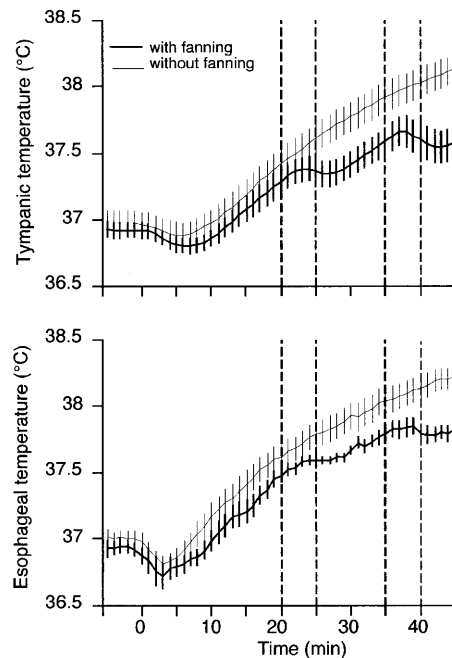


Fig. 1 The changes in the tympanic temperature (T_{ty} , top) and esophageal temperature (T_{es} , bottom) of all subjects. At time 0, the immersion was started. The thick line, with fanning; the thin line, without fanning. Values are mean \pm SE. The vertical dotted lines indicate the 5-min fanning period

sured in one subject was not influenced by fanning (not illustrated).

When compared with the control study without fanning, the time courses of T_{ty} and T_{es} during fanning were significantly different ($P=0.001$; T_{ty} and T_{es}) while the time courses of T_{ty} and T_{es} for the first 20 min of the immersion were not different (T_{ty} ; $P=0.992$, T_{es} ; $P=0.917$).

Figure 2 shows the changes of $T_{\text{s-forehead}}$ and $T_{\text{s-cheek}}$. In the condition with fanning, they reached $34.6 \pm 0.63^\circ\text{C}$ and $32.40 \pm 0.75^\circ\text{C}$ before the start of first fanning, and $35.28 \pm 0.44^\circ\text{C}$ and $34.24 \pm 0.54^\circ\text{C}$ before the second, respectively, but were decreased rapidly by the fanning. Immediately after the fanning was stopped, these temperatures started to rise. $T_{\text{s-forehead}}$ was depressed by $3.53 \pm 1.65^\circ\text{C}$ during the first fanning and by $4.57 \pm 0.66^\circ\text{C}$ during the second. This depression was significantly larger than that of $T_{\text{s-cheek}}$ ($1.29 \pm 0.88^\circ\text{C}$ for the first fanning; $2.67 \pm 2.21^\circ\text{C}$ for the second fanning; $T_{\text{s-forehead}}$ versus $T_{\text{s-cheek}}$; $P=0.029$ for the first and 0.043 for the second fanning, *t*-test). The steady levels of $T_{\text{s-forehead}}$ and $T_{\text{s-cheek}}$ attained 5–10 min after the fanning periods were identical with those of the non-fanned subjects. In contrast, $T_{\text{s-forearm}}$ did not respond to the fanning.

Figure 3 shows the time courses of thermal sensation and thermal comfort. All the subjects reported a constant temperature sensation rated "warm" during the first 20 min of immersion. The thermal sensation score was greatly reduced immediately after the start of fanning towards "neutral", with a subsequent slight but significant rise towards "slightly warm" throughout ($P=0.031$,

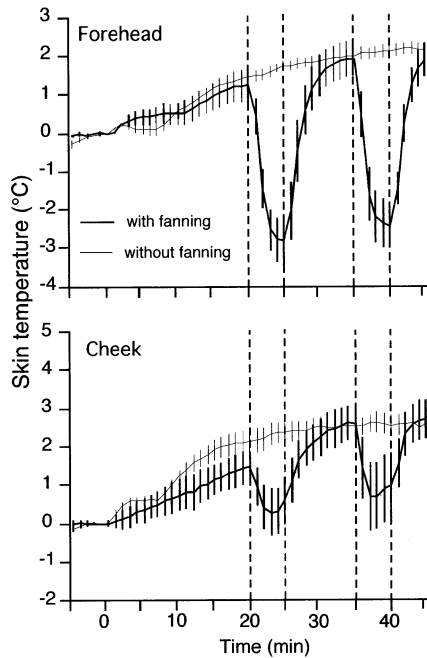


Fig. 2 The rates of change from time 0 in skin temperature at the forehead ($T_{s\text{-forehead}}$, top) and cheek ($T_{s\text{-cheek}}$, bottom) of all subjects. The thick line, with fanning; the thin line, without fanning. Values are mean \pm SE. The vertical dotted lines indicate the 5-min fanning period

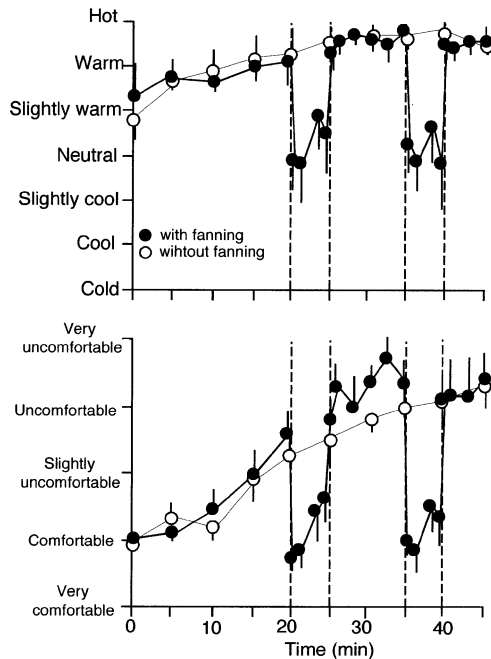


Fig. 3 The changes of the thermal sensation (top) and thermal comfort (bottom) of all the subjects. (● With fanning, ○ without fanning.) Values are mean \pm SE. The vertical dotted lines indicate the 5-min fanning period

Friedman test) but a rapid re-increase towards “warm” after the end of fanning. Immediately after the start of the second fanning the score again dropped towards “neutral” with no significant re-increase during fanning

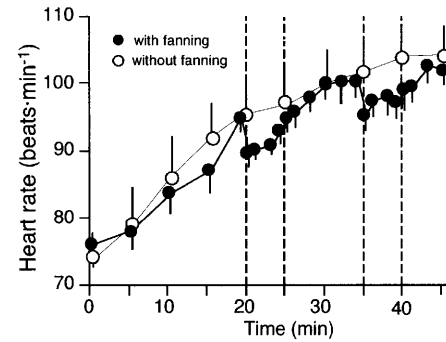


Fig. 4 The changes in the heart rate of all the subjects. (● With fanning, ○ without fanning.) Values are mean \pm SE. The vertical dotted lines indicate the 5-min fanning period

($P=0.057$, Friedman test), but rapid restoration to the rating level “warm” to “hot” after the end of fanning.

The thermal comfort ratings of the subjects gradually increased towards “uncomfortable” during the first 20 min of immersion. Each fanning caused instant and large drops of the ratings towards “comfortable” with slight but significant re-increases during fanning ($P=0.031$ for the first fanning and $P=0.024$ for the second, Friedman test). As soon as the fanning was stopped, the scores quickly returned to the more uncomfortable side. From the above results it is obvious that thermal comfort is analogous to the T_{ty} and T_{es} trend before the face was fanned, but its reduction occurred more rapidly and more distinctly after the onset of fanning than the change in T_{ty} .

As shown in Fig. 4, the heart rate increased during the first 20 min of the immersion. It responded with a significant decrease immediately after the onset of fanning ($P=0.014$ for the first fanning and 0.030 for the second, t -test), but started to re-increase slowly even while fanning continued. In general, the courses of heart rate, apart from the effects of fanning, were similar during the heat exposures in the fanned and non-fanned subjects.

Discussion

The study presents two main results concerning the influences of core temperature and facial skin temperature on the ratings of thermal sensation and thermal comfort. Result (1): during immersion without face fanning, i.e., when skin temperatures were slowly but steadily rising and core temperatures were rising too, the time trend of thermal sensation was similar to that of the skin temperature of the face, whereas the time trend of thermal comfort was similar to that of the T_{ty} or T_{es} . Result (2): during face fanning, both thermal sensation and thermal comfort ratings dropped rapidly with the rapidly decreasing face skin temperatures, irrespective of the initial further rise and delayed decreases of T_{ty} or T_{es} .

Result (1) is compatible with the results of previous studies indicating that thermal sensation is determined predominantly by the skin temperature, whereas thermal

comfort depends on both the skin and core temperatures [2, 3, 5, 17]. Result (2) shows that although the core temperature is a predominant determinant for thermal comfort when fanning is precluded, skin temperature plays a predominant role when the face is fanned. These results support the previous hypothesis that the skin temperature to some extent contributes to the perception of thermal comfort [4, 13]. However, while the influence of thermal fanning was strong, the time course of thermal comfort was not analogous to that of the skin temperature on the face during the fanning, since thermal comfort was lowest immediately after the start of fanning (Fig. 3) whereas the skin temperature was lowest at the end of fanning (Fig. 2). This discrepancy may be explained by the dynamic responses of the cutaneous thermoreceptors. It is likely that the dynamic properties of the cutaneous cold thermoreceptors elicited the transient great improvement in thermal comfort immediately after the start of face fanning.

It is generally accepted that cutaneous thermoreceptors not only have a static discharge at constant temperature, but also respond dynamically to temperature changes [16, 22]. Hensel [15] suggested the possibility that this dynamic response of the cutaneous cold receptors might influence the thermal sensation. Järvilehto [19] recorded the activities of single cold fibers in the skin of humans together with the thermal sensation induced by local cooling. In view of the dynamic response component of cold receptor activity, their data suggest for our findings that the likelihood of perceiving the change in thermal sensation from “warm” to “neutral” is greatest in the initial phase of rapidly decreasing skin temperature during face fanning.

The observation that the thermal comfort rating gradually re-increased during the face fanning is also consistent with the view that the dynamic component of the skin’s cold receptor response is involved in improving thermal comfort sensation during face fanning. Furthermore, the score of thermal sensation and thermal comfort re-increased very rapidly immediately after the end of fanning, although T_{ty} was falling during this time period. This could be explained by the reversed dynamic “undershoot” component of the skin’s cold receptor signal during the period of rapid skin re-warming.

The core and skin temperatures have been reported to contribute equally to the sensation of thermal comfort, whereas their relative contributions to determining the autonomic thermoregulatory responses reportedly range from 3:1 to 20:1 [27, 33, 34]. This indicates that the influence of the cutaneous thermoreceptors’ dynamic response would be specifically greater on thermal comfort than on the autonomic thermoregulatory responses. This greater contribution of skin temperature to thermal comfort might be an additional factor in improving thermal comfort during face fanning in hyperthermia.

A large number of studies have investigated the influences of human face or head cooling on thermal comfort [3], sweat rate [35], work load [18], and heart rate [10, 32] when hyperthermic. The majority of them demon-

strate that artificial head cooling in hyperthermic subjects reduces brain temperature, as inferred from the reduction of T_{ty} . Cabanac and Brinnet [8], and Cabanac and Caputa [9] proposed a mechanism of selective brain cooling to explain such a reduction in the brain temperature when hyperthermic. They hypothesized that human selective brain cooling is caused by the countercurrent heat exchange at the base of the brain between the arterial blood and the venous blood that has been cooled at the skin surface when it returns to the body core and thereby protects the brain from thermal damage [7]. Although the T_{ty} was similar to, or higher than, T_{es} during the control measurements, this relationship was reversed in all the subjects after the immersion began (Fig. 1). This effect suggests that the selective brain cooling is functioning in the early stages of immersion. T_{es} might also be influenced by countercurrent heat exchange between the venous blood draining from the head and the arterial blood running within the internal carotid arteries [26]. This suggestion corresponds to the observation that T_{re} is not affected by fanning and thus continues to increase throughout immersion; however, it is also generally accepted that T_{re} is only a sluggish indicator of core temperature changes, different from T_{es} .

Questions remain about how precisely T_{ty} represents brain temperature, and consequently the actual temperature signal that is generated in the hypothalamus of humans [20, 29, 30, 31]. In addition, several investigators do not consider the efficiency of the selective brain cooling mechanism in humans. This uncertainty is, however, not crucial for the interpretation of our own data, which indicate that during face fanning the skin temperature signal, in particular its dynamic component, dominates the ratings of thermal sensation and thermal comfort.

Cabanac and Caputa [10] describe the relationship between T_{ty} and heart rate during hyperthermia, and ascribe the reduction of heart rate during facial cooling to brain cooling. The face fanning effectively reduced the heart rate in our study (Fig. 4), however the time course of the heart rate reduction again did not reflect the time course of T_{ty} .

We found that T_{s} -forehead decreased with fanning more than T_{s} -cheek. It is possible that the uneven distribution of wind velocity over the face might cause this difference in skin temperature. Nadel et al. [28] and Crawshaw et al. [12] reported that the thermal sensitivity of the central sudomotor drive is greater on the face than at the other sites. In particular, since the forehead sweats more than the cheek or the neck [21], a progressive cooling of the forehead by evaporative heat loss is to be expected. The greater depression of T_{s} -forehead compared with T_{s} -cheek (Fig. 2) might be attributable to the greater amount of sweating on the forehead [21]. Furthermore, since cutaneous cold receptors are more densely distributed on the forehead [7], cold stimulation of this site might greatly influence thermal sensation and thermal comfort.

In addition to thermosensors in the hypothalamus, strong evidence exists that the body core contains warm

sensors in the abdomen, chest, and spinal cord, and that these sensors constitute a major input of the thermoregulatory system. The role played by these sensors in causing thermal sensation and thermal comfort is uncertain. However, it is supposed that temperature changes at these core sites due to fanning are negligible, as indicated by the small or non-existent depression during face fanning of T_{es} and T_{re} , respectively. Even if the information from these sensors is relevant to thermoregulation, this would not alter the interpretation of our data, namely that, during the face fanning, signals arising from the skin receptors greatly affect the improvement of thermal sensation and thermal comfort.

In conclusion, our data confirm that thermal sensation is more dependent on the skin temperature and thermal comfort more dependent on the core temperature during immersion. Our new finding is the immediate improvement of thermal sensation and thermal comfort upon reducing skin and core temperatures by face fanning. It is possible that this improvement is largely caused by the dynamic responses of the facial cold receptors. A reduction in brain temperature attributable to selective brain cooling might also be involved; however, according to our data, such an influence would be small, delayed and, moreover, seems to have been largely overridden by the skin temperature changes.

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