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Effect of transient temperature on thermoreceptor response and thermal sensation

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Abstract

This work investigates the dynamic response of cutaneous thermoreceptors (TRs) under various environmental conditions. The model consists of an electrical submodel and a Pennes bioheat transfer submodel. The electrical submodel assumes that the response of the cutaneous TRs has a static and dynamic part, in which the static one is proportional to the temperature and the dynamic part proportional to the temperature change rate. A one-dimensional multi-layer model is presented to model the heat exchange between the skin and the ambient medium. Then the temperature of the TRs and the necessary parameters of the electrical submodel are predicted using a finite difference method. Approaches proposed in this paper can help identify the difference of the warm and cold TRs under the same environmental conditions. This difference may be the real mechanism that people are more sensitive to cold stimuli than warm stimuli.

Keywords: Thermal comfort; Thermal sensation; Bioheat transfer; Thermoreceptor; Theoretical model

1. Introduction

The thermal environment is a composite of a number of climatic factors. The major variables include air temperature, air movement, surrounding humidity and radiant heat, etc. Thermal comfort also depends upon an individual's response to those climatic factors and is affected, for example, by the level of activity, metabolism, personal health situation, medication, alcohol consumption, suitability of clothing, level of acclimatization and level and length of exposure to the adverse conditions. Over the years, a large number of thermal comfort indices have been set up for evaluating the quality of indoor climates and the design of heating, ventilating and air-conditioning (HVAC) system [1–3]. Many studies have been carried out on specific thermal factors such as effects of draught, asymmetry, clothing or activity. Fanger [1] proposed a thermal sensation index to predict the mean thermal sensation vote on a standard scale for a large group of persons depending on several thermal environmental variables, the activity level and the clo-value of clothing worn by the occupants. However, the mathematical expression derived for the calculation of the "predicted mean vote" (PMV) is rather complicated. Recently, we proposed a novel strategy for evaluation of physiological comfort of biological bodies subject to a specific thermal environment using the self-sustained oscillation of action potentials in neuron [4]. Unlike the traditional way of using the thermal balance equation to evaluate the thermal comfort, this new approach fundamentally correlates the major variables such as neuron excitation, air temperature and velocity, biological activity level, body metabolism, healthy state and an individual's response to those climatic factors. It is clear that the electrical signals from the nervous systems could be used to accomplish the switching control of an external device between the cooling and heating models [5]. However, the electrophysiology of cutaneous temperature sensing in humans involves more than simple changes in firing rates of an axon. Humans have both warm and cold cutaneous thermoreceptors (TRs) in the form of differentiated afferent nerves, each

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Nomenclature

A	average air velocity (m/s),
C	specific heat of tissue (J/kg K)
C_b	specific heat of blood (J/kg K)
f	frequency of the air movement (Hz)
h_0	heat convection coefficient (W/m^2 K)
h_f	apparent heat convection coefficient between skin surface and surrounding air (W/m^2 K)
K_d	proportionality constant for the dynamic response (imp/K s)
K_s	proportionality constant for the static response (imp/K s)
P_a	vapor pressure in ambient air (kPa)
P_a^*	saturated vapor pressure at surrounding air temperature (kPa)
P_{a0}	initial vapor pressure in ambient air (kPa)
Q_m	metabolic rate of tissue (W/m^3)
R	response of thermoreceptors (imp/s)
T	tissue temperature (K)
T_a	artery temperature (K)
T_c	body core temperature (K)
T_f	air temperature (K)
t	time (s)
v	air speed (m/s)
W_b	blood perfusion rate (kg/m^3 s)
W_{rsw}	skin humidity
W_{rsw0}	initial skin humidity
x	thermoreceptors depth below the surface (m)

Greek letters

ρ	density of tissue (kg/m^3)
ρ_b	density of blood (kg/m^3)
ε	skin emissivity
σ	Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
ϕ_a	relative humidity of surrounding air
ψ	pulsant intensity of the air movement

with a different dependence of firing rate on temperature. The firing rate of warm-sensing nerves increases as the temperature increases; while the firing rate of cold-sensing nerves increases if the temperature is reduced [6].

The firing rates of the cutaneous TRs depend statically upon temperature, T, and dynamically on the temperature change rate, dT/dt, with positive coefficients for warm receptors and negative coefficients for cold receptors [6,7]. People often experience thermal transients in their daily life, e.g., one enters a cold room with air-conditioning system from the hot outdoor. At the same time, airflow in rooms is typically turbulent, i.e. the air velocity fluctuates randomly [8]. With proper determination of the desired indoor-air condition to HVAC system, it may be feasible to provide occupants with thermal comfort and acceptable air quality with efficient energy consumption simultaneously all the time. Such factors will help regulate the indoor-air temperature change with respect to the time. Further, studying the effect of the transient temperature on the response of TRs could help identify the different response of the warm and cold TRs, which would serve to establish a new index for evaluating the physiological comfort of biological bodies when subjected to a specific thermal environment. Finally, parametric studies could be performed to test whether temperature change rate or temperature would be the major factor to affect human thermal response. Thus, it is very important and practical to reveal the effect of the transient temperature on the response of TRs.

Based on the above argument, the main objectives of this paper are established as follows:

(1) To find out the relationship between thermal response of warm and cold TRs and physical environment (air temperature, humidity, air movement, radiation).
(2) To establish a criterion to discriminate the surrounding temperature to temperature change rate related thermal sensation.
(3) To interpret some basic sensation phenomena based on the response of warm and cold TRs.

2. Methods

As is well known, skin is the largest sensory organ in human body. Warm and cold TRs are distributed all around the human skin, which sense the change of the surrounding environment and stimulation. The electrical signals in TRs play an important role in this process. In order to interpret the thermal effect on electric responses of TRs embedded in human skin, the electrical signals in the TRs will be studied firstly. Then the transient temperature of the TRs will be obtained by solving the bioheat transfer equation.

2.1. Warm and cold cutaneous thermoreceptors model

The cutaneous thermal sensation is divided into cold thermal sensation and warm thermal sensation. The warm-receptors in mammals appear as differentiated C-fibers, unmyelinated afferent fibers ≈1–2 μm in diameter, while the cold receptors are differentiated $A\delta$ fibers, myelinated axons ≈3 μm in diameter. The afferent cold fibers differentiate near their end, at the sensory sites, into 5 or 10 short unmyelinated fibers. The warm-fibers differentiate similarly [6]. It was assumed that both change directionally from neutral zone with ambient temperature changes

[9,10]. Both cold thermal sensation and warm thermal sensation are assumed to be aroused in neutral zone. According to Coren et al. [9], only warm thermal sensation exists at temperature above 36 °C and only cold thermal sensation exists at temperature below 30 °C. The range of neutral zone is approximately 30–36 °C and is also a function of skin area exposed [11]. Following Hensel [12], the TR response should have a static part and dynamic part. Ring and Dear [13] have described the response of the cold TRs and warm TRs as follows.

For cold TRs:

$$R(x,t)=\begin{cases}\begin{array}{l}-K_sT(x,t)\\+K_sT_b+b,\end{array} & \partial T/\partial t>0,\\ \begin{array}{l}-K_sT(x,t)+K_sT_b\\+b-K_d\,\partial T(x,t)/\partial t,\end{array} & \partial T/\partial t<0.\end{cases}\tag{1}$$

For warm TRs:

$$R(x,t)=\begin{cases}\begin{array}{l}K_sT(x,t)\\-K_sT_b,\end{array} & \partial T/\partial t<0,\\ \begin{array}{l}K_sT(x,t)-K_sT_b\\+K_d\,\partial T(x,t)/\partial t,\end{array} & \partial T/\partial t>0,\end{cases}\tag{2}$$

where x is the depth below the surface. Generally, the cold-receptors are found at a depth of $x = 0.2$ mm in the human skin, near the interface between the dermis and epidermis. The warm-receptors may be somewhat deeper such as at $x = 0.5$ mm [6,13]. $R(x,t)$ is the response of a TR at a depth below the skin surface at the time t, K_s is the proportionality constant for the static response and K_d is the proportionality constant for the dynamic response, and $T_b = 30\,°\mathrm{C}$.

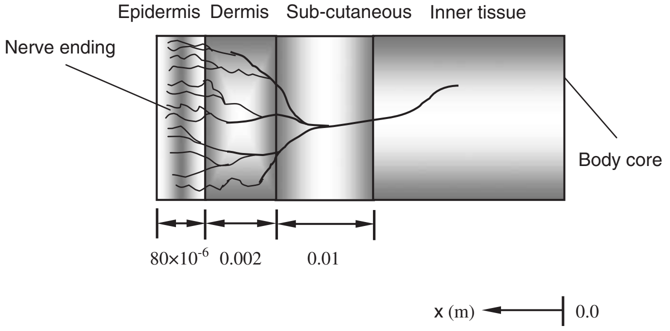


Fig. 1. Schematic geometry of three-layer skin structure.

2.2. Thermal model for temperature response in tissues

Previous calculations on the TR response using Eqs. (1) and (2) are based on the prerequisite assumption that the temperature of the TRs is given. Ring et al. [14] have studied the cutaneous TR responses to the temperature ramp-plateaux and step stimuli applied to the skin surface by thermodes. In a human body, the thermal stimuli may not be so strong due to heat transfer by the tissues and blood. In fact, the tissue temperature depends on space and is a transient value when subjected to a variable thermal environment. Therefore, the tissue temperature should be obtained before applying Eqs. (1) and (2) to predict the TR response in vivo. However, such information remains unclear up to now, which will be addressed in this paper. The human skin is generally stratified into three layers: epidermis, dermis and subcutaneous, as depicted in Fig. 1. The geometric information and thermal properties of each layer were derived from previous research [15] and listed in Table 1. The well-known Pennes equation [16] was used to model heat transfer in biological bodies:

$$\rho C\frac{\partial T(x,t)}{\partial t}=K\frac{\partial^2 T(x,t)}{\partial x^2}+W_bC_b(T_a-T(x,t))+Q_m,\tag{3}$$

where ρ, C and K are, respectively, the density, specific heat and thermal conductivity of the tissue, C_b denotes specific heat of blood, W_b the blood perfusion, T_a the supplying arterial blood temperature which is treated as a constant, T the tissue temperature, and Q_m is the metabolic heat generation. The thermoregulation mechanisms of the biological bodies have been neglected because of the slight temperature increase induced.

During the practical thermal processes, the boundary condition (BC) at the skin surface is often time dependent and the body core temperature was regarded as a constant (T_c) on considering that the biological body tends to keep its core temperature stable. At the skin–air interface, the generalized BC for the heat transfer occurring at skin surface is generally composed of three parts, i.e. convection, radiation and evaporation.

Table 1
Geometry and properties of the skin [15]

Location	Property				
	Specific heat C (J/kg K)	Volumetric blood W_b (m^3/s m^3)	Thermal conductivity K (W/m K)	Thickness l (m)	Density ρ (kg/m^3)
Epidermis	3578–3600	0	0.24	80×10^{-6}	1200
Dermis	3200–3400	0.00125	0.45	0.002	1200
Subcutaneous	2288–3060	0.00125	0.19	0.010	1000
Inner tissue	4000	0.00125	0.5	—	1000

The boundary and initial conditions to Eq. (3) can then be expressed as

$$\begin{cases} T = T_{\mathrm{c}}, & x = 0,\\ -K\frac{\partial T}{\partial x} = h_{\mathrm{f}}(T - T_{\mathrm{f}}) + \sigma\varepsilon(T^4 - T_{\mathrm{f}}^4) + & \\ (3.054 + 16.7\,h_{\mathrm{f}}W_{\mathrm{rsw}})\,(0.256T - 3.37 - P_{\mathrm{a}}), & x = L,\\ T(x,0) = T_0(x), & t = 0, \end{cases} \tag{4}$$

where $T_0(x,0) = T_0(x)$ is steady-state temperature field, T_{c} the body core temperature and often regarded as a constant, h_{f} the apparent heat convection coefficient between the skin surface and the surrounding air, T_{f} the surrounding air temperature, ε the skin emissivity, σ the Stefan–Boltzmann constant, W_{rsw} the skin humidity, generally $0 \leqslant W_{\mathrm{rsw}} \leqslant 1$, and $W_{\mathrm{rsw}} = 0, 1$, respectively, stands for that the skin is dry and entirely wet, P_{a} the vapor pressure in ambient air, $P_{\mathrm{a}} = \phi_{\mathrm{a}}P_{\mathrm{a}}^*$, where ϕ_{a} is the relative humidity of surrounding air, and P_{a}^* the saturated vapor pressure at surrounding air temperature. In above equation, the unit of pressure is kPa. The heat loss due to evaporation includes the heat loss by evaporation of implicit sweat secretion when the skin is dry and the heat loss by evaporation of explicit sweat secretion (readers are referred to [1] and [17] for more description).

This non-linear BC due to occurrence of the $\sigma\varepsilon T_{\mathrm{s}}^4$ term can be solved through an iteration as follows: (1) assume the predicted skin temperature $T_{\mathrm{s,a}}$; (2) rewrite non-linear BC as the normal format

$$-k\,\frac{\partial T}{\partial x} = h_{\mathrm{f}}\left[T_{\mathrm{s}} - \left(T_{\mathrm{f}} - \frac{\sigma\varepsilon(T_{\mathrm{s,a}}^4 - T_{\mathrm{f}}^4) + (3.054 + 16.7h_{\mathrm{f}}W_{\mathrm{rsw}})\,(0.256T_{\mathrm{s,a}} - 3.37 - P_{\mathrm{a}})}{h_{\mathrm{f}}}\right)\right]$$

(3) then calculate the skin temperature T_{s} based on $T_{\mathrm{s,a}}$; (4) determine the corrected skin temperature $T_{\mathrm{c}} = T_{\mathrm{s,a}} + \gamma(T_{\mathrm{s}} - T_{\mathrm{s,a}})$, where $0 < \gamma \leqslant 1$ is a relaxation factor; (5) check convergence: if $|T_{\mathrm{c}} - T_{\mathrm{s,a}}|/|T_{\mathrm{c}}| > \varepsilon_{\max}$ (where $\varepsilon_{\max}$ is a prescribed maximum acceptable error), then set $T_{\mathrm{s,a}} = T_{\mathrm{c}}$ and continue the iterative operations from step 2 until the relative error becomes less than or equal to $\varepsilon_{\max}$; (6) if convergence is achieved, terminate the iteration and record $T_{\mathrm{s}} = T_{\mathrm{c}}$.

To calculate the transient tissue temperature field due to varied environment, the initial temperature distribution $T_0(x)$ needs to be known. It represents the basal state of living tissues, and can be obtained through solving the following equations:

$$\begin{cases} K\frac{\mathrm{d}^2T_0}{\mathrm{d}x^2} + W_{\mathrm{b}}C_{\mathrm{b}}[T_{\mathrm{a}} - T_0(x)] + Q_{\mathrm{m}} = 0 & \\ T_0(x) = T_{\mathrm{c}}, & x = 0,\\ -K\frac{\mathrm{d}T_0(x)}{\mathrm{d}x} = h_0[T_0(x) - T_{\mathrm{f0}}] + \sigma\varepsilon(T_0^4 - T_{\mathrm{f0}}^4) + & \\ (3.054 + 16.7h_{\mathrm{f0}}W_{\mathrm{rsw0}})\,(0.256T_0 - 3.37 - P_{\mathrm{a0}}), & x = L, \end{cases} \tag{5}$$

where h_0 is the apparent heat convection coefficient between the skin surface and the surrounding air under physiological basal state and is an overall contribution from natural convection and radiation, W_{rsw0} the initial skin humidity, and P_{a0} the initial vapor pressure in ambient air.

3. Results and discussion

In the following calculations, the typical values for tissue thermal properties are applied as given in [1,17,18]:

$C_{\mathrm{b}} = 4000\,\mathrm{J/kg}\,^{\circ}\mathrm{C}$, $T_{\mathrm{a}} = T_{\mathrm{c}} = 37\,^{\circ}\mathrm{C}$, $Q_{\mathrm{m}} = 420\,\mathrm{W/m^3}$, $L = 0.03\,\mathrm{m}$, $T_{\mathrm{f0}} = 20\,^{\circ}\mathrm{C}$.

$K_{\mathrm{s}} = 1.65$, $K_{\mathrm{d}} = 33.0$, $\varepsilon = 0.9$, $W_{\mathrm{rsw}} = 0.2$, $\sigma = 5.67 \times 10^{-8}\,\mathrm{W/m^2\,K^4}$, $\phi_{\mathrm{a}} = 0.4$, $W_{\mathrm{rsw0}} = 0.2$.

The apparent heat convection coefficient due to natural and forced convection is taken as [1,17,18]

$$h_{\mathrm{f}} = \sqrt{\left(12.1\sqrt{v}\right)^2 + (4.0)^2}, \tag{6}$$

where v is the air speed. Further, as demonstrated in many works [19,20], the interior tissue temperature usually tends to a constant within a short distance such as 2–3 cm. Therefore, $L = 0.03\,\mathrm{m}$ was used in this study. For some particular issues, the distance between skin surface and the body core may exceed this depth. In that case, new bounded core large enough to neglect the influence of the surface heating should be incorporated into the calculation.

Warm and cold TRs embedded in the epidermis serve to sense the change of the surrounding thermal environment and different stimulation. The TRs' electrical property will reflect the individual response to the climatic factors. The transient temperature of TRs embedded in epidermis reflects both the environmental and individual property and can be sensed by the excited TRs behavior. Thus, the present approach could combine the major variables for evaluating thermal comfort including air temperature (T_{f}), the level of activity, metabolism (Q_{m}), air velocity (h_{f}), blood perfusion (W_{b}), and the individual response to those climatic factors. In the following, the response of the TRs subject to different thermal environments will be studied. Effect of some factors on the TRs response will be discussed.

3.1. Thermoreceptor response during environmental temperature change

3.1.1. Temperature decrease

The responses of the cold and warm TRs when the environmental temperature changed as

$$T_{\mathrm{f}} = \begin{cases} 38 - 9t\,^{\circ}\mathrm{C}, & 0 \leqslant t \leqslant 2\,\mathrm{s},\\ 20\,^{\circ}\mathrm{C}, & t > 2\,\mathrm{s} \end{cases} \tag{7}$$

are presented in Fig. 2.

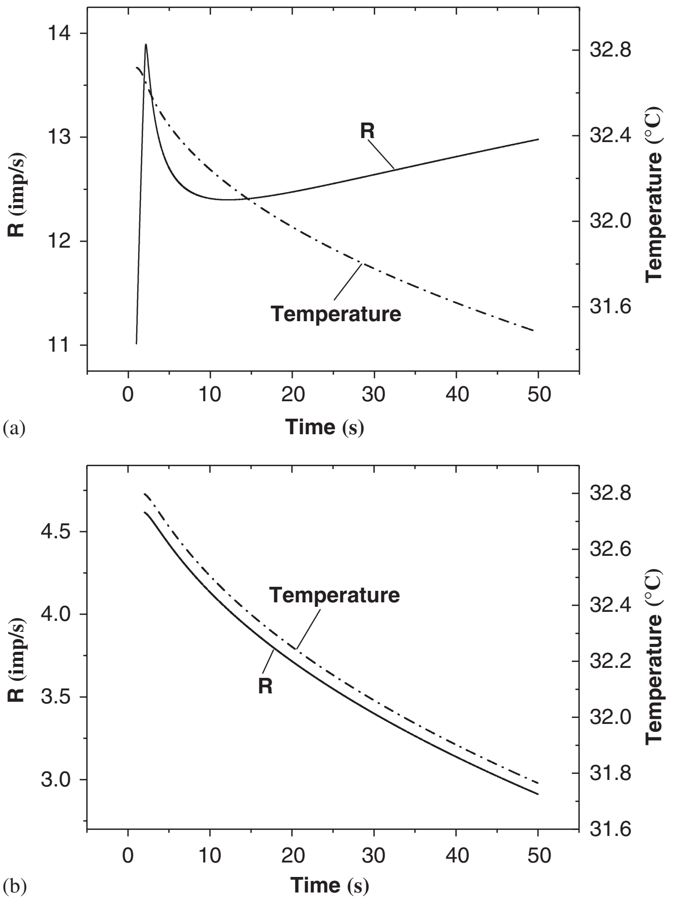


Fig. 2. Response of the cold (a) and warm (b) thermoreceptors when the environmental temperature is changed as $T_\mathrm{f} = 38 - 9t$.

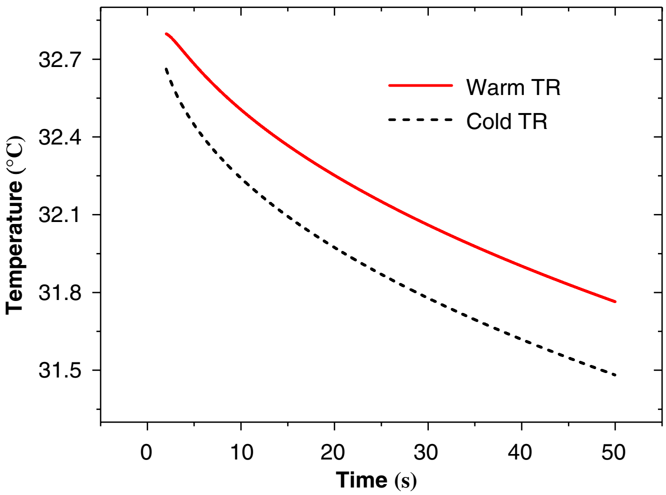


Fig. 3. Temperature response of the cold and warm thermoreceptors when the environmental temperature is changed as $T_\mathrm{f} = 38 - 9t$.

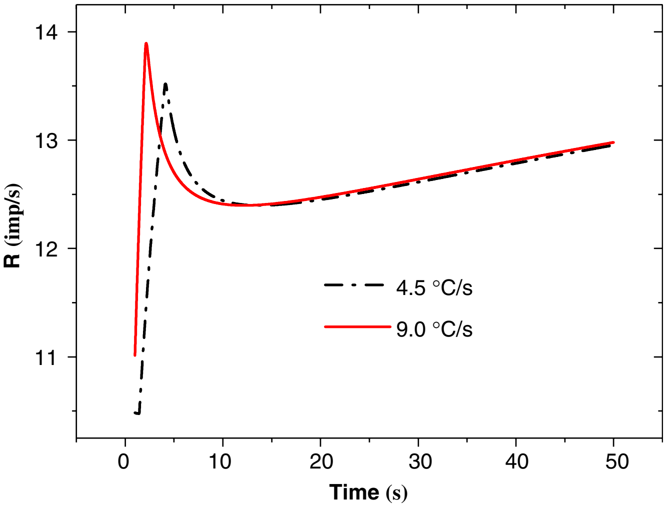


Fig. 4. Dynamic responses of cold TRs when the surrounding temperature changes from 38 to 20 °C at the rates of 9.0 and 4.5 °C/s.

TR response has a static and dynamic part and the response of the TR to a sudden drop in T yields a peaked dynamic part which after some time (s) was reduced to the static part alone. For the cold TRs, the temperature change must be down in order to excite the dynamic part, while for warm TRs the temperature change must be up. The static part should be proportional to T and the dynamic part proportional to $\mathrm{d}T/\mathrm{d}t$ [13]. The different TRs give different responses to the same thermal stimulus applied on the skin. The difference in the temperature response between a cold TR at a depth of 0.2 mm and a warm TR at 0.5 mm is also evident. The cold TR temperature decreases more quickly than the warm TR temperature does at the beginning (shown in Fig. 3). As it shows, the detecting time of the warm TRs lags behind that of the cold TRs. The difference of the temperature change rate between these two types of TRs will decrease with respect to the time. At the same time, the peak impulse frequency of the cold TRs is larger than that of the warm TRs. The response characteristics of the warm and cold TRs could explain why people always feel that the cold stimulation is quicker and stronger than warm stimulation.

Many factors influence environmental effects on humans. Fig. 4 is the dynamic response of cold TRs when the surrounding temperature changes from 38 to 20 °C with different rates. With the increase of the change rate, the peak impulse frequency becomes higher. Fig. 5 depicts the dynamic responses of cold TRs for ramps of 9.0 °C for various intensities. It is clear that the dynamic response saturates at about 15 imp/s and the length of this response depends on the length of the ramp.

3.1.2. *Temperature increase*

Fig. 6 shows the response of the cold and warm TRs when the environmental temperature is changed as

$$T_\mathrm{f} = \begin{cases} 20 + 9t, & 0 \leqslant t \leqslant 2\,\mathrm{s}, \\ 38, & t > 2\,\mathrm{s}. \end{cases} \tag{8}$$

Unlike the temperature decrease, the dynamic part of the warm TRs' response is much smaller than that of the cold TRs. The cold TRs are evidently near the surface while the

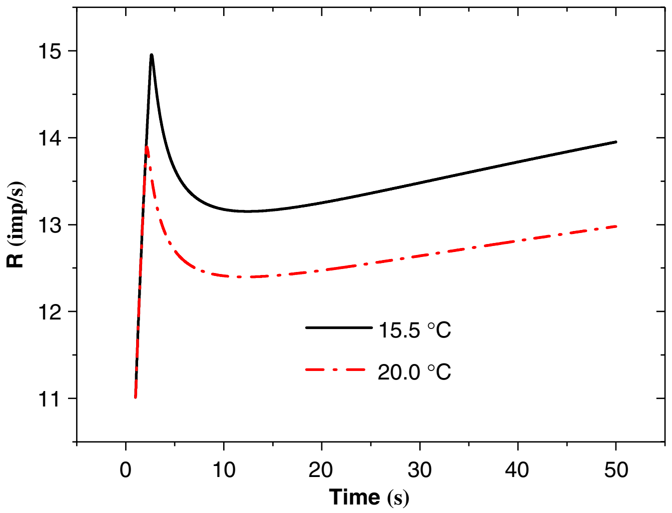
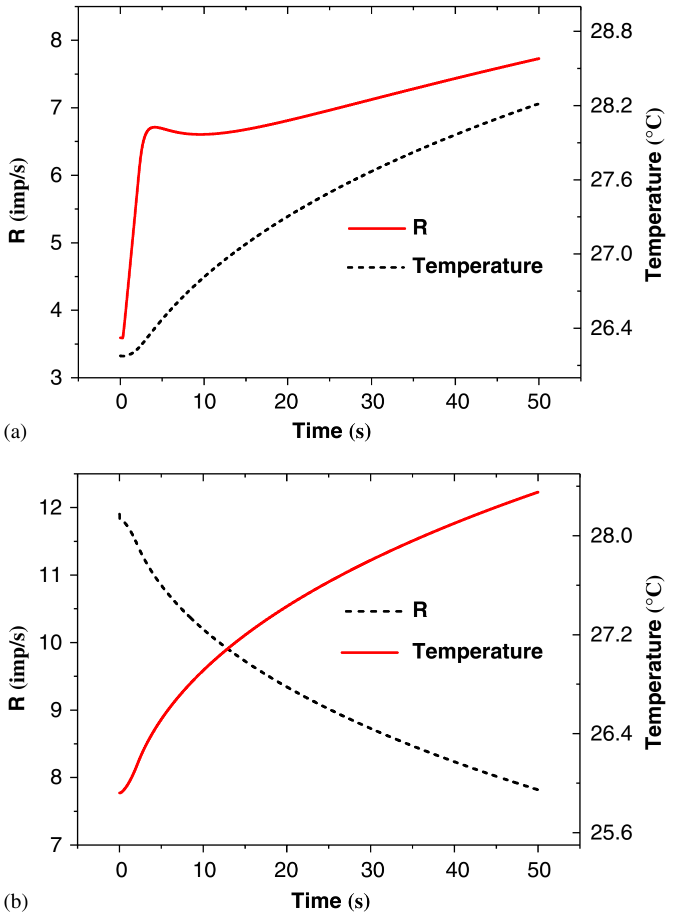


Fig. 5. Dynamic responses of cold TRs when the surrounding temperature changes from 38 to 20 and 15.5 °C at the same rate of 9.0 °C/s.



(a)

(b)

Fig. 6. Response of the warm (a) and cold (b) thermoreceptors when the environmental temperature is changed as $T_f = 20 + 9t$.

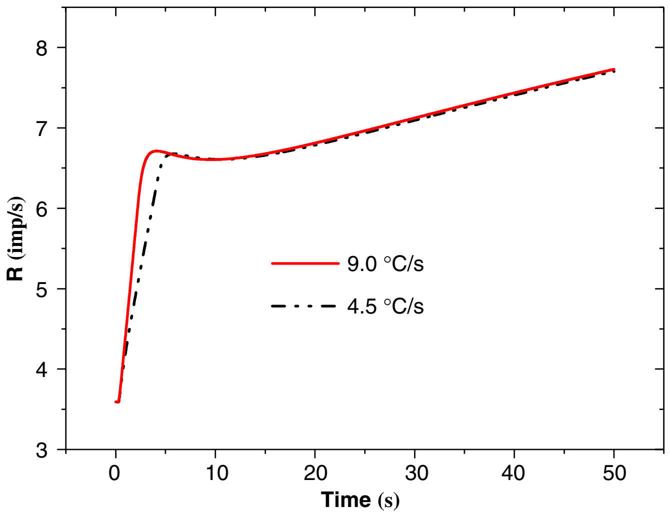


Fig. 7. Dynamic responses of cold TRs when the surrounding temperature changes from 20 to 38 °C at the rates of 9.0 and 4.5 °C/s.

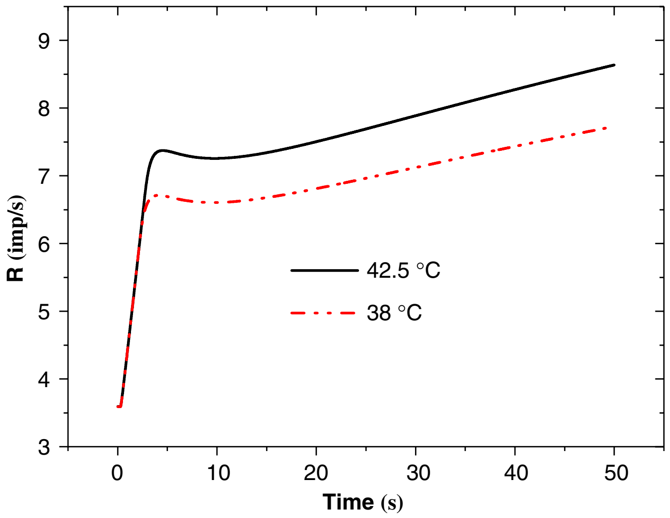


Fig. 8. Dynamic responses of cold TRs when the surrounding temperature changes from 20 to 38 and 42.5 °C at the same rate of 9.0 °C/s.

warm TRs are near the subcutaneous level. Thus, the temperature change rate $\mathrm{d}T/\mathrm{d}t$ of the cold TRs is much higher than that of the warm TRs. Figs. 7 and 8 illustrate the influence of the temperature change rates and intensities on the response of the warm TRs. With the increase of the temperature, the impulse frequency of warm TRs will increase quickly. Compared with that in the cold TRs, the contribution of the dynamic part is much smaller than the static part. It may be because the warm TRs temperature change rate is much smaller than that of the cold TRs.

In general, the skin is much more sensitive to rapid changes of temperature. If the rate of change of skin temperature is sufficiently slow, the process of adaptation may keep up with the change in temperature, so that the change is not felt at all, until the skin temperature finally moves outside the neutral zone. Thus, it is desirable to know which effect is more significant. From the above analysis, one can establish that if the temperature change rate $\mathrm{d}T/\mathrm{d}t$ plays a minor role in TRs' response, the temperature change rate contribution can be neglected. By

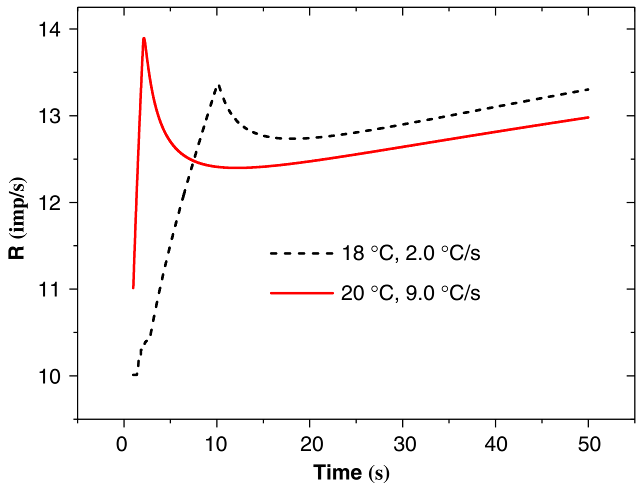


Fig. 9. Dynamic responses of cold TRs under different temperature intensities and change rates stimuli.

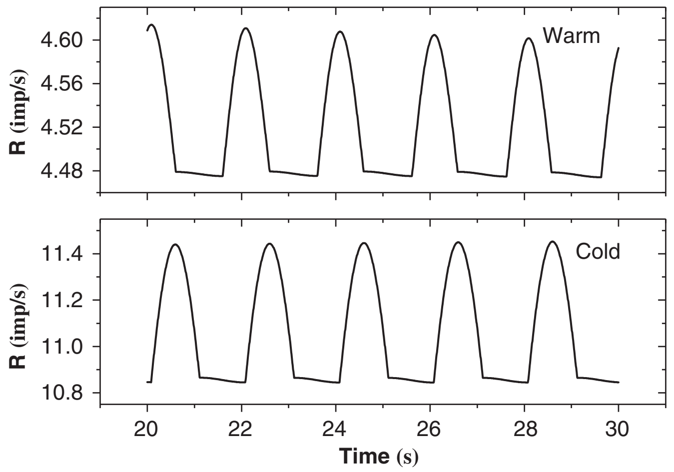


Fig. 10. Dynamic responses of cold TRs when the surrounding air velocity changes as $v = A + \sqrt{2}A\psi\,\sin(2\pi ft)(A = 1.0\,\mathrm{m/s},\ \psi = 0.2,\ f = 0.5\,\mathrm{Hz})$.

analyzing Eqs (1) and (2), one can obtain the quantitative expression to characterize this situation as follows:

For cold TRs:

$$\left|\frac{\partial T(x,t)}{\partial t}\right| \leqslant \frac{1}{10}\left|\frac{-K_s T(x,t)+K_s T_b+b}{K_d}\right|, \quad \partial T/\partial t<0. \tag{9}$$

For warm TRs:

$$\left|\frac{\partial T(x,t)}{\partial t}\right| \leqslant \frac{1}{10}\left|\frac{K_s T(x,t)-K_s T_b}{K_d}\right|, \quad \partial T/\partial t>0. \tag{10}$$

This is a simpler criterion to evaluate the contribution of the temperature change rate when the temperature change rate is very small. On the contrary, one may have misconception when the temperature change rate $\mathrm{d}T/\mathrm{d}t$ plays a significant role in TRs' response. As shown in Fig. 9, for the case of

$$T_f = \begin{cases} 38 - 9t\,^\circ\mathrm{C}, & 0 \leqslant t \leqslant 2\,\mathrm{s}, \\ 20\,^\circ\mathrm{C}, & t > 2\,\mathrm{s}, \end{cases}$$

the peak impulse frequency of cold TRs is higher than that of

$$T_f = \begin{cases} 38 - 2t\,^\circ\mathrm{C}, & 0 \leqslant t \leqslant 10\,\mathrm{s}, \\ 18\,^\circ\mathrm{C}, & t > 10\,\mathrm{s}. \end{cases}$$

Sometimes, we feel that the air temperature appears very low when we come into a cold environment from the hot environment abruptly. In fact, this feeling may be caused by the temperature change rate but not the room air temperature itself.

3.2. *Thermoreceptor response when environmental air movement changes as sinusoidal*

A steady-state air movement of fixed speed and direction is rarely found inside a room. If the velocity of the air movement changes relatively slow, then the average response of the TRs can be found from the appropriate average air speed. Energy conservation also has recently brought substantial attention to the issue of acceptable level of air movement in the office environment. Air movement is one of the most important factors to affect human thermal comfort and is also one of the simplest methods to improve thermal comfort at relatively high temperatures. In summer, many people like to use an ashake electric fan to enhance heat release from the skin. For example, when the fan turns to face our body, the heat convection coefficient increases. However, the heat convection coefficient decreases when the fan changes to other direction. In this case, the frequency of action potential firing will vary with the rotation of the fan, which could change the electrical signal of TRs. For simplicity, we assume that the air velocity changes as

$$v = A + \sqrt{2}A\psi\,\sin(2\pi ft), \tag{11}$$

where A is the average air velocity (m/s), f the frequency of the air movement (Hz), and ψ the pulsant intensity of the air movement. Fig. 10 illustrates the influences of the surrounding air velocity on the cold TRs' response. It is obvious that the peak impulse frequency of the cold TRs is larger than that of the warm TRs. This may imply that people always feel that the cold stimulation is quicker and stronger than warm stimulation. Fig. 11 shows the influence of sinusoidally varying stimuli of differing frequencies on dynamic responses of cold TRs. For the case of $f = 0.5\,\mathrm{Hz}$, the peak impulse frequency of the cold TRs is higher than that of using $f = 1.0\,\mathrm{Hz}$. It seems small frequency sinusoidal stimuli tends to maintain a high-frequency response of the cold TRs. This is because a small-frequency sinusoidal stimuli generates a large temperature change rate. Further, Fig. 12 gives the influence of sinusoidal stimuli intensity on dynamic responses of cold TRs. Clearly, the higher the stimuli intensity, the higher the increase of the response frequency of cold TRs. Fanger et al. [21] has also concluded that airflow with high turbulence caused more complaints of

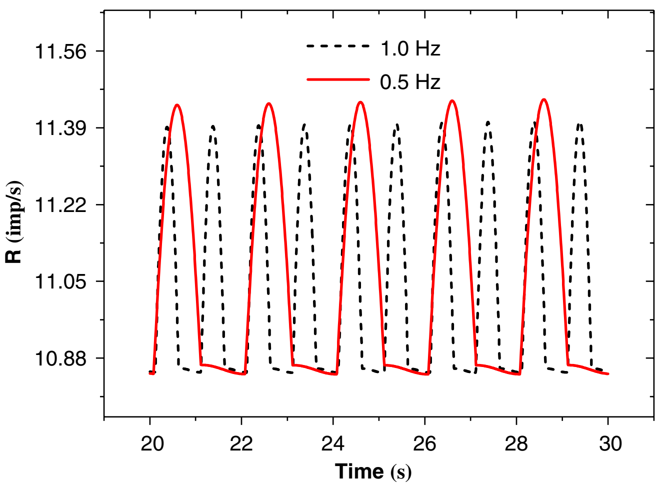


Fig. 11. Influence of sinusoidal stimuli frequency on dynamic responses of cold TRs ($A = 1.0\,\mathrm{m/s}$, $\psi = 0.2$).

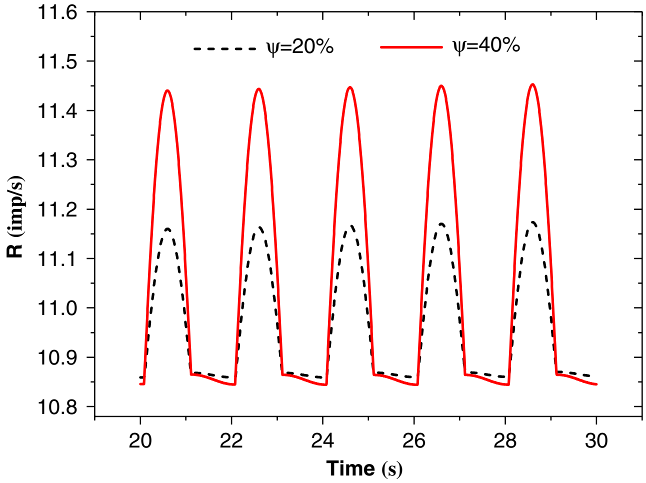


Fig. 12. Influence of sinusoidal stimuli intensity on dynamic responses of cold TRs ($A = 1.0\,\mathrm{m/s}$, $f = 0.5\,\mathrm{Hz}$).

draft than airflow with low turbulence at the same mean velocity and air temperature.

3.3. Influence of environment variables

Many factors influence environmental effects on humans. The individual's psychology and physiology and the organizational and social context in which they function are important [22]. Study of these factors has determined air quality standards. In our research, Eqs. (3)–(5) could be used to show the steady-state temperature of human TRs after being subjected to the environments for 1 h. Then, the influence of environment variables could be studied with this model. We have shown the effect of the blood perfusion and thermal conductivity of tissue on neuron response in previous study [4]. For simplicity, the TRs' depths and skin humidity are specially discussed in the following. The TRs' depths for different people such as young or old have some distinction. Even for the same person, the TRs may embed in different depths at different place. The temperature difference between that at the skin surface and the one at the deep skin is obvious. Thus, the TRs' depths will affect the biological response to the surrounding thermal condition. Fig. 13 depicts the dynamic responses of cold TRs at different depths when the surrounding temperature changes from 38 to 20 °C at the rate of 9.0 °C/s. The TRs near the surface could enhance the response to thermal environmental change. This will help us to better understand that different people may have different sensation to the same thermal condition.

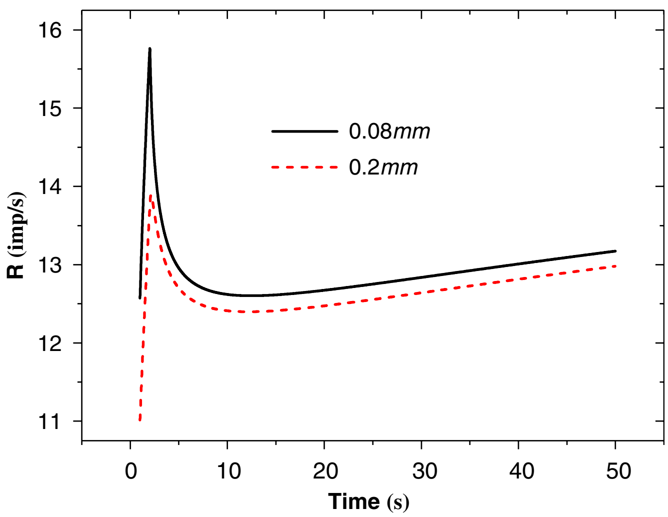


Fig. 13. Dynamic responses of cold TRs at different depths when the surrounding temperature changes from 38 to 20 °C at the rate of 9.0 °C/s.

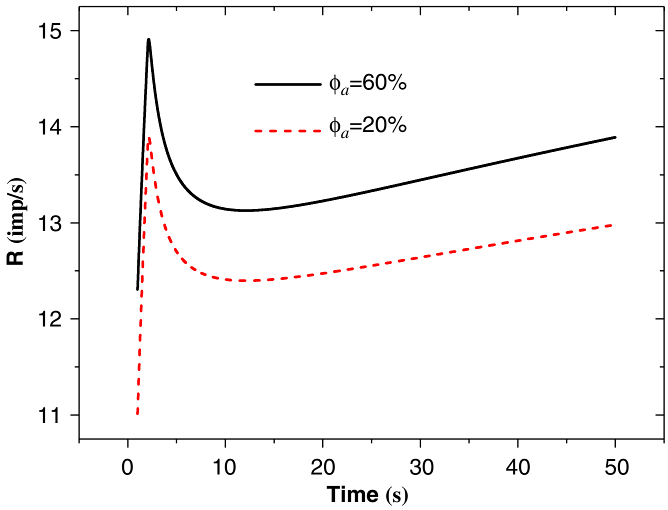


Fig. 14. Effects of skin humidity W_{rsw} on dynamic responses of cold TRs when the surrounding temperature changes from 38 to 20 °C at the rate of 9.0 °C/s.

The production and evaporation of sweat is the body's most powerful temperature control mechanism. If the ambient humidity increases, the skin wetness will increase. It will be seen that skin wetness correlates very well with subjective reports of discomfort and therefore provides a very useful quantitative descriptor. Fig. 14 presents effect of skin humidity W_{rsw} on dynamic responses of cold TRs when the surrounding temperature changes from 38 to 20 °C at the rate of 9.0 °C/s. The frequency of action potential TRs increases with the increase of the skin humidity. This may imply that people do not feel comfortable when the environmental humidity is too high. This accords with our normal cognition. Many people feel more comfortable in a low-humidity environment than in a high-humidity environment. The frequency of TRs changing with the skin humidity may be a fundamental explanation to this phenomenon.

4. Conclusion

The thermal environment is a composite of a number of climatic factors. The major variables include air temperature, air movement, humidity and radiant heat. It also depends upon an individual's response to those climatic factors and is affected, for example, by the level of activity, metabolism, personal health, medication, alcohol consumption, suitability of clothing, level of acclimatization and level and length of exposure to the adverse conditions. Evaluation of a given thermal environment is still too complicated to find a final answer. The present study has investigated the dynamic response of cutaneous thermoreceptors under various environmental conditions. Model developed by Ring and Dear [13] was used to depict the thermoreceptors transient response and a one-dimensional multi-layer finite difference model was developed to calculate transient temperature. Approaches proposed in this paper can possibly identify the difference of the warm and cold thermoreceptors under the same environmental conditions. This difference may be the real mechanism that people are more sensitive to cold stimuli than warm stimuli. However, due to lack of theoretical model on human cutaneous thermoreceptors, especially warm and cold thermoreceptors, the analysis performed in this paper has adopted the model given by Ring and Dear [13]. This model is only suitable for the continuous environmental changes. In practice, airflow in rooms is typically turbulent, i.e. the air velocity fluctuates randomly [8]. All of these uncertain problems require further experimental and theoretical studies in the near future.

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