Dynamic Model of Facial Cooling

PETER TIKUISIS AND RANDALL J. OSCZEVSKI

Defence Research and Development Canada—Toronto, Toronto, Ontario, Canada

(Manuscript received 14 February 2002, in final form 22 May 2002)

ABSTRACT

Recent modifications to windchill forecasting have motivated the development of a rate-of-tissue-cooling model for the purpose of predicting facial cooling times. The model assumes a hollow cylindrical geometry with a fixed internal boundary temperature and adherence to the dimensions and tissue thermal properties of the cheek. Convective and radiative heat exchanges at the skin surface are also taken into account. The explicit finite-difference solution of the thermal conduction problem was applied to predict the transient temperature profile in the cheek model, composed of 25 concentric annular compartments with equally spaced nodes. Model predictions compare favorably to reported incidents of facial frostbite and to several laboratory studies on facial cooling. A sensitivity analysis demonstrates the effect of varying the values of tissue thermal resistance and cheek dimensions on the predicted facial cooling rate.

1. Introduction

The windchill index (WCI) has been widely accepted in the public domain for guidance on the cooling effect of wind during cold-air exposure despite the many errors, limitations, and misconceptions regarding the index (Kessler 1993). Osczevski (1995) addressed the inadequate simulation of the human body with the introduction of a physical model of facial cooling that more accurately reflects the thermal and anatomical properties of the head. Osczevski found that, when compared with the model, the WCI greatly overestimated the rate of heat transfer from bare skin.

Bluestein and Zecher (1999) applied an iterative mathematical procedure that combined conduction, convection, and radiation from a cylindrical annulus to determine steady-state skin temperatures. They concluded that the effects of wind have been exaggerated by the WCI, in concurrence with the findings of Osczevski (1995). Osczevski (2000) more recently proposed the determination of windchill from the windward side of a vertical cylinder as a more realistic representation of facial cooling. This proposal subsequently formed the basis of a model that has been widely adopted for predicting a new windchill index (available online at the time of writing at http://www.msc.ec.gc.ca/windchill/index_e.cfm and www.nws.noaa.gov/om/windchill/). This new index will be referred to herein as windchill 2001 to distinguish it from the original WCI.

These recent developments have motivated this study to model the rate of tissue cooling for the purpose of predicting facial cooling times and specifically predicting the onset of freezing. Windchill charts (eg., Osczevski 1995) indicate the risk of tissue freezing, but given the misconceptions uncovered with the original development of the WCI, a reexamination of these risks is warranted. For example, a WCI of 2132 W m^{-2} (2000 kcal m^{-2} h^{-1}) is associated with a risk of facial frostbite in 1 min. Yet, in the original source (Siple and Passel 1945) of this declaration, the freezing time is also reported to be approximately 6 min for the cheeks vs 30–120 s for the nose. Such variations in freezing time relate to, among other factors, differences in the size and shape of specific facial features, and they should be discernible through a theoretical/modeling analysis.

Brauner and Shacham (1995) developed an analytical model of tissue cooling based on heat transfer through tissue of semi-infinite extent. Their additional development of a finite-slab model yielded predictions that they considered too liberal by comparison, and therefore they recommended use of the semi-infinite version. However, this version is valid only for short exposure times (relative to tissue thickness), and it has not been validated against human exposure data.

Herein, by using numerical procedures, we develop a tissue-cooling model that is constrained neither by exposure time nor by body shape or size. The present focus, however, is on facial cooling, as advocated by Osczevski (1995, 2000) and intrinsic in windchill 2001. We specifically address the dynamic aspect of cheek cooling and compare the model predictions with several reported observations.

2. Model development

The model construction is based on the conventional assumption of a cylindrical geometry (Steadman 1971;

Corresponding author address: Dr. Peter Tikuisis, Defence Research and Development Canada—Toronto, 1133 Sheppard Ave. West, P.O. Box 2000, Toronto, ON M3M 3B9, Canada.
E-mail: peter.tikuisis@drdc-rddc.gc.ca

Brauner and Shacham 1995). The steady-state facial skin temperature can be obtained by equating the rate of heat transfer through the facial "shell" to the rate of heat removal from the facial surface at steady state. The resultant rate of conductive heat transfer through the shell (W m^{-2}) is given by

$$q_{\mathrm{cond}} = \frac{(T_c - T_s)}{R}, \qquad (1)$$

where R is the thermal resistance (m^2 K W^{-1}) of the entire shell and T_c and T_s refer to the core and skin temperatures, respectively. In this application, the core temperature is represented by the interior surface of the cheek.

The rate of convective heat removal from the facial surface is given by

$$q_{\mathrm{conv}} = h_c(T_s - T_a), \qquad (2)$$

where h_c is the forced convective heat transfer coefficient (W m^{-2} K^{-1}) and T_a is the air temperature. The convective heat transfer coefficient depends on the shape of the object being cooled, through the Nusselt number Nu

$$h_c = \frac{\mathrm{Nu}k_{\mathrm{air}}}{2r_s}, \qquad (3)$$

where k_{air} is the thermal conductivity (W m^{-1} K^{-1}) of air and r_s is the facial radius (m). The appropriate expression for facial cooling at the cheek level is given by (Kreith 1976)

$$\mathrm{Nu} = 1.14\mathrm{Re}^{0.5}\mathrm{Pr}^{0.4}[1 - (50/90)^3], \qquad (4)$$

where (50/90) represents the angular orientation of the cheek relative to a frontal wind. At an angle of 50°, the local heat transfer coefficient is also approximately equal to the average for the front 160° of a cylinder. Here, Re and Pr are the Reynolds and Prandl numbers, respectively, given by (Sissom and Pitts 1972)

$$\mathrm{Re} = \frac{2r_s v\rho_{\mathrm{air}}}{\mu} \quad \text{and} \qquad (5)$$

$$\mathrm{Pr} = \frac{\mu c_{\mathrm{air}}}{k_{\mathrm{air}}}, \qquad (6)$$

where v is the wind speed (m s^{-1}), μ is the dynamic viscosity of air (kg m^{-1} s^{-1}), and ρ_{air} and c_{air} are the density (kg m^{-3}) and specific heat (J kg^{-1} K^{-1}) of air, respectively, all at the mean of skin and air temperature.

The rate of radiative heat transfer from the cylindrical surface is given by

$$q_{\mathrm{rad}} = h_r(T_s - T_r), \qquad (7)$$

where h_r is the radiative heat transfer coefficient (W m^{-2} K^{-1}) given by (Nishi 1981)

$$h_r = 4\varepsilon\sigma[273.15 + (T_s + T_r)/2]^3, \qquad (8)$$

and where ε is the emissivity of skin (assumed equal to unity), σ is the Stefan–Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), and T_r is the mean radiant temperature approximated by

$$T_r = 0.5(T_a + T_\infty), \qquad (9)$$

T_∞ is the effective atmospheric radiant temperature (K), or clear-sky temperature, determined by (Lunardini 1981)

$$T_\infty = T_a(0.6 + 0.05\sqrt{P_a})^{0.25}, \qquad (10)$$

where the term in parentheses is the emissivity of the clear sky and P_a is the ambient vapor pressure (hPa). All predictions reported herein assume a relative humidity of 50%, although T_r is decreasingly sensitive to humidity with increasing cold. Under indoor conditions, T_∞ assumes the ambient temperature.

By equating q_{cond} [Eq. (1)] to the sum of Eqs. (2) and (7) [evaporative heat loss is assumed to be negligible under the dry, cold skin conditions considered herein (Tikuisis 1999)], we obtain the steady-state skin temperature,

$$T_{ss} = \frac{R(h_c T_a + h_r T_r) + T_c}{R(h_c + h_r) + 1} \qquad (11)$$

We now apply the explicit finite-difference solution of the thermal conduction problem through a cylindrical shell (Ozisik 1968) to predict the transient temperature distribution in the shell. The shell is composed of concentric annular compartments with equally spaced nodes from the inner ($n = 1$) to the outer ($n = N$) boundaries. Upon exposure to cold air, the heat balance in the outermost shell ("skin" layer) is affected first, and over time all compartments settle toward a new steady-state temperature distribution. It is also inherently assumed that the cheek thermal resistance undergoes an instantaneous change to reflect a vasomotor change upon exposure to cold. The final skin temperature must evolve to the value predicted by Eq. (11). The inner boundary is assumed to have a constant fixed temperature. During the transient phase, the change in the other nodal temperatures is predicted by the thermal diffusion equation,

$$\frac{\Delta T_n}{\Delta t} = \frac{k_{\mathrm{tis}}}{\rho_{\mathrm{tis}} c_{\mathrm{tis}}}\nabla^2 T_n, \qquad (12)$$

where ∇ is the differential operator, Δt is the time step (s) (its value is chosen to be sufficiently small to ensure a convergent solution), ρ_{tis} and c_{tis} are the density (kg m^{-3}) and specific heat (J kg^{-1} K^{-1}) of the tissue shell region, respectively, and k_{tis} is the tissue thermal conductivity (W m^{-1} K^{-1}) defined by (Sekins and Emery 1982)

$$k_{\mathrm{tis}} = \frac{r_N \ln(r_N/r_1)}{R}, \qquad (13)$$

where r is the nodal radius. Note that N and s are interchangeable subscripts (both refer to the skin surface), depending on usage.

TABLE 1. Model parameter values.

Parameter	Value	Source
Outer shell radius r_N	0.069 m	Donelson and Gordon (1991)
Cheek thickness $(r_N - r_1)$	0.012 m	Measured
Nodal spacing Δr	0.000 48 m	Based on 25 compartments
Thermal resistance R	0.05 m^2 K W^{-1}	Osczevski (1995)
Density ρ_{tis}	1000 kg m^{-3}	Sekins and Emery (1982)
Specific heat c_{tis}	3000 J kg^{-1} K^{-1}	Sekins and Emery (1982)
Inner cheek temperature T_i	34°C	Beynon (1973)
Initial skin temperature T_{so}	32°C	Gavhed et al. (2000)
Time step Δt	0.5 s	Fixed

The numerical solution of the Laplacian of the interior nodes ($2 \le n \le N - 1$) is given by (Ozisik 1968)

$$\nabla^2 T_n = \left(\frac{1}{\Delta r^2}\right)\left[\left(1 - \frac{\Delta r}{2r_n}\right)T_{n-1} + \left(1 + \frac{\Delta r}{2r_n}\right)T_{n+1} - 2T_n\right], \quad (14)$$

where Δr is the nodal spacing ($=r_n - r_{n-1}$). The Laplacian of the outer node or skin surface is given by

$$\nabla^2 T_N = \frac{2}{\Delta r^2}(T_{N-1} - T_N) + \frac{2}{k\Delta r}\left(1 + \frac{\Delta r}{2r_N}\right)[h_c(T_a - T_N) + h_r(T_r - T_N)] \quad (15)$$

Model predictions are based on a 25-compartment configuration using the parameter values displayed in Table 1. The number of nodes employed was chosen to ensure an accurate determination of the temperature gradient within the tissue, which was tested separately by comparison with known solutions of heat conduction. The outer shell radius is the average of values based on the measurement of the bizygomatic breadth (upper cheek) of 487 males (Donelson and Gordon 1991). The inherent assumption is that the larger breadth of the upper cheek (as compared with its midpoint) more closely represents the actual diameter of the cheek midpoint given that the bizygomatic breadth is not aligned with the central axis of the head. A cheek thickness ($r_N - r_1$) of 12 mm was based on the average of six males measured in our laboratory with calipers. The thermal resistance of 0.05 m^2 K W^{-1} approximates the average value measured over a wide range of cheek skin temperatures (Osczevski 1995). The resultant thermal conductivity of 0.26 W m^{-1} K^{-1} [Eq. (13)] concurs with the value for poorly perfused cold tissue (Sekins and Emery 1982). The inner cheek temperature of 34°C was arbitrarily chosen within the range reported for closed mouth conditions (Beynon 1973). The initial skin temperature of 32°C pertains to a thermoneutral condition (Gavhed et al. 2000), and the initial nonlinear temperature profile through the cheek was calculated by assuming a steady-state condition.

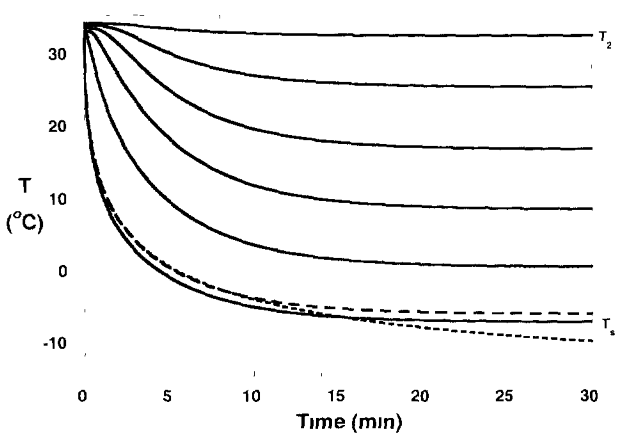

FIG. 1. Predicted cheek temperature profiles plotted against time for an outdoor exposure to −20°C and 16 m s^{-1} wind. The solid profiles refer to the temperatures of evenly spaced nodes, and T_s and T_2 refer to the temperatures of the skin surface and the first node (out of 26) adjacent to the inner cheek boundary, respectively. The dotted line refers to the prediction of the facial cooling model [Eq. (16)] of Brauner and Shacham (1995), and the dashed line refers to the current model prediction assuming the parameters in Table 1 and neglecting radiative heat loss.

3. Results

a. *Tissue temperature profiles*

Figure 1 shows the predicted temperature profiles of the 25-compartment model for a 30-min outdoor exposure to −20°C and 16 m s^{-1} wind (at face level) using the parameter values in Table 1. This condition pertains to a WCI of 2088 W m^{-2} (1800 kcal m^{-2} h^{-1}) (Siple and Passel 1945). Steady state of the skin temperature is nearly reached after the 30-min exposure at a predicted value of −7.6°C. Subzero temperatures are also predicted to penetrate 2.3 mm into the cheek at this time. Tissue temperatures below −5°C are predicted to penetrate only within 0.9 mm of the skin surface.

Superimposed on Fig. 1 is the predicted T_s from the facial-cooling model derived by Brauner and Shacham (1995)

$$T_s = T_a + (T_{so} - T_a)\exp(\xi^2)\,\mathrm{erfc}(\xi), \quad \text{where} \quad (16)$$

$$\xi = h_c\sqrt{\frac{t}{k_{tis}\rho_{tis}c_{tis}}} \quad (17)$$

TABLE 2. Prediction of steady-state cheek skin temperatures for various combinations of air temperature and wind speed. WCI is the original windchill index (Siple and Passel 1945) shown in SI units and kcal m^{-2} h^{-1} in square brackets. Windchill 2001 values are the new windchill equivalence temperatures. The last two columns show the predicted times to skin temperatures of −1° and −4.8°C, respectively (not attained indicated by "—").

WCI (W m^{-2})	T_a (°C)	v (m s^{-1})	Windchill 2001 (°C)	T_{cheek} (°C)	t (min) to −1°C	t (min) to −4.8°C
1740	−11	23	−27	−2.1	11.6	—
[1500]	−16	10	−31	−2.6	12.4	—
	−23	4.5	−35	−3.2	13.1	—
2088	−20	16	−39	−7.6	4.8	8.8
[1800]	−36	4.5	−52	−11.2	5.3	8.0
2320	−34	7.5	−53	−13.4	3.7	5.6
[2000]	−45	4.5	−64	−16.7	3.6	5.1

Equation (16) is based on a semi-infinite mass characterized by the thermal properties of the cheek. Also shown on Fig. 1 is the current model prediction neglecting the radiative component of heat transfer [as is the case in Eq. (16)] for comparative purposes. Both approximations yield similar rates of facial cooling during the first several minutes of exposure, and they indicate a slightly lower cooling rate because of the absence of radiative heat loss. However, the model prediction of Brauner and Shacham begins to diverge to increasingly lower skin temperatures as expected given that $T_s \rightarrow T_a$ as $t \rightarrow \infty$ in Eq. (16). Indeed, Brauner and Shacham acknowledged that their model is limited to relatively short exposure times.

b. Comparison with reported observations

Wilson (1967) reported on several cases of frostbite in the Antarctic. Specific sites were not identified except for cases of finger frostbite that were reported to occur at WCI values below 1624 W m^{-2} (1400 kcal m^{-2} h^{-1}) and are ignored in the current analysis. Table 2 shows the predicted steady-state skin temperatures for various combinations of air temperature and wind speed (at 1.5 m off the ground) recorded at the time of the incidents. The cases shown were purposely selected according to various WCI values [1740 W m^{-2} (1500 kcal m^{-2} h^{-1}) is the least severe condition for which facial frostbite was reported and for which wind speed was known]. Also shown are the new windchill 2001 values and the predicted times to skin temperatures of −1° and −4.8°C, the former considered to be the minimum temperature required for tissue freezing (Keatinge and Cannon 1960) and the latter considered to represent a 5% risk of freezing (Danielsson 1996). Not surprising, the predicted steady-state skin temperatures decrease with increasing severity of the cold stress. These values are also approximately proportional to the windchill 2001 values, as expected.

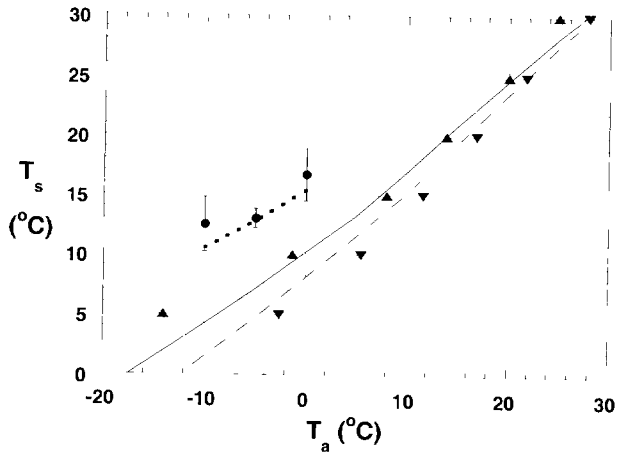

FIG. 2. Comparison of model-predicted (lines) and measured (±std dev where indicated) cheek skin temperatures after 10 min of exposure to various combinations of air temperature and wind speed. Shown are the data of Tochihara et al. (1996) for v = 2 m s^{-1} (●) and LeBlanc et al. (1976) for v = 8.9 (▲) and 17.8 m s^{-1} (▼). The respective model predictions are indicated by the dotted, solid, and dashed lines.

Figure 2 shows good agreement between the model and the measured cheek skin temperatures from two studies involving 10-min cold exposures. In the study by Tochihara et al. (1996), four males were exposed to air temperatures of 0°, −5°, and −10°C at a wind speed of 2 m s^{-1}. In the other study, LeBlanc et al. (1976) measured the cheek temperature of 25 males exposed to various combinations of air temperature (from −20° to 24°C) and wind speed (up to 17.9 m s^{-1}). The latter investigators regressed their data to isolate specific combinations of T_a and v that would result in cheek skin temperatures from 5° to 30°C after 10 min of exposure, as shown without any variances in Fig. 2. Data for wind speeds of less than 8.9 m s^{-1} from LeBlanc et al. were excluded from the current analysis because the reported skin temperatures are considered to be unrealistically high (Steegmann 1979). The model agreement shown in Fig. 2 for these data was obtained by applying a temperature-dependent thermal resistance of the cheek based on the findings of Osczevski (1995). This variability in R (from about 0.03 to 0.07 m^2 K W^{-1}) likely reflects changes in tissue perfusion, which is known to affect thermal conductivity (Tikuisis and Ducharme 1991). The effect of changes in R on the facial cooling rate and steady-state temperatures is examined further below.

Figure 3 shows the mean cheek temperature of six caucasian males exposed to 0°C at 3 m s^{-1} for 70 min, as reported by Steegmann (1979). Also shown is the model temperature profile using the parameter values described earlier (including the variability in R as applied above) except for the cheek thickness. In this instance, Steegmann (1972) reported the same bizygomatic breadth as used herein (i.e., r_N = 0.069 m) but a markedly reduced cheek thickness of 0.007 m than was

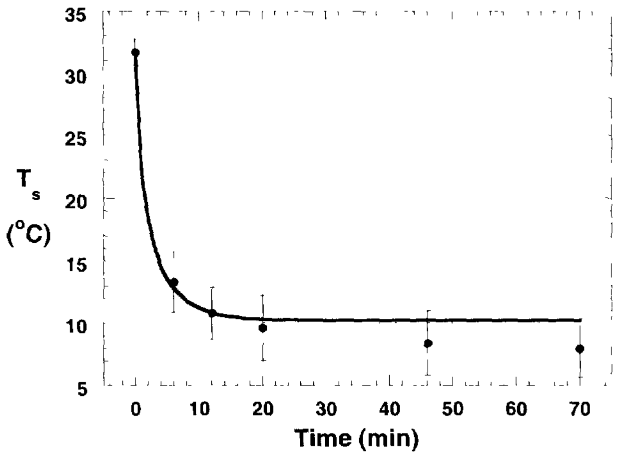

FIG. 3. Comparison of model-predicted (line) and measured (● ± std dev, Steegmann 1979) cheek skin temperatures for an exposure to 0°C and 3 m s^{-1} wind for 70 min.

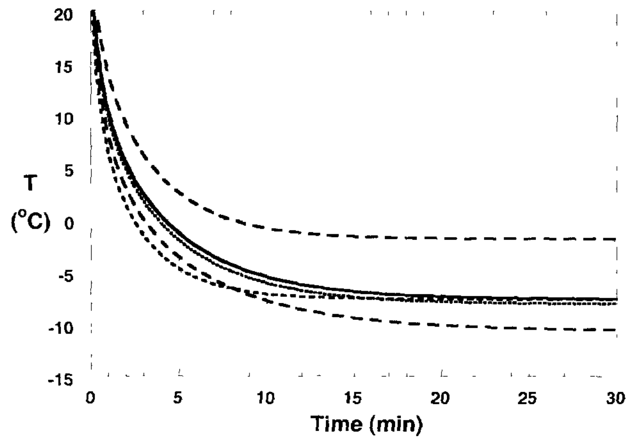

FIG. 4. Predicted cheek skin temperatures for an outdoor exposure to −20°C and 16 m s^{-1} wind. The solid line pertains to the model parameters given in Table 1. The upper and lower long-dashed lines pertain to thermal resistance values of 0.03 and 0.07 m^2 K W^{-1}, respectively. The short-dashed line pertains to a cheek thickness of 0.007 m (vs 0.012 m for the solid line), and the dotted line pertains to a cheek radius of 0.062 m (vs 0.069 m for the solid line).

incorporated in the current analysis. As can be seen, the resultant temperature profile falls within the variance of the measured cheek temperatures.

In the final experiment that we examine, Gavhed et al. (2000) exposed eight male subjects to −10°C at wind speeds of 1 and 5 m s^{-1} for 30 min. Although their data display similarly rapid initial decreases in cheek skin temperature as in the other studies, the data were not tabulated and thus cannot be easily reproduced for comparison with the model prediction. Instead, we note that the subjects' mean cheek skin temperatures were approximately 15° and 8°C for the light and moderate wind speed conditions, respectively, after 30 min of exposure. By decreasing the thermal resistance from 0.05 to 0.04 m^2 K W^{-1} (which lies within the acceptable range) and without changing any other parameters listed in Table 1, model temperatures of 15.0° and 7.7°C were obtained for these respective exposures.

c. *Sensitivity analysis*

We now consider the effect of changes in a few key parameters on the model prediction. The variables under consideration are thermal resistance R, inner cheek temperature T_c, the cheek radius r_N, and the cheek thickness ($r_N - r_i$). Variation in R, as measured by Osczevski (1995), is attributed to changes in tissue perfusion (Tikuisis and Ducharme 1991). The latter two anatomical parameters are particularly relevant to populations (e.g., females) not considered in the above analyses. Using the conditions of Fig. 1 as a reference, predictions of skin temperature are shown in Fig. 4 for variations in the above parameters. For example, increasing or decreasing R by 0.02 m^2 K W^{-1} markedly enhances/reduces the cooling rate and, respectively, decreases/increases the final or steady-state temperature.

The steady-state skin temperature T_{ss} is predicted to increase or decrease from −7.6° to −6.9° or −8.3°C for an increase or decrease from T_c = 34° by 3°C, respectively. The effect of this change in T_c on the rate of skin cooling is somewhat less pronounced: times to −1° and −4.8°C respectively become 5.0 and 10.0 min or 4.6 and 8.1 min as compared with the baseline values of 4.8 and 8.8 min.

Decreasing cheek thickness causes more rapid cooling without affecting the final skin temperature because the cooling rate [Eq. (12)] is governed by the cheek thickness [via Eq. (13)] whereas the steady-state temperature [Eq. (11)] remains unchanged. This is in contrast to the effect of a smaller cheek radius, which both increases the cooling rate and lowers the steady-state temperature. Although the effect is relatively small by the example shown in Fig. 4 where r_N was decreased by only 10%, this example nevertheless demonstrates the enhanced vulnerability of those regions of the body that are considerably smaller in dimension such as the nose and fingers, as amply documented by others (Wilson 1967, Danielsson 1996).

4. Discussion

Skin freezing is predicted to occur in 1 min according to a WCI of 2320 W m^{-2} (2000 kcal m^{-2} h^{-1}) (Siple and Passel 1945, Osczevski 1995). This time is considerably shorter than the current model prediction of 3–6 min (Table 2). However, the shorter time pertains to small narrow body segments such as the nose. Indeed, Siple and Passel (1945) reported faster freezing times of the nose as compared with the cheeks. For example, at −32.5°C and 7 m s^{-1}, the nose freezes in approximately 1 min, whereas the cheeks and the side of the temple were reported to freeze in just over 6 min. According to the present model prediction, the cheek skin temperature would reach −1° and −4.8°C in 4.3 and 6.5 min, respectively, using the parameter values of Table 1. Under a more severe condition of WCI = 2677 W m^{-2} (2308 kcal m^{-2} h^{-1}), Siple and Passel reported a cheek freezing time of about 2 min in concurrence with the model prediction of, for example, 1.7 and 2.5 min to cheek temperatures of −1° and −4.8°C, respectively, for an outdoor exposure to −37.5°C and 15 m s^{-1} wind. Thus, the model predictions are generally consistent with the reported rates of cheek cooling, whether outdoors or under laboratory conditions.

The example exposure shown in Fig. 1 demonstrates the enhancement of facial cooling through radiative heat loss, but not to a great extent. Sunshine, on the other hand, can have a greater effect. Sunshine was excluded from the analysis, because it did not pertain to the experimental data that were examined. For completeness, however, one can incorporate into Eqs. (11) and (15) the additional heat transfer caused by sunshine on the skin if one had knowledge of the solar radiation incident on the skin surface. Its value is governed by such factors as the direction of solar radiation, cloud cover, skin reflectivity, and so on. The model prediction of cheek cooling excluding sunshine can thus be considered as conservative.

The variation in tissue thermal resistance, as required to fit the model to certain observations of facial cooling cited herein, has been attributed to changes in tissue perfusion. Peripheral tissue perfusion is regulated according to the thermal status of the individual, which can be affected by any number of factors, including clothing and activity. For example, a decrease in R can be expected with increased tissue blood perfusion as occurs with increased heat gain through physical activity (Beynon 1973). A decrease in R increases the rate at which heat reaches the skin, and is characteristic of an adaptation to cold (Young 1986). It also increases the rate of heat loss, but this disadvantage is overwhelmingly compensated by a lowered risk of freezing, in contrast to an increase in R, as demonstrated in Fig. 4. In this example, the decrease in R (from 0.05 to 0.03 m^2 K W^{-1}) yields tissue temperatures of greater than −2°C. The increase in local heat flux [via Eq. (1)] and consequent increase in metabolic cost to maintain this elevated temperature at steady state is 363 W m^{-2}, or 44% higher than the heat flux when R = 0.05 m^2 K W^{-1}. Although this increase might seem substantial, the area involved is less than 0.04 m^2 so that the net metabolic cost is very small. Thus, it would be prudent to remain physically active during cold exposure, not only to maintain a warm core temperature, but also to lessen the risk of frostbite.

REFERENCES

Beynon, A., 1973: Effects of an Antarctic environment on dental structures and health. *Polar Human Biology*, O. Edholm and E. Gunderson, Eds., Heinemann Medical Books, Chichester, United Kingdom, 105–113.

Bluestein, M., and J. Zecher, 1999: A new approach to an accurate wind chill factor. *Bull. Amer. Meteor. Soc.*, **80**, 1893–1899.

Brauner, N., and M. Shacham, 1995: Meaningful wind chill indicators derived from heat transfer principles. *Int. J. Biometeor.*, **39**, 46–52.

Danielsson, U., 1996: Windchill and the risk of tissue freezing. *J. Appl. Physiol.*, **81**, 2666–2673.

Donelson, S. M., and C. C. Gordon, 1991: 1988 anthropometric survey of U.S. Army personnel: Pilot summary statistics. U.S. Army Natick RD&E Center, Natick, MA, Tech. Rep. NATICK/TR-91/040, 614 pp.

Gavhed, D., T. Makinen, I. Holmer, and H. Rintamaki, 2000: Face temperature and cardiorespiratory responses to wind in thermoneutral and cool subjects exposed to −10°C. *Eur. J. Appl. Physiol.*, **83**, 449–456.

Keatinge, W. R., and P. Cannon, 1960: Freezing-point of human skin. *Lancet*, **1**, 11–14.

Kessler, E., 1993: Wind chill errors. *Bull. Amer. Meteor. Soc.*, **74**, 1743–1744.

Kreith, F., 1976: *Principles of Heat Transfer*. New York Intext Educational Publishers, 656 pp.

LeBlanc, J., B. Blais, B. Barabe, and J. Cote, 1976: Effects of temperature and wind on facial temperature, heart rate, and sensation. *J. Appl. Physiol.*, **40**, 127–131.

Lunardini, V. J., 1981: *Heat Transfer in Cold Climates*. Van Nostrand Reinhold, 731.

Nishi, Y., 1981: Heat exchange between human body and environment. *Thermophysiology*, T. Nakayama, Ed., Rikogakusha, Tokyo, Japan, 33–72.

Osczevski, R. J., 1995: The basis of wind chill. *Arctic*, **48**, 372–382.

——, 2000: Windward cooling: An overlooked factor in the calculation of wind chill. *Bull. Amer. Meteor. Soc.*, **81**, 2975–2978.

Ozisik, M. N., 1968: *Boundary Value Problems of Heat Conduction*. International Textbook, 505 pp.

Sekins, K. M., and A. F. Emery, 1982: Thermal science for physical medicine. *Therapeutic Heat and Cold*, J. F. Lehmann, Ed., Williams & Wilkins, 84 pp.

Siple, P. A., and C. F. Passel, 1945: Measurements of dry atmospheric cooling in subfreezing temperatures. *Proc. Amer. Philos. Soc.*, **89**, 177–199.

Sissom, L. E., and D. R. Pitts, 1972: *Elements of Transport Phenomena*. McGraw-Hill, 814 pp.

Steadman, R. G., 1971: Indices of windchill of clothed persons. *J. Appl. Meteor.*, **10**, 674–683.

Steegmann, A. T., 1972: Cold response, body form, and craniofacial shape in two racial groups of Hawaii. *Amer. J. Phys. Anthropol.*, **37**, 193–222.

——, 1979: Human facial temperatures in natural and laboratory cold. *Aviat. Space Environ. Med.*, **50**, 227–232.

Tikuisis, P., 1999: Considerations for the measurement and analysis of heat debt for cold exposure. *J. Human-Environ. Syst.*, **2**, 9–18.

——, and M. B. Ducharme, 1991: Finite-element solution of thermal conductivity of muscle during cold water immersion. *J. Appl. Physiol.*, **70**, 2673–2681.

Tochihara, T., G. Ohlsson, E. Karlsson, D. Gavhed, and I. Holmer, 1996: Effects of facial cooling on thermal responses of humans. *Environmental Ergonomics: Recent Progress and New Frontiers*, Y. Shapiro, D. S. Moran, and Y. Epstein, Eds., Freund, Tel Aviv, Israel, 127–130.

Wilson, O., 1967: Objective evaluation of wind chill index by records of frostbite in the Antarctica. *Int. J. Biometeor.*, **11**, 29–32.

Young, A. J., 1986: Human adaptation to cold. *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes*, K. B. Pandolf, M. N. Sawka, and R. R. Gonzalez, Eds., Cooper, 401–434.