Windchill and the risk of tissue freezing

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Danielsson, Ulf. Windchill and the risk of tissue freezing. J. Appl. Physiol. 81(6): 2666–2673, 1996.—Low air temperatures and high wind speeds are associated with an increased risk of freezing of the exposed skin. P. A. Siple and C. F. Passel (Proc. Am. Phil. Soc. 89: 177–199, 1945) derived their wind-chill index from cooling experiments on a water-filled cylinder to quantify the risk of frostbite. Their results are reexamined here. It is found that their wind-chill index does not correctly describe the convective heat transfer coefficient (hc) for such a cylinder; the effect of the airspeed (v) is underestimated. New risk curves have been developed, based on the convection equations valid for cylinders in a cross flow, h_c \sim v^{0.62}, and tissue freezing data from the literature. An analysis of the data reveals a linear relationship between the frequency of finger frostbite and the surface temperature. This relation closely follows a normal distribution of finger-freezing temperatures, with an SD of 1°C. As the skin surface temperature falls from −4.8 to −7.8°C, the risk of frostbite increases from 5 to 95%. These data indicate that the risk of finger frostbite is minor above an air temperature of −10°C, irrespective of v, but below −25°C there is a pronounced risk, even at low v.

It is well known that wind increases the risk of frostbite during exposure in a cold climate. The explanation is that increased airspeeds enhance heat transfer from the body. This effect was quantified by Siple and Passel in the 1940s (20). They measured the time needed for water, inside a cylinder, to freeze during exposure to various combinations of airspeed and temperature. From these data, they developed the so-called windchill index (WCI) for predicting the heat transfer rate from nude body parts. In addition, they exposed bare skin to different climates and observed at what rate from nude body parts. It is found that their windchill index does not correctly describe the convective heat transfer coefficient (h_c) for such a cylinder; the effect of the airspeed (v) is underestimated. New risk curves have been developed, based on the convection equations valid for cylinders in a cross flow, h_c \sim v^{0.62}, and tissue freezing data from the literature. An analysis of the data reveals a linear relationship between the frequency of finger frostbite and the surface temperature. This relation closely follows a normal distribution of finger-freezing temperatures, with an SD of 1°C. As the skin surface temperature falls from −4.8 to −7.8°C, the risk of frostbite increases from 5 to 95%. These data indicate that the risk of finger frostbite is minor above an air temperature of −10°C, irrespective of v, but below −25°C there is a pronounced risk, even at low v.

The purpose of this study was to find explanations for the lack of consistency between different studies on the risk of frostbite. A physical approach is used to as a basis for modeling the risk of frostbite, unless the origins of the conflicting results are understood. Possible explanations for the discrepancies are that there are differences within and between groups of individuals regarding, for example, the temperature at which skin freezes, the blood flow, and thus the heat input to the skin. Other sources of variation are methodology, e.g., measurements of temperature and heat loss.

The airflow characteristics around a circular cylinder depend strongly on the Reynolds number (Re) [no dimensions (ND)], given by

\[ Re = \frac{v \cdot D}{v} \] (1)

where

\[ v \] is the airspeed,

\[ D \] is the diameter of the cylinder,

\[ v \] is the kinematic viscosity of the air.

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where \( v \) (m/s) is the airspeed, \( D \) (m) is the diameter of the cylinder, and \( \nu \) (m²/s) is the kinematic viscosity. Hilpert (9) found that the average Nusselt number, \( \text{Nu} \) (ND), for a cylinder could be written as

\[
\text{Nu} = \frac{h_r}{\nu D} = 0.193 \cdot R_e^{0.62} \cdot Pr^{1/3}
\]

(2)

where \( h_r \) (W·m⁻²·K⁻¹) is the forced convection coefficient, \( \lambda \) (W·m⁻¹·K⁻¹) is the thermal conductivity of the surrounding medium, and \( Pr = \nu \alpha / \lambda \) is the Prandtl number (ND), where \( \alpha \) is the thermal diffusivity (m²/s). Hilpert found that under atmospheric conditions this formula could also be used for noncircular cylinders, where \( d \) is the diameter measured at right angles to the wind direction.

\[
h_r = 4.47 \cdot d^{0.38} \cdot \nu^{0.62}
\]

(3)

for an air temperature of \(-25^\circ \text{C}\). At \(0^\circ \text{C}\), the coefficient decreases from 4.47 to 4.37. The equation obtained by Daniels-Heiser (6) has shown that if \( Fo \) is

\[
\ln(\frac{T_i}{Tam}) - \frac{1}{2} \left( \frac{r_2}{r_1} \right)^{2} \cdot \ln(\frac{r_2}{r_1}) \cdot \lambda \cdot (\frac{r_2}{r_1}) \cdot L
\]

(7)

where \( T_i \) (°C) is the temperature of the inner surface of the innermost layer and \( T_{am} \) (°C) is the ambient temperature. The radii (m) \( r_1 \) and \( r_2 \) denote the inner radii of the first and second layers, respectively, and \( r_3 \) is the outer radius of the cylinder. The thermal conductivities of the two material layers are \( \lambda_a \) and \( \lambda_b \). The forced convection heat transfer coefficient at the envelope is \( h_e \) and at the top and bottom surfaces is \( h_i \), and the radiation coefficient is \( h_r \) (W·m⁻¹·K⁻¹). The length of the cylinder is \( L \) (m).

Equation 7 has been applied to the Siple and Passel cylinder. First, only the pyrolin layer (\( \lambda_b \)) was considered, and \( T_i \) was then the inner surface temperature (0°C) of this layer. Then an additional calculation was done by assuming that the water inside the cylinder was partly frozen. A second ice layer was included, where \( \lambda_{e2} = \lambda_{ice} = 1.88 \) (W·m⁻¹·K⁻¹).

When \( Bi = 1 \) (Eq. 6), the water temperature should not be used as the outer surface temperature (\( T_s \)). A more relevant temperature is calculated from

\[
T_s = \Phi[A_e \cdot (h_e + h_r) + A_s \cdot (h_i + h_r)] + T_{am}
\]

(8)

where \( A_e \) and \( A_s \) are the envelope and top plus bottom surface areas, respectively. Tissue freezing is rarely associated with low airspeeds, so the free convection component has been ignored here. Compared with the forced convection component, the \( h_r \) can generally be considered small under windy and cloudy conditions.

Body part calculations. The skin temperature was calculated by assuming that the heat transfer in the radial direction dominates and by ignoring heat transportation in the axial direction. Then the finger heat flow rate and surface temperature can be calculated from

\[
\Phi = (T_i - T_{am}) + (\ln(\frac{r_2}{r_1})/(2\pi \cdot \lambda_b \cdot L)) + \frac{1}{2}(\ln(\frac{r_2}{r_1})/(2\pi \cdot \lambda_a \cdot L))
\]

(9)

and

\[
T_s = \Phi/[(2\pi \cdot r_2 \cdot L) \cdot (h_e + h_r)] + T_{am}
\]

(10)

The thermal conductivity of a tissue with a minimum of blood circulation is similar to that of the Siple and Passel (20) pyrolin cylinder. Because a finger diameter is less than that of the cylinder, \( Bi = 1 \) was certainly not satisfied during the Wilson and Goldman (21) exposures. The temperature at the skin surface should be lower than, for example, that in the cutis. If an exposed finger is considered as a cylinder in a cross flow, the temperatures at various depths of skin can be estimated, provided that the thermal conductivity and the thickness of the various layers are known. Over most body parts, the thickness of the epidermis ranges from 0.1 to 0.7 mm. The thickness of the cutis is 1–2 mm. The thermal conductivity of the epidermis (\( \lambda_a \)) is \( 0.21 \) W·m⁻¹·K⁻¹ and that for the cutis (\( \lambda_b \)) is \( 0.37 \) W·m⁻¹·K⁻¹. The temperature of the finger surface has been calculated from these \( \lambda \) values and by assuming thicknesses of 0.2 mm (\( r_3 - r_2 \)) for the epidermis and 1.5 mm (\( r_2 - r_1 \)) for the cutis. A finger diameter of 2 cm (\( 2r_1 \)) was assumed. Equations 9 and 10 describe steady-state temperature conditions. However, the temperature development during cold exposure is dynamic, so it would be useful to compare the steady-state surface temperatures with those obtained from unsteady-state calculations.

The Fourier number (\( Fo \)) (ND) is defined as

\[
Fo = \alpha \cdot t \cdot r^2
\]

(11)

where \( t \) is the time (s), and \( r \) is the radius of the cylinder. Heisler (6) has shown that if \( Fo > 0.2 \), the transient one-dimensional temperature can be solved graphically by approximative solutions for an infinite cylinder. For a homogeneous cylinder composed of muscle tissue, where \( d = 0.02 \) m, \( \alpha = 1.8 \cdot 10^9 \) m²/s, and \( \lambda = 0.34 \) W·m⁻¹·K⁻¹, the
temperature distribution can be estimated for \( t > 1 \) min. The internal temperature, \( T_{r=0,t} \), is calculated from
\[
T_{r=0,t} = \Theta_1 \cdot (T_{i0} - T_{am}) + T_{am}
\]
where \( T_{i0} \) is the initial internal temperature. At an \( \nu \) of, for example, 10 m/s, the constant \( \Theta_1 \) has values of 1.0, 0.7, 0.52, 0.39, and 0.25 at 1, 2, 3, 4, and 5 min, respectively. The temperature below the surface is calculated from
\[
T(r,t) = \Theta_2 \cdot (T_{r=0,t} - T_{am}) + T_{am}
\]
where \( \Theta_2 = 0.31 \) at the skin surface and 0.46 at a depth of 1.7 mm from the surface (cutis/subcutis level).

Surface temperature. Surface temperatures are difficult to measure accurately. If thermocouples are used, accuracy is affected by, for example, thermocouple thickness, airspeed, surface properties, and how the sensor is attached to the surface. Molnar and Rosenbaum (17) found that a 1-mm-thick thermocouple, attached to a glass cylinder, gave a temperature error of 15°C when the airspeed was 13 m/s and the surface temperature difference was 20°C. The thermal conductivity of the epidermis is lower than that of glass, so the expected error is greater.

The temperature of a thermocouple normally differs from that of the surface it is attached to. However, correction factors can be derived for various airspeed and temperature combinations. The heat balance of a thermocouple sensor can be expressed as
\[
(T_s - T_t) \cdot h_k \cdot A_k = (T_s - T_{ta}) \cdot h_c \cdot A_a
\]
where \( T_s \) and \( T_t \) are the surface and thermocouple temperatures, respectively, and \( T_{ta} \) (°C) is the temperature of the boundary air layer surrounding the thermocouple. The conduction heat transfer coefficient and the contact surface area are \( h_k \) (W·m⁻²·K⁻¹) and \( A_k \) (m²), respectively. The area of the thermocouple surface exposed to the boundary air layer is \( A_a \) (m²).

If the thermocouple thickness is less than that of the boundary air layer, the air temperature surrounding the thermocouple, \( T_{ta} \), can be calculated from
\[
T_{ta} = T_s - d_t/2 \cdot (T_s - T_{ta})/d_{in}
\]
where \( d_t \) (m) is the thermocouple thickness. The boundary air layer thickness \( (d_{in}) \) (m), can be estimated from
\[
d_{in} = \lambda_{air}/h_c
\]
The thickness of the boundary air layer depends on both the airspeed and the angle to the wind (3). For a circular cylinder, the greatest \( h_c \) value is normally obtained on the windward side, and the maximum at 0° to the wind. The shape of the body part and the activity rate are also factors of importance. The maximum and average \( h_c \) values for various body parts were measured under conditions of different airspeeds and physical activities. The ratio between maximum and average \( h_c \) values was found to be 1.4 (1, 2) and is the ratio used here.

Equation 14 shows that if the conduction heat transfer from the skin to a thermocouple is low, then the temperature of the sensor depends mainly on the temperature of the boundary air layer. The heat conduction to a thermocouple was found from the Molnar and Rosenbaum (17) data; they used thermocouples 1 mm thick, which is much thicker than the boundary air layer at the airspeed of 13 m/s they used. The conduction coefficient and the contact surface area cannot be separated, but if 15% of the thermocouple is assumed to be in contact with the surface, a skin heat transfer coefficient of 89 W·m⁻²·K⁻¹ is obtained. Other contact surface areas (and resulting conduction coefficients) hardly affect the thermocouple error.

**RESULTS**

Cylinder convection coefficient. Figure 1 shows the relationship between the external airspeed and convection coefficient, calculated according to Hilpert (9) (Eq. 3), for a cylinder having the same diameter as Siple and Passel’s cylinder (20). The figure also shows the corresponding relation calculated from the data of Siple and Passel, where the curve can be expressed as \( h_c \sim \nu^{0.25} \). The figure shows that above airspeeds of ~4 m/s, the Siple and Passel equation underestimates the expected convection coefficient at the outer surface of a cylinder in a cross flow.

Cylinder heat flow rate. Figure 2 shows the relationship between the measured (20) and calculated (Eq. 7) heat flow rates from a cylinder with the same dimensions as that used by Siple and Passel (20). The convection coefficients used are valid for a cylinder in a cross flow, where the cylinder’s top and bottom are exposed to a parallel airflow. It is assumed that the cylinder is filled with water at a temperature of 0°C. The predicted results correlate well with the rate of heat of fusion measured by Siple and Passel. Figure 2 also shows that if half the cylinder volume is filled with water and the rest is ice, then only a minor change is obtained.

Surface temperature error. Figure 3 shows the surface temperature error that can be expected with various combinations of airspeeds and temperature differences between the surface and ambient air. It is assumed that the thermocouple with its lead wires is glued to the 2-cm-wide cylinder (finger) on the windward side (0° to the wind). If the thermocouple lead wires are wrapped around the cylinder, the error is...
reduced by 30%, because the temperature along the wires affects the temperature at the measuring point. The thermocouple thickness, 0.2 mm, is the same as that used by Wilson and Goldman (21). At airspeeds <15 m/s, \( d_{th} = 0.2 \) mm, the heat transfer to the sensor is a result of convection from the boundary air layer and conduction from the underlying surface (a minor part).

Skin temperature. The finger temperature (Table 1) was predicted from Eq. 10. The temperature between the cutis and subcutis, 1.7 mm below the skin surface, was assumed to stay steady at \(-1.0^\circ C\) when frostbite occurs, irrespective of the WCI. The thermocouple error was added to the predicted finger temperatures (Fig. 3). The resulting temperatures were compared with the corresponding ones measured by Wilson and Goldman (21). Figure 4 shows that there was a close relationship between the predicted and measured temperatures. The average difference was 0.9°C.

Risk of finger frostbite. The predicted (steady-state) skin surface temperatures (Table 1) were related to the

### Table 1. Skin surface temperatures when the temperature is \(-1^\circ C\) in the layer between subcutis and cutis, at a depth of 1.7 mm from the outer skin surface

<table>
<thead>
<tr>
<th>Air Temperature/ Air Speed, °C/(m/s)</th>
<th>Assigned Temperature Cutis/Subcutis, °C</th>
<th>Calculated Temperature Skin Surface, °C</th>
<th>Thermocouple Error (Fig. 3), °C</th>
<th>Calculated Skin Temperature + Thermocouple Error, °C</th>
<th>Measured (21) Temperature Skin Surface, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>-15/15</td>
<td>-1.0</td>
<td>-7.3</td>
<td>-3.9</td>
<td>-12.2</td>
<td>-12.1</td>
</tr>
<tr>
<td>-5/15</td>
<td>-1.0</td>
<td>-2.8</td>
<td>-1.1</td>
<td>-3.9</td>
<td>-4.5</td>
</tr>
<tr>
<td>-25/10</td>
<td>-1.0</td>
<td>-10.4</td>
<td>-5.5</td>
<td>-15.9</td>
<td>-15.6</td>
</tr>
<tr>
<td>-15/10</td>
<td>-1.0</td>
<td>-6.5</td>
<td>-3.2</td>
<td>-9.7</td>
<td>-9.5</td>
</tr>
<tr>
<td>-25/5</td>
<td>-1.0</td>
<td>-8.2</td>
<td>-3.9</td>
<td>-12.1</td>
<td>-13.4</td>
</tr>
<tr>
<td>-15/5</td>
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<td>-5.2</td>
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<td>-7.5</td>
<td>-10.3</td>
</tr>
</tbody>
</table>

Skin surface temperature measured (21) and calculated (Eq. 7) values are compared. Also shown are predicted thermocouple errors at various combinations of temperature and air speed (see Fig. 3).

Fig. 2. Correlation between measured (see Ref. 20) and calculated (Eq. 7) heat flow rates when effect of cylinder wall on surface temperature is considered and assuming that cylinder is filled with water at a temperature of 0°C (solid line). Dotted line shows correlation obtained if half of the water is frozen and half is fluid.

Fig. 3. Surface temperature error for various surface-air temperature \( T_s - T_a \) differences and airspeeds \( v \). Error refers to a 0.2-mm thermocouple glued on windward side of a cylinder, diameter = 2 cm.

Fig. 4. Correlation between measured (21) and calculated (Eq. 10) skin surface temperatures, including thermocouple errors (see Fig. 3). Dotted line shows line of identity.
frequency of finger frostbite for the various combinations of airspeeds and temperatures (21). The results (Fig. 5) indicate that the risk of finger frostbite, for those individuals tested, increased linearly from 0 to 100% as the skin surface temperature dropped from −4.6 to −8.0°C. The skin surface temperatures calculated from transient conditions in a homogeneous muscle-tissue cylinder were found to be similar to the steady-state temperatures (average difference 1.1°C). In both the transient and steady-state models, the skin temperatures were based on a cutis/subcutis temperature of 21°C.

Windchill curves. Figure 6 shows the risk of finger freezing at various combinations of airspeeds and temperatures. The risk is based on the frequency of finger frostbite in the Wilson and Goldman investigation (21). The airspeeds and temperatures were selected so that Eq. 10 would give finger surface temperatures of −4.8, −6.3, and −7.8°C, corresponding to 5, 50, and 95% frequency of finger frostbite, respectively (Fig. 5). Siple and Passel’s “1,400 line” is shown in Fig. 6 for comparison. The figure shows that there is little risk of finger freezing above −10°C, even at high airspeeds. Below −15°C, however, the risk seems to increase rapidly with increasing airspeeds.

DISCUSSION

Convection coefficient. Siple and Passel (20) proposed that the convection coefficient could be expressed as

$$ h_c = 1.16 \cdot (10 \cdot v^{0.5} - v + 10.45) $$

and suggested that this was applicable for airspeeds up to 12 m/s. Their equation can be expressed as a power function as

$$ h_c = 21.5 \cdot v^{0.25} $$

This differs considerably from the expression proposed by Hilpert (9) of

$$ h_c = 13.3 \cdot v^{0.62} $$

for a similar cylinder. Winslow et al. (23) gave

$$ h_c = 11.6 \cdot v^{0.5} $$

for the whole human body, and Hill et al. (8) obtained

$$ h_c = 23.8 \cdot v^{0.5} + 4.95 \approx 25.8 \cdot v^{0.5}. $$

Their exponent of 0.5 is considerably greater than the 0.25 of Siple and Passel but somewhat lower than the 0.62 of Hilpert (9). The difference between 0.5 and 0.62 can be accounted for by natural convection. The different coefficients given by Hill et al. (8) and Winslow et al. (23) are due to differences in diameter: the nude human body has an average “convection” diameter of ~16 cm (1); the kata thermometer was 2 cm wide. Hence, the ratio between convection coefficients (Eq. 3) of Hill et al. (8) and Winslow et al. (23) is

$$(2/16)^{0.38} = 2.2. $$

This is also the ratio obtained from their proposed formulas: 25.8/11.6 = 2.2. These two studies, therefore, produced convection coefficients consistent with these expected for cylinders in a cross flow. The $h_c$ value of Siple and Passel (20), however, is not consistent with these results.

WCI. The WCI is calculated from

$$ WCI = (10 \cdot v^{0.5} - v + 10.45) \cdot (33 - T_{am}) $$

Siple and Passel suggested that this formula should not be used for $v > 12$ m/s because the indexes would decrease. Even so, the WCI significantly underestimates the effect of the airspeed. The reason is that Siple and Passel’s cylinder surface temperature was not, as they expected, similar to that of the freezing water. However, Fig. 2 shows that general convection formulas give approximately the same heat flow rates as those measured. Although Siple and Passel measured the convection heat flow rate accurately, the convection coefficient was incorrect because the temperature difference over the cylinder wall was not considered. They calculated the heat flow rate from the moment of constant water temperature when the ice formed. The freezing process continuously

![Fig. 5. Relationship between calculated steady-state skin surface temperature (Eq. 10) and frequency of finger frostbite (21). Arrows denote 5, 50, and 95% risk of tissue freezing and corresponding skin surface temperatures.](image-url)
changed the wall thickness and thus the wall temperature. The heat flow rate was recalculated here (Eq. 7) by assuming that half of the volume was ice and the rest was water. Whether the cylinder is filled with water or has a thick inner layer of ice with water in the middle, the result is about the same (Fig. 2). Hence, a WCI based on \( V^{0.25} \) should be more relevant than one based on \( V^{0.38} \), suggested by Siple and Passel.

Tissue freezing. Wilson and Goldman (21) made numerous experiments on the time required to freeze finger skin. They assumed that a thin body part (finger) would freeze at a lower WCI than a thick part, because of the greater convection coefficient of the former. However, they found that the risk for finger frostbite was no greater than that for other parts of the body (face) found by Siple and Passel (20). The risk should be less, because diameter of the head is roughly ten times that of the finger (\( 2/20 \approx 2.4 \)). But local \( h_c \) values can vary widely, depending on the shape of the body and on blocking from adjacent parts (1, 2). Molnar et al. (18) measured the rate at which the finger surface temperature decreased under various climatic conditions. They found a correlation between finger diameter and the time to onset of cold-induced vasodilatation (CIVD). The time constant of the temperature drop (\( \tau \)) can be interpreted as the resistance to convective heat transfer relative to the amount of heat stored. Hence, a large time constant implies a reduced risk of tissue freezing. After reanalysis of the results of Molnar et al. (18), then \( \tau \propto r^{1.4} \) for fingers of various diameters. There seems thus to be a risk-radius dependence, with the risk being less for the wider body part.

The temperature at which skin starts to freeze has been disputed. Keatinge and Cannon (11) suggested that the freezing point of blood and tissue is \(-0.6^\circ C\) but that the freezing process starts when the skin temperature is around \(-1^\circ C\). This differs considerably from the data of Wilson and Goldman (21) and Wilson et al. (22), who found that the skin tissue started to freeze at roughly \(-13\) and \(-9^\circ C\), respectively. Their explanation was that the skin reached subfreezing temperatures before ice formed. These temperatures are probably some 3–4°C too low, owing to thermocouple errors, an effect of the boundary air layer temperature and the conduction heat transfer rate (Fig. 3). However, the main reason is that these investigators measured the temperature on a surface with \( B_i \approx 1 \), whereas Keatinge and Cannon (11) measured the skin temperature from an intracutaneous track, with the finger precooled to a low temperature.

Wilson et al. (22) estimated the “true” skin freezing temperature by extrapolating the skin temperature rise from the point of ice crystalization. They suggested a freezing temperature of about \(-2.9^\circ C\). However, when the data are corrected for the thermocouple error (\(-2.1^\circ C\) for a thermocouple wrapped around the finger), it gives nearly the same freezing temperature (\(-0.8^\circ C\)) as that suggested by Keatinge and Cannon (11). At low skin temperatures, the tissue may be protected from freezing by CIVD, which increases the local heat input. Greenfield et al. (4) found that the maximum heat flow rate from the finger tip during CIVD was roughly 8 W when the subject was in thermal comfort. This is \( \approx 40\% \) greater than the heat flow rate from a finger exposed to a wind of 10 m/s and \(-25^\circ C\). CIVD can thus cope with severe climatic conditions. However, CIVD can be activated only if the blood in the superficial vessels is not already frozen. Ice is formed in isolated biological samples after supercooling to between \(-5\) and \(-15^\circ C\) (14). Supercooling, however, does not occur in a streaming fluid. So when a supercooled tissue freezes, a rapid process because of the thermal conductivity of ice (12), the skin blood temperature should not be lower than \(-1^\circ C\).

The validity of using steady-state skin temperatures can be questioned, as the cooling process is a transient one. However, starting from a finger core temperature of 30°C, the time-dependent skin temperature curves have a similar shape to the measured curves (21). Furthermore, the transient surface temperatures are similar to the steady-state temperatures when the cutis/subcutis temperature reaches \(-1^\circ C\). This indicates that both the steady-state and the transient infinite (length-to-radius ratio > 10) finger models can be used under these conditions, although Molnar (15) has found a significant heat transfer from those parts of the finger not exposed to a wind. However, Shitzer et al. (19) showed analytically that the cylinder axis temperature drop is rather insensitive to the distance along the axis, except during the initial phase of the cooling process.

Frostbite risk. Figure 5 shows that the frequency of skin frostbite is linearly related to the predicted skin surface temperature. For skin surface temperatures above about \(-4.6^\circ C\), the finger is not expected to freeze, whereas frostbite should always occur below \(-8^\circ C\) in those individuals who participated in the experiments (21). The relation could be different for other subjects, as the cooling rate depends on, for example, age, body constitution, and body heat content (5, 10). The freezing temperature for a group of people can be characterized by its mean value and SD, \( \sigma \). Another group might be represented by another average. If \( \sigma \) is small, two groups of individuals may seem to respond quite differently to tissue cooling. Figure 7 shows the normal and the cumulative probability distribution functions based on the same mean (\(-6.3^\circ C\)) as that found in Fig 5. If \( \sigma = 1^\circ C \), the cumulative function is close to the risk-skin temperature curve, i.e., 68% of all finger frostbite cases are expected to occur between \(-5.3\) and \(-7.3^\circ C\), and the risk of frostbite increases from 20 to 80% over this range. Thus a fairly small change in the mean freezing temperature due to, for example, adaptation, results in a large change in the estimated freezing risk. Massey (13) found that people in their second year in the Antarctic showed greater immunity to frostbite than newcomers, with 29% of cold exposures resulting in frostbite, compared with 74%, respectively. According to Fig 6, an adapted person can withstand twice the airspeed that a nonadapted person can, with the same frostbite risk.
It is difficult to validate the risk curves for finger tissue freezing for ethical reasons. Table 2 shows a comparison between predicted (Fig. 6) and observed frostbite frequencies from Wilson et al. (22), Molnar et al. (16), and previously unpublished data of Wilson and Goldman (21). The data of Wilson et al. (22) are given as average frostbite risks (45%) because the number of exposures under each climatic condition are not known. There seems to be fairly good agreement between predicted and observed data, except with the previously unpublished data (21). The experimental conditions for the latter are still unknown.

A low air temperature is needed for the skin to freeze. Doubling the temperature difference doubles the heat flow rate, but doubling the airspeed only increases the heat flow rate by 50%. Wilson and Goldman (21) have suggested that a low air temperature is the main reason for tissue freezing and that the skin should not freeze at air temperatures above −10 to −15°C, irrespective of airspeed. Siple and Passel (20) have also suggested that low temperatures cause a greater risk for tissue freezing than high airspeeds do. Figure 6 indicates that the risk of frostbite is significant even at −10°C if the airspeed is >15 m/s, which rather contradicts the above suggestions. However, the greatest speed used by Wilson and Goldman (21) was 15 m/s. Siple and Passel (20) based their windchill curve on airspeeds up to 12 m/s and advised against extrapolation.

Siple and Passel discovered that below a WCI of 1,400 few frostbite injuries occurred. Compare this level with the 5% risk curve (Fig. 6). The curves intersect at about −10°C and 10 m/s. At higher airspeeds and temperatures, the 1,400 curve indicates a greater risk than the 5% curve does. Below −20°C, it approaches the 50% risk curve (Fig. 6). At these low temperatures, however, a change in the airspeed of 2–3 m/s can change the risk by >50%. Such risk curves should therefore be used with caution, because minor changes in the climatic, behavioral, or physiological conditions can have a considerable effect on the risk of tissue freezing. However, a rough recommendation is that the risk is fairly small with air temperatures above −10°C but great below −25°C.

Summary. The WCI values given by Siple and Passel (20) underestimate the effect of airspeed on the convection heat transfer rate for exposed body parts. The reason is that the authors did not consider the properties of the cylinder wall in their model. However, a conventional cylinder model explains the heat flow rates measured by Siple and Passel. A similar model, based on the thickness and thermal properties of the epidermis and cutis, is used here to describe the heat loss from a finger in a cross flow. The skin surface temperature is found to correlate well with the frequency of frostbite for various airspeeds and temperatures. The skin frostbite temperatures seem to be normally distributed around −6.3°C with an SD of 1°C when the temperature between the cutis and subcutis is −1°C. The model indicates that, for a group of people nonadapted to cold, the risk of tissue freezing increases from 5 to 95% as the finger surface temperature falls from −4.8 to −7.8°C. Risk curves have been developed from this relation. The risk of freezing the skin seems to be minor above −10°C, whereas the risk is pronounced below −25°C, except at very low airspeeds.

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