Guidelines on the Risk and Time to Frostbite during Exposure to Cold Winds

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ABSTRACT

The objective of the present study was to define the risk and the time required to develop frostnip on the face during exposure to cold winds. Twelve subjects (6 males and 6 females) were exposed to sixteen 45 min tests where the wind intensity varied between 0, 16 and 32 km/h. The tests were conducted at 0, -10, -20, -30, -40 and –50°C (only 0 km/h wind was present at -50°C). During the tests, the subjects were dressed for thermal comfort, and rested seated while facing the wind with their bare face fully exposed to the cold wind. Each test was terminated when the elapsed time reached 45 min, or when frostnip developed. The results show that no frostnip was observed at 0°C and -10°C for any wind intensity. The frequency of frostnip development increases inversely with temperature, while the time to develop frostnip increases with temperature. At -20°C, 17 and 58% of the subjects developed frostnip for the 16 and 32 km/h wind conditions, while at –30 and -40°C, all the subjects developed frostnip at those conditions. For the no wind conditions, 0, 11, 22, and 60% of the subjects developed frostnip for the –20, -30, -40 and -50°C conditions, respectively. The time to develop frostnip decreased from 20 min at -20°C for the 16 and 32 km/h wind conditions to 14, 4, 2.5 and 1.5 min for the -30°C and 16 km/h, -30°C and 32 km/h, -40°C and 16 km/h, and -40°C and 32 km/h condition, respectively. It was concluded from these results that the risk of frostbite and times to develop frostbite estimated from Siple and Passel are based on conditions that are too severe and need revision to include more mild conditions. A new guideline based on the new Wind Chill Index is proposed to protect the general population against the development of freezing injuries, particularly on the face.

1.0 INTRODUCTION

Past studies have examined the effect of the wind chill on the development of frostnip in the fingers [2; 8]. There is limited data available for the risk and time to frostnip for the skin on the face.

Wilson [7] has suggested that different parts of the body (e.g., the finger and the head) will cool at different rates due to differences in diameter. In addition, the turbulence of air flow varies for objects of different shape [7]. Therefore, the risk and time to frostnip data that is available for the fingers will not necessarily apply to the face.

Siple and Passel [6] provided facial frostnip data by recording the time and location of frostnip on various parts of the face. However, their research took place under only two environmental conditions that were quite severe (i.e., the first at -32.5°C, 7 m/s wind or an average cooling rate of 2000 kg cal/m^2/h, and the second for an average cooling rate of 2308 kg cal/m^2/h).

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Frostnip occurred in every case (17 cases and 18 cases, for the two conditions, respectively) that Siple and Passel tested. Therefore, the risk of frostnip was 100% for both conditions. The Siple and Passel data did not provide information about the risk of frostnip on the face under less severe conditions, which would most likely be more informative to the general public, but especially for people who have to spend time outdoors (soldiers, construction workers, postal workers, etc.). In addition, the frostnips in Siple and Passel's study occurred very quicky (often after one minute or less) due to the severity of the conditions. It would be informative to know the time to develop frostnip under more mild conditions.

Knowing the risk of frostnip and the time it will take to develop frostnip are both useful in helping people decide what to wear on a particular day and in providing a framework to allow individuals to make decisions about whether or not they will go outdoors. For example, a military officer may choose to abort certain outdoor operations if the risk of frostbite to his/her soldiers is elevated.

The overall objective of the present study was to define the risk and the time required to develop frostnip on the face over a wider range of environmental conditions (0°C to -50°C, 0 to 9 m/s wind) compared to the Siple and Passel [6] study. It is proposed that the new guidelines are to be used with the new Wind Chill Index recently described by Osczevski and Bluestein [4] and currently used by Environment Canada and the US Weather Service since 2001 [3; 5].

2.0 METHODS

2.1 Subjects

Six male and six female volunteers with the following characteristics were recruited (mean ± SD): age 33 ± 8 years, height 174 ± 9 cm, weight 76 ± 16 kg, body surface area 1.89 ± 0.22 m^2, and body fat of 20±4%. Subjects with a history of frostbite in their face were excluded from the study. Potential subjects were fully informed of the details, discomforts, and risks associated with the experimental protocol and were granted medical approval, before being asked for their written informed consent. The protocol was approved by the Human Ethics Research Committee at DRDC Toronto.

Following the medical screening, anthropometric characteristics and body skin fold measurements were taken to determine percentage body fat. Subjects performed a one-hour familiarization run in the cold chamber at -10°C (20 min at 0 m/s, 20 min at 4.5 m/s, and 20 min at 9 m/s) where they were introduced to the measurements taken during the actual experiment.

2.2 Experimental Protocol

Subjects were exposed to six different air temperatures (-50°C, -40°C, -30°C, -20°C, -10°C, and 0°C) at three different wind speeds [0 m/s, 4.5 m/s (16 km/h), and 9 m/s (32 km/h)], except at -50°C, when subjects were only exposed to a wind speed of 0 m/s. The wind speed was measured at a height of 1.5 m. Each subject participated in six sessions in addition to a familiarization run, completing one experimental session every 3 to 5 days. Subjects were randomly exposed to each ambient condition and wind speed. The subjects were exposed to one experimental temperature per day and each session was at the same time of the day for each subject to eliminate circadian effects. Each subject was exposed for a maximum of 45 min per test. However, a test was terminated prior to this 45 min time period if frostnip occurred on the face. Frostnip is a superficial and reversible ice crystal formation in the superficial layers of the skin. Frostnip appears as a white or yellowish firm plaque on the skin that is easily detectable. The experiment was considered safe for subjects because the frostnip was detected very quicky by an investigator inside the cold chamber and the skin was rewarmed within 30 seconds of the frostnip development by an investigator waiting in the subject monitoring room outside the cold chamber. The investigator placed his warm palm on the frostnipped site until a normal skin colour returned. Following each cold test, subjects

were rewarmed in the monitoring room (ambient temperature of 20 to 25°C) until the skin on his/her face returned to normal (above 30°C) as measured by fine thermocouples (40-gauge, type-T) located on the forehead, right and left cheeks, nose and chin.

2.3 Clothing Worn

The clothing worn for each of the ambient conditions is shown in the table 1. More details about the clothing ensemble may be found in Brajkovic and Ducharme [1]. Subjects wore wool socks, mukluks and heavy mitts during all exposures and a ski hat was worn which covered the ears but left the entire face exposed. The dressing was modified for each subject based on their subjective thermal comfort. If required by the subject, additional insulation was provided during the coldest conditions by adding a -30ºC rated sleeping bag over the legs and torso. An objective of the experiment was to keep the subjects thermally comfortable (except for the face) so that there was minimal body cooling and minimal sweating. All ambient conditions below -10°C were always started with the 0 m/s wind condition, which decreased the chances of frostbite development due to perspiration around the neck and face. Prior to entering the cold chamber, subjects wore an insulated hood with a built-in plastic visor that covered the entire head. The hood prevented the subject from being exposed to the cold wind prior to starting the data collection. Once the data collection was started, the hood will be removed immediately and the change in skin temperature on the face was monitored.

3.0 RESULTS

Results from Fig 1 and 2 are expressed as a function of equivalent temperature (which has no unit associated with the value) based on the new wind chill index developed in 2001 [4]. The results show that no frostnip was observed at 0°C and -10°C for any wind intensity (see Fig, 1). In conditions with no wind, the risk of frostnip increased exponentially as equivalent temperature increased, whereas in conditions with wind, the risk of frostnip followed a sinusoidal path as equivalent temperature increased. At -20°C, 17% and 58% of the subjects developed frostnip for the 4.5 m/s and 9.0 m/s wind conditions, while at -30 and -40°C, all the subjects developed frostnip at those conditions. For the no wind conditions, 0%, 11%, 22%, and 60% of the subjects developed frostnip for the -20°C, -30°C, -40°C and -50°C conditions, respectively.

The time to develop frostnip increased exponentially with temperature (see Fig. 2). The time to develop frostnip decreased from 20 min at -20°C for the 4.5 m/s and 9.0 m/s wind conditions to 14 min, 4 min, 2.5 min and 1.5 min for the -30°C and 4.5 m/s, -30°C and 32 km/h, -40°C and 4.5 m/s, and -40°C and 9.0 m/s conditions, respectively.

Table 1: Clothing typically worn by subjects for each ambient air and wind condition. Clothing could be slightly altered based on subjective thermal comfort.

Condition	Clothing Worn
-50°C, 0m/s	All 3 layers of new CF Arctic clothing ensemble + long underwear
-40°C, 0m/s	All 3 layers of new CF Arctic clothing ensemble + long underwear
-40°C, 4.5m/s	All 3 layers of new CF Arctic clothing ensemble + long underwear
-40°C, 9m/s	All 3 layers of new CF Arctic clothing ensemble + long underwear
-30°C, 0m/s	All 3 layers of new CF Arctic clothing ensemble
-30°C, 4.5m/s	All 3 layers of new CF Arctic clothing ensemble
-30°C, 9m/s	All 3 layers of new CF Arctic clothing ensemble + long underwear
-20°C, 0m/s	CF Fleece layer and outer insulated coat layer
-20°C, 4.5m/s	CF Fleece layer and outer insulated coat layer
-20°C, 9m/s	All 3 layers of new CF Arctic clothing ensemble
-10°C, 0m/s	CF Fleece layer and middle un-insulated coat layer
-10°C, 4.5m/s	CF Fleece layer and outer insulated coat layer
-10°C, 9m/s	CF Fleece layer and outer insulated coat layer
0°C, 0m/s	CF Fleece layer and middle un-insulated coat layer (unzipped top)
0°C, 4.5m/s	CF Fleece layer and middle un-insulated coat layer
0°C, 9m/s	CF Fleece layer and middle un-insulated coat layer

CF Canadian Forces

From the 52 cases of frostnip observed, 73% (38 cases) were observed on the nose, while 15% (8 cases), 8% (4 cases) and 4% (2 cases) were observed on the chin, cheek, and forehead, respectively.

4.0 DISCUSSION

Based on an examination of the data presented in this study, the risk of frostbite and times to develop frostbite estimated from Siple and Passel are based on conditions that are too severe and need revision to include more mild conditions. In addition, Siple and Passel's frostbite guidelines need to be revised to reflect the decreased risk and the increased times needed to develop frostbite under certain environmental conditions. For example in examining Figure 3, the highest equivalent temperature at which there is a "considerable danger" of developing frostbite is -32°C (-15°C ambient temperature, 24 km/h wind). According to Siple and Passel, the "flesh may freeze within one minute" at a -32°C equivalent temperature. In comparison, in examining Figure 4, using the new proposed frostbite guidelines with the new wind chill chart, the same equivalent temperature (-32°C) (-20°C ambient temperature, 25 km/h wind) indicates that "there is an increasing risk (i.e., 5 to 95% chance) of frostbite for most people in 10 to 30 min of exposure" (see frostbite guide in Fig. 4). On the other hand, if we use the same ambient conditions (-15°C ambient temperature, 24 km/h wind), Figure 4 indicates no risk to develop frostbite (equivalent temperature of -25°C). In examining Figs. 1 and 2, an equivalent temperature of -32°C corresponds to a risk of frostnip of 30%, and a time to frostnip of 23 min, respectively.

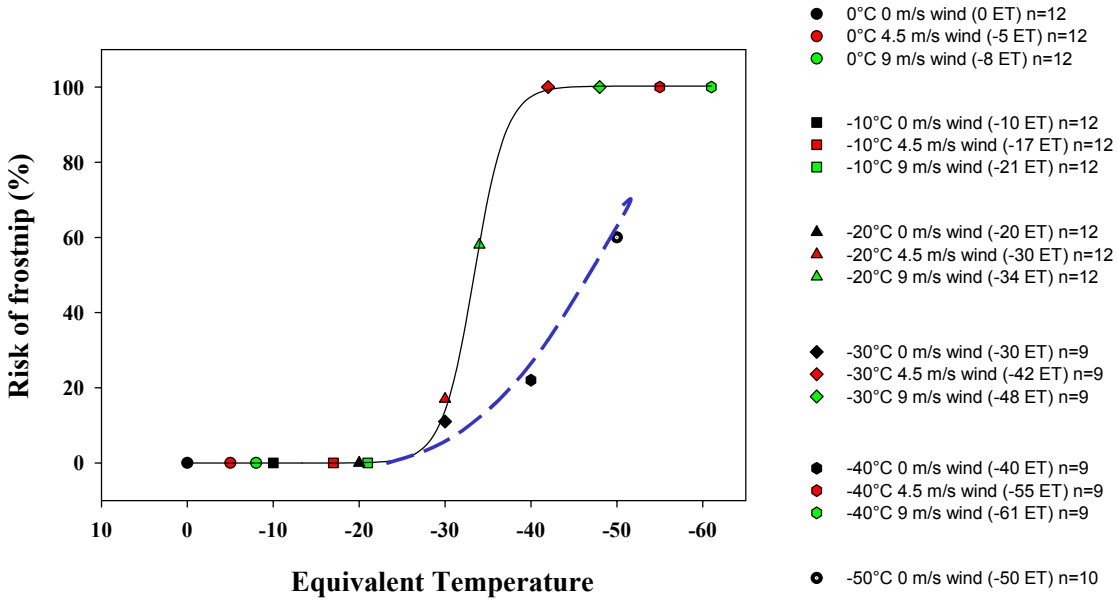


Figure 1: Risk of frostnip as a function of equivalent temperature (ET). The dashed line represents the curve fit for those conditions from -20°C to -50°C when there was no wind. The solid line represents the curve fit for all other ambient/wind combinations.

It should be noted that conditions in the present study were most likely done under a more controlled environment compared to the human subject experiments done by Siple and Passel. In the present study, a controlled climatic chamber was used in addition to controlling the thermal comfort of the subjects, whereas in Siple and Passel's study, it is assumed that the experiments were done outdoors where, in addition to an unlikely constant wind speed, there may have been drifting snow that could have moistened the face of subjects during the frostnip experiments, and hence, increasing the risk of frostbite and decreasing the time to frostnip.

In the present study, from the 52 cases of frostnip observed, 73% (38 cases) were observed on the nose, while 15% (8 cases), 8% (4 cases) and 4% (2 cases) were observed on the chin, cheek, and forehead, respectively. Similarly, in Siple and Passel's 35 cases of frostnip observed, 66% (23 cases) were observed on the nose, while 9% (3 cases), 14% (5 cases) and 0% were observed on the chin, cheek, and forehead, respectively.

It is interesting to compare the times to frostnip of the fingers and the face.

Wilson and Goldman [8] found that at -15ºC with a 10 m/s (36 km/h) wind speed (equivalent temperature of -27), 55% of the subjects (6 out of 11) developed frostnip of the fingers, but only 14% (1 out of 7) subjects developed frostnipped fingers if the wind was decreased to 5 m/s (18 km/h) (equivalent temperature of -24).

In addition, Danielsson [2] reported previously unpublished data of Wilson and Goldman [8] which found that observed frostbite risk in the fingers was 63% when the ambient temperature was -11.5ºC with a 10 m/s (36 km/h) wind (equivalent temperature of -22), whereas the finger frostbite risk was 0% during exposure to -9.5ºC with a 10 m/s wind (equivalent temperature of -20).

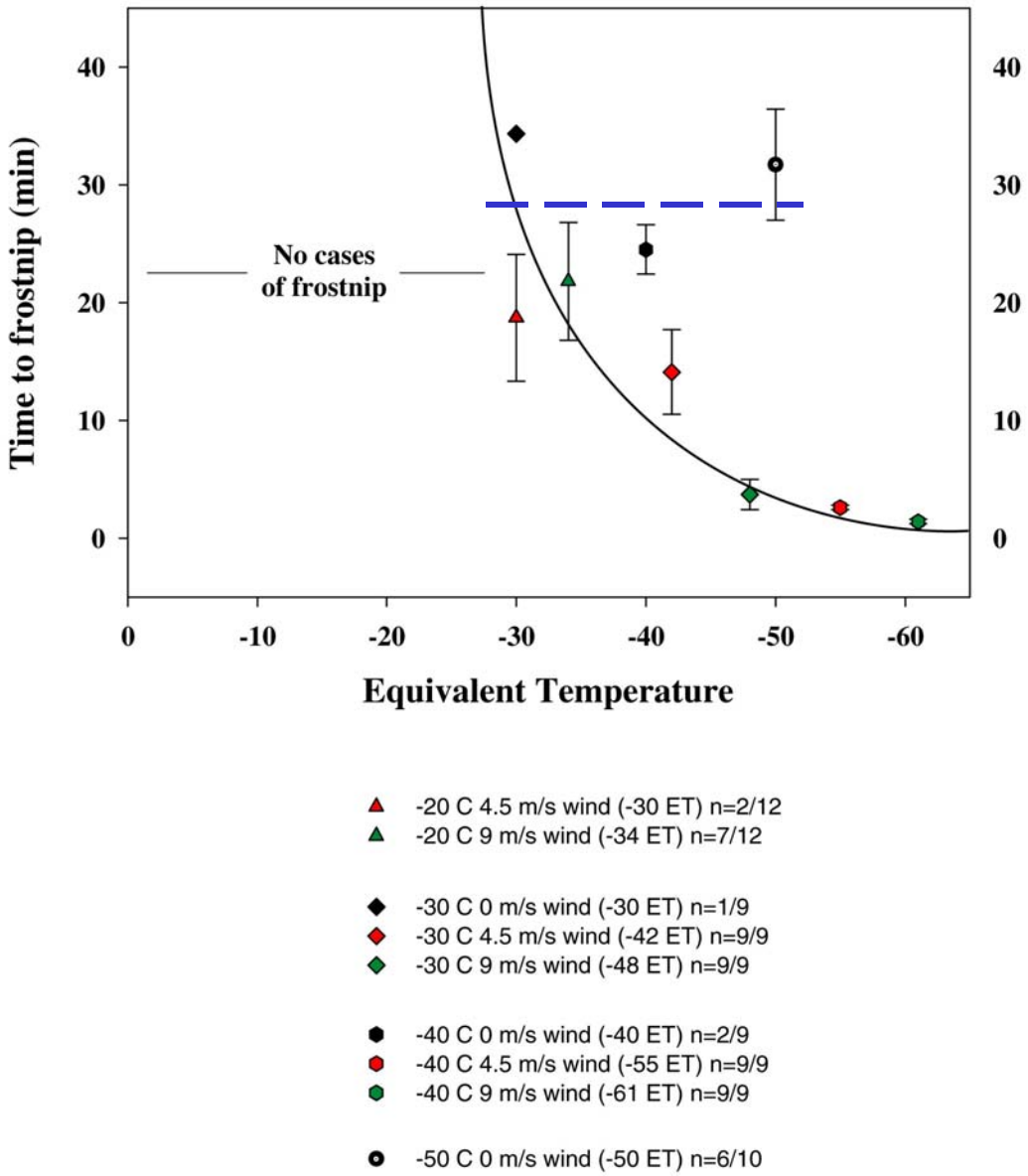
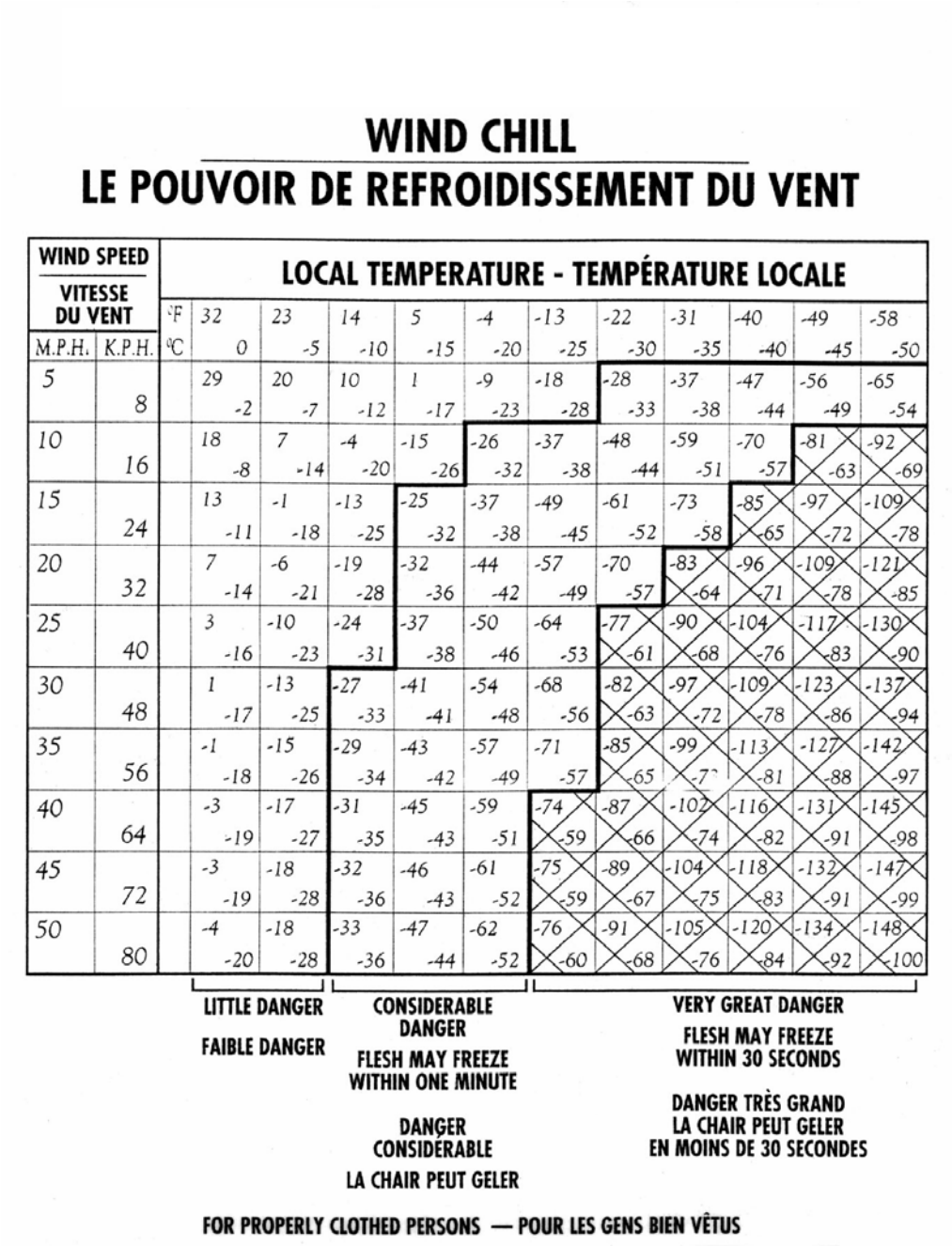


Figure 2: Time to frostnip (±SE) as a function of equivalent temperature (ET). The dashed line represents the linear fit for those conditions from -30°C to -50°C when there was no wind. The solid line represents the curve fit for all other ambient/wind combinations.



WIND CHILL
LE POUVOIR DE REFROIDISSEMENT DU VENT

WIND SPEED / VITESSE DU VENT		LOCAL TEMPERATURE - TEMPÉRATURE LOCALE										
	°F	32	23	14	5	-4	-13	-22	-31	-40	-49	-58
M.P.H.	K.P.H.	°C	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	8		29 -2	20 -7	10 -12	1 -17	-9 -23	-18 -28	-28 -33	-37 -38	-47 -44	-56 -49	-65 -54
10	16		18 -8	7 -14	-4 -20	-15 -26	-26 -32	-37 -38	-48 -44	-59 -51	-70 -57	-81 -63	-92 -69
15	24		13 -11	-1 -18	-13 -25	-25 -32	-37 -38	-49 -45	-61 -52	-73 -58	-85 -65	-97 -72	-109 -78
20	32		7 -14	-6 -21	-19 -28	-32 -36	-44 -42	-57 -49	-70 -57	-83 -64	-96 -71	-109 -78	-121 -85
25	40		3 -16	-10 -23	-24 -31	-37 -38	-50 -46	-64 -53	-77 -61	-90 -68	-104 -76	-117 -83	-130 -90
30	48		1 -17	-13 -25	-27 -33	-41 -41	-54 -48	-68 -56	-82 -63	-97 -72	-109 -78	-123 -86	-137 -94
35	56		-1 -18	-15 -26	-29 -34	-43 -42	-57 -49	-71 -57	-85 -65	-99 -7[illegible]	-113 -81	-127 -88	-142 -97
40	64		-3 -19	-17 -27	-31 -35	-45 -43	-59 -51	-74 -59	-87 -66	-102 -74	-116 -82	-131 -91	-145 -98
45	72		-3 -19	-18 -28	-32 -36	-46 -43	-61 -52	-75 -59	-89 -67	-104 -75	-118 -83	-132 -91	-147 -99
50	80		-4 -20	-18 -28	-33 -36	-47 -44	-62 -52	-76 -60	-91 -68	-105 -76	-120 -84	-134 -92	-148 -100

LITTLE DANGER
FAIBLE DANGER

CONSIDERABLE DANGER
FLESH MAY FREEZE WITHIN ONE MINUTE
DANGER CONSIDERABLE
LA CHAIR PEUT GELER

VERY GREAT DANGER
FLESH MAY FREEZE WITHIN 30 SECONDS
DANGER TRÈS GRAND
LA CHAIR PEUT GELER EN MOINS DE 30 SECONDES

FOR PROPERLY CLOTHED PERSONS — POUR LES GENS BIEN VÊTUS

Figure 3: Frostbite guidelines of Siple and Passel using the old wind chill chart. The bold lines dissecting the chart indicate where there is a change in the risk and time to frostbite. The values in the chart are equivalent temperatures based on the ambient temperature (first row of chart) and wind speed (first column of chart).

Wind Chill Calculation Chart

where T air = Air temperature in °C and V_{10} = Observed wind speed at 10m elevation, in km/h.

T air	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
V_{10}												
5	4	-2	-7	-13	-19	-24	-30	-36	-41	-47	-53	-58
10	3	-3	-9	-15	-21	-27	-33	-39	-45	-51	-57	-63
15	2	-4	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66
20	1	-5	-12	-18	-24	-30	-37	-43	-49	-56	-62	-68
25	1	-6	-12	-19	-25	-32	-38	-44	-51	-57	-64	-70
30	0	-6	-13	-20	-26	-33	-39	-46	-52	-59	-65	-72
35	0	-7	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73
40	-1	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74
45	-1	-8	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75
50	-1	-8	-15	-22	-29	-35	-42	-49	-56	-63	-69	-76
55	-2	-8	-15	-22	-29	-36	-43	-50	-57	-63	-70	-77
60	-2	-9	-16	-23	-30	-36	-43	-50	-57	-64	-71	-78
65	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79
70	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-80
75	-3	-10	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80
80	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81

FROSTBITE GUIDE
Low risk (<5% chance) of frostbite for most people
Increasing risk (5 to 95% chance) of frostbite for most people in 10 to 30 minutes of exposure
High risk (>95% chance) of frostbite for most people in 5 to 10 minutes of exposure
High risk (>95% chance) of frostbite for most people in 2 to 5 minutes of exposure
High risk (>95% chance) of frostbite for most people in 2 minutes of exposure or less

Figure 4: New proposed frostbite guidelines to be added to the *new wind chill chart [4]. The different coloured regions indicate the risk and time to frostbite. The values in the chart are equivalent temperatures based on the ambient temperature (first row of chart) and wind speed (first column of chart).

***The new wind chill chart was developed for healthy adults with no history of cold injuries and it also based on using subjects with dry bare skin on the face and subjects limited to a exposure time of 45 min.**

***The new index has been harmonized with that used in the United States (though the Farenheit scale is used there), thus giving a consistent index used throughout North America.**

Therefore, the data above suggests that it is likely that the fingers will freeze at an equivalent temperature between -22 and -27.

In comparison, in the present study, it is interesting to note that there is a "low risk (<5% chance) of frostbite" at an equivalent temperature of higher than -28 (see Fig. 4). Unlike the fingers, there is an increasing risk (5% to 95% chance) of frostbite on the face for most people when the equivalent temperature is -28 or below. The slightly lower equivalent values (-22 to -27) at which frostnip occurs in the fingers relative to equivalent value at which there is increased risk of freezing of the skin on the face (-28) is possibly related to the smaller diameter of the fingers which would enhance cooling [7].

5.0 CONCLUSION

The frostbite guidelines of Siple and Passel are in need of a revision. A new guideline based on the new Wind Chill Index has been proposed to protect the general population against the development of freezing injuries, particularly on the face.

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