LOCAL FINGER INSULATION AND ITS EFFECT ON COOLING RATE.

Ralph F. **Goldman,** PhD
Arthur D. Little, Inc.
Acorn **Park,** Cambridge, MA 02140-2390, USA

INTRODUCTION

The wind chill index (WCI)[1] combines **the** effects of **air** temperature (Ta) and **wind** velocity **(WV)** in a simple equation. It **has** proven useful in predicting both the cooling perceived during human exposures, and the actual cooling rates **and** occurrence of freezing cold injuries of fingers and toes[2]. WCI **presents** a calculated rate of heat loss, in **kcal/m²·hr,** from the bare skin at a comfortably warm human Ts of **33°C,** at any **specified** Ta and WV. A WCI of 1400 is suggested **as** a threshold for freezing **bare flesh;** this appears valid, **as shown** by actual cold injuries noted in an inhumane "study" during **the Manchurian** war. The index is usually expressed in **terms** of an "equivalent WCI temperature"; however, the cooling will not reach the equivalent WCI temperature but will approach actual Ta at the same cooling rate **as** if **at** the equivalent WCI. Note that while wet skin *can* freeze at Ta of - 0.6°C (31°F), *dry skin* seldom freezes **at** > -10°C (-15°F) in the absence of precipitation regardless of the WCI equivalent **temperature**[3].

Insulation does not add heat; it simply protects the covered surface against losing whatever heat is supplied to it The problems of increasing the thickness (the way to increase insulation) around such thin cylinders **as** fingers and toes without simultaneously increasing the surface **area** for heat loss is well known[4].

METHOD

The clo value, defined to characterize the loss of heat through clothing, *can* also be used to define the temperature difference maintained between the skin surface and ambient *air.* One **clo** of insulation limits heat flow through the clothing, from the skin surface (at Ts) to the **air** (at Ta) to ***5.55* kcal/m²·hr·°C.** The **corollary** is that 1 clo will maintain a 0.18°C difference between Ta and Ts for each **kcal/m²·hr** supplied **to** the skin surface **as** circulatory heat input ("q"). This relationship *can* be **used**[4] to calculate the equilibrium **temperature** (Teq) established between the heat loss through the insulation **(as** expressed by 1 / 5 3 = 0.18) and the circulatory heat input, q, **as:**

$$Teq = Ta + 0.18 * q * clo \qquad \text{Equation 1}$$

There are large differences between overall and local insulation; 5th fingertip insulation is the ***critical*** value and is not necessarily well correlated with overall glove insulation, **as** shown below.

	INSULATION VALUE (clo)	
HAND WEAR	**overall**	5th finger
NONE (bare hand)	0.41	0.27
WOOL, 5-finger GLOVE insert (alone)	0.66	0.49
VINYL COATED COTTON GLOVE, w/wool insert	0.78	0.59
LEATHER GLOVE, w/wool insert	0.75	0.64
MITTEN SHELL, trigger finger, w/insert	1.07	0.96
MITTEN, POL, 3-finger, alone	1.11	0.96
MITTEN, POL, 3-finger, w/wool **insert**	1.14	0.95
FIRE **FIGHTERS,** wool, **DOUBLE** MITTEN	1.40	0.96
ARMY ARCTIC **MITTEN,** w/3-finger wool insert	2.19	1.34
ARMY ARCTIC MITTEN, w/wool glove insert	2.40	1.54
Highest measured MITTEN (1" polyfoam)	2.70	2.00

Studies of extremity circulatory heat input (q) suggest q ranges **from** 7 to **440 kcal/m²·hr, as** a function of the body heat balance[4]; **q** = 72 **kcal/m²·hr** when comfortable, at rest. The rate of cooling, **i.e.,** the time (t) to reach Teq starting at a temperature To, and the skin temperature at **any** time Tt, *can* be calculated using:

$$Tt = Teq + (To - Teq)e^{-t/a} \qquad \text{Equation 2}$$

where a, the time constant, is determined by three factors:

1) physical size of the finger (surface/mass);
2) insulation of the finger;
and 3) the effective WV across it (whether by air, body or vehicle motion).

Although more study is needed, basic time constants have been determined experimentally, as a function of local body area size, for a few areas; 28 minutes for an un-insulated 5th finger (base of the nail bed) in still air and 32 minutes for a 2nd finger. The effect of insulation appears adequately expressed by a modified a' (= (100*clo - a); the effect of air motion (WV in mph), by a further modified time constant, a", derived from the WCI as:

$$a'' = 10.45*(100*clo-a)/(10.45 + 6.69*\sqrt{WV} - .447WV) \qquad \text{Equation 3}$$

RESULTS

The equilibrium temperature for the 5th finger nailbed is strongly *affected* by both insulation and temperature with a "comfortable" circulatory heat input of 72 kcal/m^2.hr, as shown below:

EQUILIBRIUM 5th FINGER TEMPERATURE AS Ta FALLS FROM +20 TO -40°F
AND LOCAL INSULATION INCREASES FROM 0.5 TO 2.0 CLO UNITS.

	Ta=	+20	0	-20	-40 °F
CLO	0.5	31.7	11.7	- 8.3	-28.3 °F
	1.0	43.4	23.4	3.4	-16.6
	1.5	55.1	35.1	15.1	- 4.9
	2.0	66.8	46.8	26.8	6.8

While the decreased cooling rate as a result of the "mass damping" provided by extremity insulation is quite significant, so is the increased cooling with increasing air motion. For example, as wind speed increases from 5 to 20 mph, the cooling time constant (a") for the base of the nail bed of the 5th finger falls from 9.9 min (at 5 mph) to 7.3 min (at 20 mph) with 0.5 clo of local insulation. With 1.0 clo, the corresponding values are 32.5 and 23.9 min; with 1.5 clo, 55 and 40.6 min; and with 2.0 clo the a" would be 77.6 min at 5 mph and 57.2 min at 20 mph.

CONCLUSIONS

These equations provide a model for predicting the required hand wear insulation at any Ta, WV and work rate for comfort; they can also be used to predict the duration of exposure before manual dexterity is lost (5th finger c 6°), and time to significant risk of freezing (Ts < -10°C (-15°F)), or non-freezing, cold injuries (Ts < + 5°C (40°F)) .

REFERENCES

1. Siple, P.A. and Passel CF. 1945, Measurements of *dry* atmospheric cooling in subfreezing temperatures, Roc. *Amer.* Philos. Soc. 89, 177-199.

2. Hanson, H.E. and Goldman R.F. 1969, Cold injury in man: a review of its etiology and discussion of its prediction, Mil. Med. 134(11), 1307-1316.

3. Wilson, O. and Goldman RF. 1970, Role of air temperature and wind in the time necessary for a finger to freeze, J. Appl. Physiol. 29(5), 658-664.

4. van Dilla, M., Day R. and Siple, P.A. 1957, Special problems of hands, in L.H. Newburgh (ed) The physiology of temperature regulation and the science of clothing. (Hafner, New York), 374-388.