LOCAL FINGER INSULATION AND ITS EFFECT ON COOLING RATE.

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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/m^2.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/m^2.hr.°C.** The corollary is that 1 clo will maintain a 0.18°C difference between Ta and Ts for each **kcal/m^2.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/m^2.hr,** as a function of the body heat balance[4]; **q = 72 kcal/m^2.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:**

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

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
	0.5	**31.7**	**11.7**	**- 8.3**	**-28.3 °F**
C					
	1.0	43.4	23.4	3.4	-16.6
L					
	1.5	55.1	35.1	15.1	- 4.9
O					
	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.**