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CHANGES IN THERMAL INSULATION DURING UNDERWATER EXERCISE*

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= Abstract =

1. Steady-state thermal insulation was measured in protected and unprotected subjects during rest and exercise in water of critical temperature.
2. In unprotected subjects, maximal body insulation at rest increased as a linear function of mean subcutaneous fat thickness. In all subjects, however, body insulation declined as an exponential function of the exercise intensity, reaching approximately 25% of the resting value at work loads above 4 Met. These suggest that over 75% of maximal body insulation in resting subjects is achieved by use of skeletal muscle as an insulative barrier.
3. In wet-suited subjects, the overall insulation decreased to 1/2 with 2 Met and to 1/3 of the resting value with 3 Met exercise. This decrease in total insulation was due in part to the reduction in body insulation and in part to the decrease in insulation afforded by wet-suits. The reduction in apparent suit insulation during exercise may be attributed primarily to an increase in the effective heat exchange surface area as a result of exercise hyperemia of the limbs which are poorly insulated as compared with the trunk.
4. As a practical consequence, both in protected and unprotected individual, heat generated by muscular exercise in water colder than critical temperature cannot offset cooling unless the exercise intensity is great.

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When exposed to cold, human body increases thermal insulation by peripheral vasoconstriction. There are ample evidences which suggest that vasoconstriction occurs not only in the superficial tissues, such as skin and fat, but also in deep muscle tissues. It is generally agreed that subcutaneous fat provides an insulative barrier to the body heat loss during immersion in cold water.[1,2,3] However, the importance of muscle shell as an insulative barrier has not been well recognized until recently.

In a previous study[4] we have attempted to quantify the relative value of subcutaneous fat vs. muscle during immersion in cool water. Subjects clothed in swim-suits were immersed upto the neck in vigorously stirred water. Subjects seated motionless or performed arm and leg exercise at a constant intensity for 3 h. In order to evaluate the thermal insulation at the maximal degree of peripheral vasoconstriction, water temperature for each subject was adjusted to the critical temperature, the lowest temperature a resting individual can tolerate for 3 h without shivering.[5] The average critical water temperature of 7 subjects were 30℃. The $\dot{V}_{O2}$ and rectal temperature (T_{re}) were measured at appropriate intervals, and the overall body insulation (I) was calculated using the following equation :

$I\ (℃/kcal/m^2 \cdot h) = (T_{re} - T_w)/(0.92\ \dot{M} \pm S)$ where T_w is water temperature, $\dot{M}$ is metabolic heat production (4.83 $\dot{V}_{O2}$), and S is the loss or gain of body heat stores ($\Delta T_{re} \times 0.83 \times 0.6 \times$ body wt). Respiratory heat loss was assumed to be 0.08 $\dot{M}$ at rest and during exercise and was subtracted from $\dot{M}$ to give skin heat loss of 0.92 $\dot{M} \pm S$.

Fig. 1 depicts the values of overall body insulation (I) as a function of exercise level in 7 subjects. The exercise intensity is expressed as a metabolic rate above resting. In all subjects the insulation declined progressively as the work load increased. The most obese subject (top curve) had a largest overall insulation at rest (0.23℃/kcal/m²·h) and underwent the greatest decline to a value of 0.07 at an exercise level of 3 Met ($\Delta\dot{M}$= 100 kcal/m²·h). Two skinny subjects (bottom curves) had the smallest body insulation at rest (0.11℃/kcal/m²·h) and underwent the least decline to a value of 0.04 at 3 Met exercise.

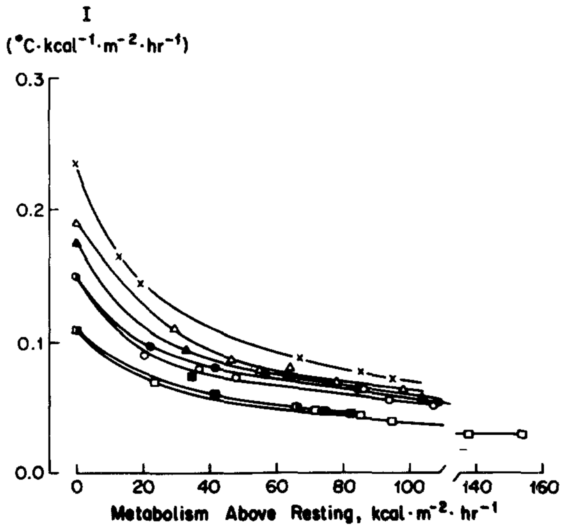

Fig. 1. Overall body insulations, I, of 7 subjects, measured during final hour of a 3-h immersion in water of critical temperature (28°C~32°C) and plotted as function of metabolism above resting, $\Delta\dot{M}$. The I value of resting subjects are shown at the far left where $\Delta\dot{M}$=0. Each subject was studied during 3-h of exercise on 4 or more occasions and the I values for each subject are connected by a curvilinear line drawn by eye. (Park et al., 1984.)

The proportionate decrease in insulation was, however, virtually identitical in each subject.

Fig. 2 depicts the overall body insulation as a function of subcutaneous fat thickness for all subjects at various levels of exercise ($\dot{M}$=50 at rest, 75, 100 and 150 kcal/m²·h). As observed in many other studies,[6,7,8,9] the insulation at rest increased linearly with the fat thickness. This, probably, is the major reason why the subcutaneous fat layer has been so much emphasized as a thermal barrier in cold water. The dashed line depicts the insulation due to the fat layer (0.058℃/kcal/m²·h). It is evident that in all subjects the overall body insulation at rest was mostly atrributed to the tissues other than fat, and

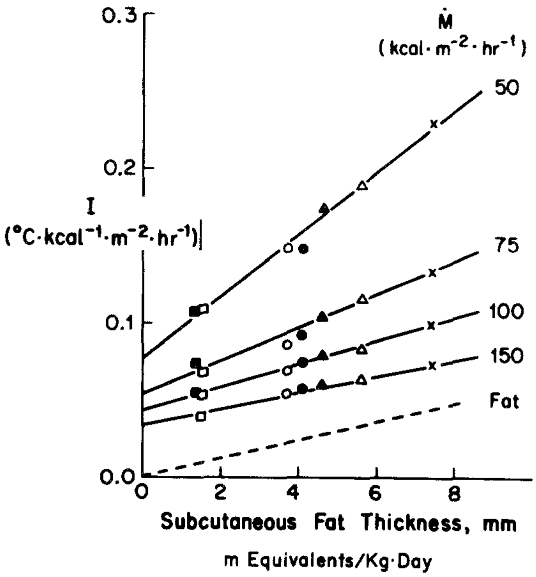

Fig. 2. Overall body insulation, I, plotted as a function of subcutaneous fat thickness in 7 subjects. Maximal I values during 3rd h of immersion in water of critical temperature are depicted by the top line, $\dot{M}$=50 kcal/m²·h. Each of the lower solid lines depicts I during 3rd h of exercise at 75, 100, and 150 kcal/m²·h. Dashed line depicts physical insulation of fat alone, i.e., 0.058°C/kcal/m²·h. (Park et al., 1984.)

that this portion of insulation decreased progressively as exercise intensity increased. These indicate that the non-fatty insulation was due to unperfused muscle.

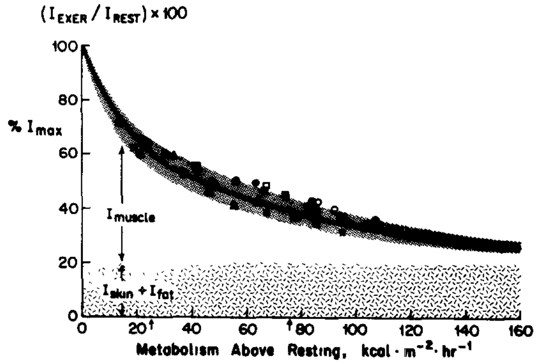

Fig. 3. Percentage of maximal insulation at rest, % I_{max}, is plotted for all 7 subjects as a function of metabolism above resting. At $\Delta\dot{M}$=50 kcal/m²·h, % I_{max}=48. The asymptote for % I_{max} approaches 25% when $\Delta\dot{M}$ exceeds 150 kcal/m²·h. (Park et al., 1984.)

Fig. 3 illustrates relative changes in body insulation as a function of exercise intensity in all subjects. On the average, the insulation decreased to approximately 50% of the resting value with 2 Met ($\Delta\dot{M}$=50kcal/m²·h) and to 25% at 4 Met ($\Delta\dot{M}$=150kcal/m²·h) exercise. Thus skeletal muscle appears to provide as much as 75% of the total body insulation in subjects resting in water of critical temperature, with subcutaneous fat and skin accounting for the remainder. A similar conclusion had been drawn in another study,[3] in which superficial shell (fat and skin) insulation was estimated from direct measurements of fat and skin temperatures and skin heat flux. This suggests that for subjects immersed in moderately cold water, heat loss is controlled largely by blood flow to skeletal muscle with unperfused subcutaneous fat and skin providing a less important role than commonly supposed.

The reason for the skeletal muscle plays such an important role in providing insulation is due to the fact that thermal control of blood flow (hence insulation) is mostly accomplished in the extremities, and not in the trunk.[10] Cannon and Keatinge[11] have observed that in the subject immersed in water, thermal conductance of the hands and feet decreased drastically from 0.048 cal/㎠/min/℃ at 35℃ to 0.001 at 22℃. For the same temperature variation, conductance of the chest decreased by only 36% from 0.028 to 0.018 cal/㎠/min/℃. Barcroft and Edholm[12] have observed that when an arm is immersed in 13℃ water the forearm blood flow falls to only 0.5 ml/100 ml/min compared with 17.6 ml/100 ml/min observed during immersion in 43℃ water. Such a reduction in limb blood flow will not only retard heat transfer from the body core to the extremities but will also increase the efficiency of countercurrent heat conservation mechanism, since the system is only effective when blood flow is sufficiently small.[13] Therefore, most of the loss of heat generated in the core of the subject resting in cold water is through the trunk surface rather than through the limbs.

This mechanism may be even more important in wet-suited subjects. Since physical insulation of foamed neoprene will decrease as the curvature of surface increases, as pointed out by Van Dilla et al.,[14] in connection with the insulation of clothing, the insulative value of wet-suits will be much smaller in the limb than in the trunk. Furthermore, the design of divers wet-suits is such that most of the trunk surface is covered by double sheets (pants and jacket) and the limbs by a single sheet. Thus wet-suits provide a good insulatin to the trunk but a poor insulation to the limbs. Consequently, restriction of blood flow to the limbs will greatly increase the efficiency of thermoregulation in the wet-suited diver. We attempted to test this hypothesis in a study on Korean women wet-suit divers.[15]

Subjects were clad in their personal wet-suits (jacket, pants and boots of 5~6mm thick) and were immersed up to the neck in water of critical temperature. The average critical water temperature of 4 divers with wet-suits was 16.5±1.2 (SE)℃. In order to prevent convective heat loss from under the suit[16] we tapped the suit at the ankles and the wrists.

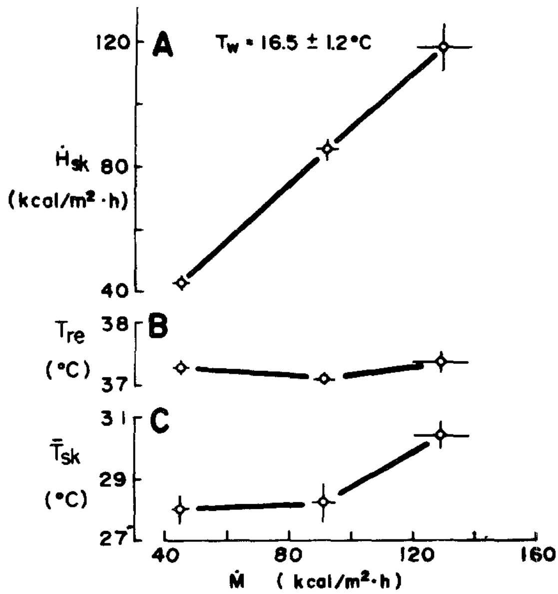

Fig. 4. Average skin heat loss ($\dot{H}_{sk}$, A), rectal temperature (T_{re}, B) and mean skin temperature ($\bar{T}_{sk}$, C) of 4 wet-suited subjects during final 1 h of rest and exercise in water of critical temperature (16.5±1.2°C). Values are means±SE. (Yeon et al., 1987.)

Fig. 4 depicts average steady-state skin heat loss, rectal and skin temperatures at rest and during exercise in 4 subjects. The heat loss increased linearly with the exercise intensity. However, the rectal temperature was not different whether the subjects were resting or were exercising at the various levels tested (less than 3 Met). These results indicate that the thermal insulation of the subjects decreased inversely with work load.

In fact, as shown in Fig. 5, the overall insulation decreased from about 0.5℃/kcal/m²·h at rest (% resting $\dot{M}$=100) to approximately one half at 2 Met and to 1/3 of the resting value at 3 Met exercise. This decrease in total insulation (I_{total}) appeared to be due in part to the reduction in body insulation (I_{body}) and in part to the decrease in insulation afforded by wet-suits (I_{suit}). The apparent I_{suit} estimated from the difference between the I_{total} and I_{body} ($I_{suit}=I_{total}-I_{body}$, Fig. 5, inset) was on the average 0.27℃/kcal/m²·h at rest, but it decreased gradually with exercise intensity until it reached approximately 0.12℃/kcal/m²·h at above 3 Met. The latter value of I_{suit} is similar to the physical insulation of 5 mm neoprene wet-suit obtained using a copper manikin.[17] Physical insulation of the wet-suit should not vary unless its thickness is changed. Since there was no apparent reason for change in suit thickness between rest and exercise, we speculate that the unexpectedly high functional insulation of wet-suits in resting subjects is a consequence of physiological regulations in cold water.

As described above, insulative value of the wet-suit is relatively low in the limbs because of its design (single sheet) and the high curvature. As a consequence, the skin temperature underneath the suit will become much lower in the extremities than in the trunk during immersion in cold water (31.3℃, chest vs. 26℃, leg in the present study). In other words, immersion with wet-suits is analogous to exposing the limb to water colder than that exposing the trunk. This will lead to strong vasocontriction in the extremities. Restriction

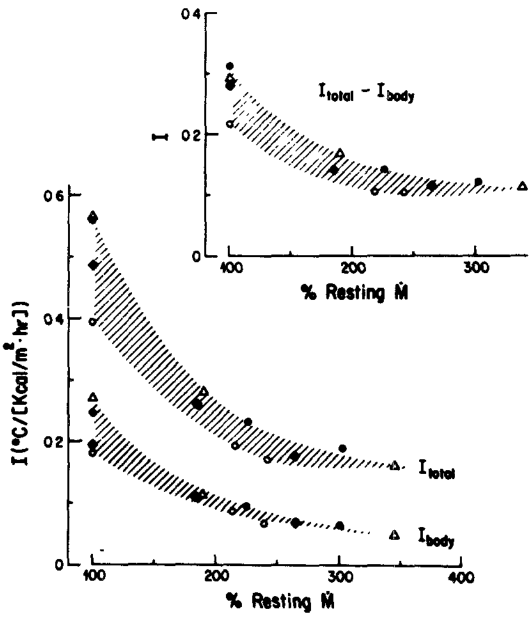

Fig. 5. Total peripheral insulation (I_{total}) and body tissue insulation (I_{body}) of 4 subjects with wet-suits measured during final hour of immersion in water of critical temperature (16.5±1.2°C) plotted as a function of exercise intensity. Exercise intensity was expressed as a percent of resting metabolic rate (% Resting $\dot{M}$). I values of resting subjects are shown at far left when % Resting $\dot{M}$ is 100. Each subject was studied during 2-h exercise at two different levels. Each symbol represents an individual subject. Hatched area includes all values of insulation obtained at rest and during exercise. Inset: changes in $I_{total}-I_{body}$ (i.e., apparent wet-suit insulation) in wet-suited subjects as a function of exercise intensity. (Yeon et al., 1987.)

of limb blood flow will greatly reduce the surface area for heat exchange and most of the heat exchange between the body core and water will take place at the trunk surface where suit insulation is relatively high. For these reasons, wet-suits provide far greater physiological insulation at rest than during exercise. The exercise hyperemia reduces not only the thermal insulation from the deep tissue to the skin but also thermal insulation down the length of the limb. Therefore, much of the heat produced in the skeletal muscle is dissipated through the large surface area of limbs rather than returning to the body core. In other words, the effect of exercise is to extend the area for heat exchange over a poorly insulated region in parallel to the trunk.

Fig. 6 shows the effective heat exchange area (A) estimated for the present subjects using the following formula :

$$A = I_{suit} \times 0.92\dot{M}/(T_{sk} - T_w)$$

where $\dot{M}$ is steady-state metaboloc rate in kcal/h, T_{sk} is the steady-state mean skin temperature, and I_{suit} is the physical insulation of wet-suits which was assumed to be constant at 0.12℃/kcal/m²·h in all conditions. The area at rest was only 0.66m², which was equivalent to 40% of the total suit surface area, but it increased with exercise and became almost identical to the actual suit surface area at $\dot{M}$ of approximately 200 kcal/h. This anlysis strongly supports a notion that the relatively high apparent suit insulation in the resting subject may be due to a reduced surface area for heat exchange.

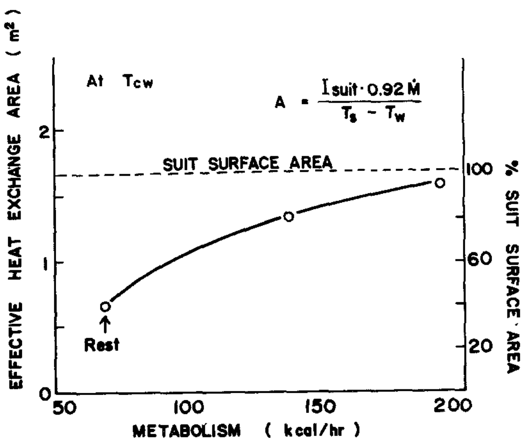

Fig. 6. The effect of heat exchange area of wet-suit (A) at rest and at two levels of exercise. The formula for A is shown in the inset. The value of I_{suit} was set at 0.12°C/kcal/m²·h, which was observed for the 5 mm neoprene wet suit using an electrically heated manikin. (Based on Yeon et al., 1987.)

An obvious practical implication of the present finding is that if a wet-suited diver is in a situation when escape from the cold water is not possible, it is better to hold still than to swim if the heat loss is to be effectively reduced. It has been documented that exercise in cold water increases heat loss more than it increases heat production in an unprotected individual.[18,19] The present study indicates that, even in protected individual, exercise increases heat loss as much as heat production in cold water.

REFERENCES

1. Hatfield HS, LGC Pugh : Thermal conductivity of human fat and muscle. Nature 168 : 918, 1951
2. Bullard RW, GM Rapp : Problems of body heat loss in water immersion. Aerosp Med 14 : 1269, 1970
3. A Veicsteinas, G Ferretti, DW Rennie : Superficial shell insulation in resting and exercising men in cold water. J Appl Physiol 52 : 1557, 1982

4. Park YS, DR Pendergast, DW Rennie : Decrease in body insulation with exercise in cool water. Undersea Biomed Res 11 : 159, 1984
5. Rennie DW, BG Covino. BJ Howell, SH Song, BS Kang, SK Hong : Physical insulation of Korean diving women. J Appl Physiol 17 : 961, 1962
6. Rennie DW : Thermal insulation of Korean diving women and non-divers in water. In : Rahn H., ed. Physiology of Breath-Hold Diving and the Ama of Japan. Washington, D.C. National Academy of Science, National Research Council, 1965, pp 315~324
7. Hong SK : Pattern of cold adaptation in women divers of Korea (ama). Fed Proc 32 : 1614, 1973
8. Hanna JM, SK Hong : Critical water temperature and effective insulation in scuba divers in Hawaii. J Appl Physiol 33 : 770, 1972
9. Park YS, DW Rennie, IS Lee, YD Park, KS Paik, DH Kang, DJ Suh, SH Lee, SY Hong, SK Hong : Time course of deacclimatization to cold water immersion in Korean women divers. J Appl Physiol 54 : 1708, 1983
10. Burton AC, OG Edholm : Man in a Cold Environment. New York : Hafner, 1969
11. Cannon P, WR Keatinge : The metabolic rate and heat loss of fat and thin men in heat balance in cold and warm water. J Physiol(Lond.) 154 : 329, 1960
12. Barcroft H, OG Edholm : The effect of temperature on blood flow and deep body temperature in the human forearm. J Physiol(Lond.) 102 : 5, 1943
13. Bazett HC, L Love, M Newton, L Eisenberg, R Day, R Forster : Temperature changes in blood flowing in arteries and veins in men. J Appl Physiol 1 : 3, 1948
14. Van Dilla M, R Day, PA Siple : Special problem of hands. In : Newburgh, L. H., ed. Physiology of Heat Regulation and the Clothing. Philadelphia, PA : Saunders, 1949, pp 374~388
15. Yeon DS, YS Park, JK Choi, JS Kim, IS Lee, DH Kang, SH Lee, SY Hong, DW Rennie, SK Hong : Changes in thermal insulation during underwater excercise in Korean female wet-suit divers. J Appl Physiol 62 : 1014, 1987
16. Wolff AH, SRK Coleshaw, CG Newstead, WR Keatinge : Heat exchanges in wet suits. J Appl Physiol 58 : 770, 1985
17. Goldman RF, JR Breckenridge, E Reeves, EL Beckman : "Wet" versus "dry" suit approaches to water immersion protective clothing. Aerosp Med 37 : 485, 1966
18. Crittenden G, JF Morlock, TO Moore : Recovery patterns following underwater exercise. Aerosp Med 45 : 1225, 1974
19. Keatinge WR : Survival in Cold Water. Oxford, UK : Blackwell, 1969