Thermal and metabolic responses to cold-water immersion at knee, hip, and shoulder levels

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Lee, Dae T., Michael M. Toner, William D. Mc Ardle, Ioannis S. Vrabas, and Kent B. Pandolf. Thermal and metabolic responses to cold water immersion at knee, hip, and shoulder levels. J. Appl. Physiol. 82(5): 1523–1530, 1997.—To examine the effect of cold-water immersion at different depths on thermal and metabolic responses, eight men (25 yr old, 16% body fat) attempted 12 tests: immersed to the knee (K), hip (H), and shoulder (Sh) in 15 and 25°C water during both rest (R) or leg cycling [35% peak oxygen uptake; (E)] for up to 135 min. At 15°C, rectal (Tre) and esophageal temperatures (Tes) between R and E were not different in Sh and H groups (P > 0.05), whereas both in K group were higher during E than R (P < 0.05). At 25°C, Tre was higher (P < 0.05) during E than R at all depths, whereas Tes during E was higher than during R in H and K groups. Tre remained at control levels in K-E at 15°C, K-E at 25°C, and in H-E groups at 25°C, whereas Tes remained unchanged in K-E at 15°C, in K-R at 15°C, and in all 25°C conditions (P > 0.05). During R and E, the magnitude of Tre change was greater (P < 0.05) than the magnitude of Tes change in Sh and H groups, whereas it was not different in the K group (P > 0.05). Total heat flow was progressive with water depth. During R at 15 and 25°C, heat production was not increased in K and H groups from control level (P > 0.05) but it did increase in Sh group (P < 0.05). The increase in heat production during E compared with R was smaller (P < 0.05) in Sh (121 ± 7 W/m² at 15°C and 97 ± 6 W/m² at 25°C) than in H (156 ± 6 and 126 ± 5 W/m², respectively) and K groups (155 ± 4 and 165 ± 6 W/m², respectively). These data suggest that Tre and Tes respond differently during partial cold-water immersion. In addition, water levels above knee in 15°C and above hip in 25°C cause depression of internal temperatures mainly due to insufficient heat production offsetting heat loss even during light exercise.

thermoregulation; core temperature; heat flow; heat production; rest; exercise; humans

BECAUSE OF THE LARGE CONDUCTIVE HEAT TRANSFER FROM THE BODY SURFACE DURING COLD-WATER IMMERSION, EVEN A SLIGHT DROP IN WATER TEMPERATURE CAN CAUSE A MUCH GREATER HEAT LOSS THAN THE MAGNITUDE OF TES CHANGE IN SH AND H GROUPS, THEREBY LOWERING INTERNAL BODY TEMPERATURE.

Several investigators report that during rest in cold water the trunk is the major site of heat loss and distal parts of the body are more insulative compared with the trunk region (8, 24). With exercise, on the other hand, the fall of internal body temperature is often accelerated, presumably due to highly perfused active muscle areas (4, 14, 28) in addition to elevated convective heat loss (26) through the periphery. This causes a relatively greater heat loss during exercise compared with rest. Thus it is of interest to know the thermoregulatory and metabolic responses of humans to cold water at varying levels of immersion. To our knowledge, the data on this topic are sparse.

All previous studies dealing with human physiological responses to cold-water exposure have used whole body or head-out immersion, leaving uncertainty as to the effect of different immersion levels on thermal balance. The present study investigated this question by immersing individuals to the knee, hip, and shoulder at water temperatures of 15 and 25°C during exercise or rest. Thermal balance was then determined by measures of M and heat loss. We hypothesized that exercising while immersed in cold water above the knee would not facilitate thermal balance. On the other hand, rest in cold water would be less effective than exercise for thermoregulation at any level of immersion.

METHODS

Subjects. Subjects were eight men with a mean age, stature, body mass, body surface area, percent body fat, mean skinfold thickness, and peak oxygen uptake (VO2peak) of 24.8 ± 2.0 yr, 173.7 ± 3.6 cm, 74.8 ± 3.0 kg, 1.91 ± 0.06 m², 15.7 ± 1.7%, 4.1 ± 0.5 mm, and 46.3 ± 2.2 ml·kg⁻¹·min⁻¹, respectively. Each individual was cleared for participation in this study after completion of medical history, physical examination, blood and urine chemistries, and resting electrocardiogram. The experimental procedures were explained in detail, and written informed consent was obtained from all subjects. The study had been approved by the appropriate institutional review board.

Procedures. Preexperimental procedures included determining physical characteristics, body composition, and VO2peak tests in air on a cycle ergometer (12). Subjects pedaled initially at 50 W for 2 min. Exercise intensity was increased by 30 W every minute thereafter, until the subject could no longer maintain the 60 revolutions/min pedaling frequency. From the values obtained during the VO2peak test, a submaximal intensity of ~35% of VO2peak was determined for each subject. Pedaling rate was selected by using the equation with no fins by Shapiro et al. (20) and ranged from 46 to 50 revolutions/min. This submaximal intensity was performed in all exercise procedures during cold-water immersion.

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RESULTS

Duration of immersion. Mean durations of immersion in Sh group were 75 ± 19, 81 ± 18, 109 ± 18, and 118 ± 17 min in R at 15°C, E at 15°C, R at 25°C, and E at 25°C, respectively. Subjects in H group endured 116 ± 17, 117 ± 17, 111 ± 17, and 117 ± 17 min, and subjects in K group endured 131 ± 2, 135 ± 3, 133 ± 1, and 132 ± 0 min for corresponding conditions. In general, subjects were discontinued due to the restrictive limit placed on core temperature, whereas one subject withdrew from both the Sh-R at 15°C and the Sh-E at 15°C before reaching the limit. Also to be noted is the fact that one subject performed only four testings of the K condition.

Temperature responses. For each water temperature, \( T_{sk} \) was the same for E and R at each water level (Fig. 1). At the three water levels, \( T_{sk} \) was the lowest (\( P < 0.05 \)) in Sh (16.6 ± 0.1, 16.2 ± 0.1, 25.9 ± 0.0, and 25.5 ± 0.0°C in R at 15°C, E at 15°C, R at 25°C, and E at 25°C, respectively) and the highest (\( P < 0.05 \)) in K group (27.4 ± 0.1, 28.2 ± 0.1, 30.5 ± 0.0, and 30.6 ± 0.1°C in R at 15°C, E at 15°C, R at 25°C, and E at 25°C, respectively) during the immersions. In the H group, \( T_{sk} \) was 23.5 ± 0.1, 23.9 ± 0.0, 28.8 ± 0.1, and 28.8 ± 0.0°C in R at 15°C, E at 15°C, R at 25°C, and E at 25°C, respectively. \( T_{sk} \) was reduced (\( P < 0.05 \)) from the control-air value during all immersions except for the K-E group at 25°C (\( P > 0.05 \)).

Internal body temperature responses are shown in Fig. 2. Regardless of the water temperatures, or R or E conditions, both \( T_{re} \) and \( T_{es} \) values were the highest in K and the lowest in Sh group. Whereas the immersion level significantly affected \( T_{re} \) at both water temperatures and \( T_{es} \) at 15°C (\( P < 0.05 \)), no effect was noted for \( T_{es} \) at 25°C (\( P > 0.05 \)). During immersions, \( T_{re} \) and \( T_{es} \) did not fall below the control-air values in the K-E at 15°C, K-E at 25°C, and H-E at 25°C groups, nor did \( T_{es} \) in the K-E at 15°C and H-E at 15°C groups and in all conditions at 25°C. At 15°C, \( T_{re} \) and \( T_{es} \) between R and E were not significantly different in Sh and H groups, whereas both in K group were higher during E than during R (\( P < 0.05 \)). In all the conditions at 25°C, exercise...

Cowan CD-4 gasometer. Samples of expired air were taken from a 7-litre mixing chamber and analyzed for oxygen (Applied Electrochemistry S-3A, Sunnyvale, CA) and carbon dioxide (Ametek CD-3A). M was calculated as previously reported (30).

An insulated immersion tank of 1,500-litre capacity was used for these experiments, with the water temperature maintained within ± 0.5°C. The water was continuously circulated by the use of a pool filter. Ambient temperature was maintained at 24.0 ± 0.1°C.

Statistics. Analysis of variance with repeated measures (SAS) was utilized to compare the obtained variables among three water levels between R and E. When a significant F ratio was found, Tukey’s post hoc test was conducted. The Pearson product-moment correlation coefficient determined the degree of relationship between selected variables. Values were noted as means ± SE. Statistical significance was accepted at \( P < 0.05 \).
resulted in higher $T_r$ and $T_e$, except for $T_e$ in Sh-E group.

Table 1 shows comparisons between the $\Delta T_r$ and $\Delta T_e$, $D_T/e/min$ and $D_T/e/min$ among all conditions. When the immersion levels were compared, these differences and rates of change in temperature were greater in the order of Sh > H > K ($P < 0.05$) during E at $15^\circ C$, whereas those for Sh were greater than those for H and K groups ($P < 0.05$) in R at $15^\circ C$. In $25^\circ C$ water, $\Delta T_r$ and $\Delta T_e/min$ results in Sh group were greater than in K group during R ($P < 0.05$). When the comparisons were made between R and E conditions, $\Delta T_r$ and $\Delta T_e/min$ were different in H at $25^\circ C$ and K at $25^\circ C$ groups, whereas $\Delta T_e$ and $\Delta T_e/min$ were different in H at $15^\circ C$ group ($P < 0.05$). When $\Delta T_r$ and $\Delta T_e$ were compared, $\Delta T_r$ was greater than $\Delta T_e$ in Sh and H groups during both R and E at each water temperature ($P < 0.05$).

Fig. 1. Mean skin temperature at $15^\circ C$ (A) and $25^\circ C$ (B) water. *Significantly different from control-air value (min 0), $P < 0.05$.

Fig. 2. Rectal temperature at $15^\circ C$ (A, top) and $25^\circ C$ (B, top) and esophageal temperature at $15^\circ C$ (A, bottom) and $25^\circ C$ (B, bottom) water (see Fig. 1 for symbols). *Significantly different from control-air value (min 0); †significantly different between exercise and rest, $P < 0.05$. 
Table 1. Average magnitude and rate of change of internal temperatures during immersion in each condition

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<th>15°C</th>
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<th>25°C</th>
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<td></td>
<td>Shoulder</td>
<td>Hip</td>
<td>Knee</td>
<td>Shoulder</td>
<td>Hip</td>
<td>Knee</td>
</tr>
<tr>
<td>ΔT&lt;sub&gt;re&lt;/sub&gt;, °C</td>
<td>Rest</td>
<td>-1.291 ± 0.11†</td>
<td>-0.765 ± 0.071†</td>
<td>-0.353 ± 0.051&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>-0.666 ± 0.056†</td>
<td>-0.526 ± 0.052†</td>
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<td></td>
<td>Exercise</td>
<td>-1.263 ± 0.095†</td>
<td>-0.747 ± 0.060†</td>
<td>0.120 ± 0.027&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>-0.585 ± 0.052†</td>
<td>-0.117 ± 0.034t</td>
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<tr>
<td>ΔT&lt;sub&gt;es&lt;/sub&gt;/min, °C/min</td>
<td>Rest</td>
<td>-0.024 ± 0.002</td>
<td>-0.010 ± 0.001</td>
<td>-0.005 ± 0.001&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>-0.010 ± 0.001</td>
<td>-0.007 ± 0.001</td>
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<td></td>
<td>Exercise</td>
<td>-0.023 ± 0.001</td>
<td>-0.011 ± 0.001</td>
<td>0.001 ± 0.001&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>-0.009 ± 0.001</td>
<td>-0.002 ± 0.001</td>
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<tr>
<td>ΔT&lt;sub&gt;es&lt;/sub&gt;, °C</td>
<td>Rest</td>
<td>-0.516 ± 0.071</td>
<td>0.032 ± 0.059</td>
<td>0.000 ± 0.039&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.180 ± 0.048</td>
<td>-0.014 ± 0.057</td>
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<td></td>
<td>Exercise</td>
<td>-0.706 ± 0.103</td>
<td>-0.340 ± 0.051</td>
<td>0.219 ± 0.032&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>-0.113 ± 0.031</td>
<td>0.284 ± 0.043</td>
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<tr>
<td>ΔT&lt;sub&gt;es&lt;/sub&gt;/min, °C/min</td>
<td>Rest</td>
<td>-0.006 ± 0.002</td>
<td>0.005 ± 0.002</td>
<td>0.002 ± 0.001&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>-0.001 ± 0.001</td>
<td>0.002 ± 0.001</td>
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<tr>
<td></td>
<td>Exercise</td>
<td>-0.012 ± 0.002</td>
<td>-0.005 ± 0.001</td>
<td>0.003 ± 0.001&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>0.000 ± 0.001</td>
<td>0.006 ± 0.001</td>
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</table>

Values are means ± SE. See text for variable calculations. ΔT<sup>e</sup> re, change in rectal temperature; ΔT<sup>e</sup> es, change in esophageal temperature. *Significant difference between rest and exercise; †significant difference between ΔT<sup>e</sup> re and ΔT<sup>e</sup> es of corresponding conditions; ‡, §, and ‖: significant difference between shoulder (Sh)- and hip (H)-immersed groups, between H and knee-immersed (K) groups, and between K and Sh groups, respectively; during rest or exercise; P < 0.05.

Table 2 shows the relationship between T<sub>re</sub> and T<sub>es</sub> during each condition. During all immersions, correlation analyses revealed a high degree of association between T<sub>re</sub> and T<sub>es</sub> (P < 0.05) and between ΔT<sub>re</sub> and ΔT<sub>es</sub> (P < 0.05), except for K-E at 25°C group. When ΔT<sub>es</sub>/min and ΔT<sub>es</sub>/min values were compared, only the H-R at 15°C, H-E at 15°C, and H-R at 25°C groups were significantly related.

Heat-flow responses. The magnitude of heat-flow difference at each site between E and R (E minus R; Δh) is shown in Table 3. Comparisons among immersion levels showed that Δh was significantly smaller in the forearm site in the H than in the Sh group at 15°C, and in H than in Sh or K groups at 25°C (P < 0.05), whereas no differences were observed at the other sites (P > 0.05). When the sites at 15°C were compared, Δh in the calf site was higher than that in the chest site in Sh group, and Δh in the thigh site was higher than that in the forearm site in H group (P > 0.05). In the H group at 25°C, Δh was higher in the thigh site than in any other sites (P < 0.05).

During both R and E at 15°C, h was greater (P < 0.05) in Sh than in H and K groups, whereas no differences (P > 0.05) were found between H and K groups (Fig. 3). During R at 25°C, h was greater in Sh than in both H and K groups, whereas H was greater than K (P < 0.05). During E at 25°C, h was greater in Sh than in K group (P < 0.05).

The amount of h for each site was converted for an estimation of its fractional contribution to h (Fig. 4). During R at 15°C, each site among the water levels showed a different fractional contribution (P < 0.05). The fractional h of the calf site was greater (P < 0.05) in K compared with H and Sh groups and in H compared with Sh at both water temperatures in R and E. The value of h at the thigh site was greater (P < 0.05) in H than in Sh and K groups, whereas that of the chest site was greater (P < 0.05) in Sh than in H and K groups at both 15 and 25°C during R and E. During H at both water temperatures, the thigh site showed greater fractional heat loss during E compared with R (P < 0.05), whereas each of the forearm, triceps, and chest sites contributed less to the total h during E than R (P < 0.05).

Metabolic responses. Regardless of the water temperature and the immersion level, E condition induced higher M compared with R (Fig. 5, P < 0.05). At 15°C in both R and E conditions, M was higher in Sh group than for H and K groups (P < 0.05). In K-R at 15°C, M did not increase compared with the control-air value (P > 0.05). During R at 25°C, M was higher in Sh than in H and K groups, but no significant differences (P > 0.05)
were found among the water levels during E. During R in H and K groups, M did not increase significantly compared with the control-air value ($P > 0.05$).

When the differences of M between E and R were calculated (M in E minus M in R), the value was lower in Sh group ($121.4 \pm 7.4$ and $97.1 \pm 5.8$ W/m$^2$) than that of H ($155.6 \pm 6.4$ and $126.2 \pm 4.9$ W/m$^2$) and K groups ($154.7 \pm 4.3$ and $164.6 \pm 6.3$ W/m$^2$ at 15 and 25°C, respectively) in both water temperatures ($P < 0.05$). The value in K group was higher than in H group at 25°C ($P < 0.05$) but not at 15°C.

**DISCUSSION**

Cold-water exposure generally induces a fall of internal body temperature (4, 6, 9, 22). This fall can be either accelerated by exposing a greater body surface area, lowering water temperature (6), and enhancing the convective component of heat loss (2, 4), or countered by increasing vasomotor tone and heat liberation (7, 13, 26). During cold-water immersion at varying immersion levels, however, the thermal stimuli and resultant metabolic adjustments may not be equal to those noted for whole body immersion. Thus the present experiments were conducted to determine the impact of various depths of cold-water immersion and exercise on thermal balance indexes, particularly on internal body temperatures.

### Table 3. Mean heat flow differences between exercise and rest at each measuring site

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<tr>
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<th>15°C</th>
<th>25°C</th>
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<tr>
<td></td>
<td>Shoulder</td>
<td>Hip</td>
</tr>
<tr>
<td>Calf</td>
<td>138.5 ± 12.3^1</td>
<td>107.1 ± 19.9</td>
</tr>
<tr>
<td>Thigh</td>
<td>85.5 ± 13.0</td>
<td>242.4 ± 27.3^2</td>
</tr>
<tr>
<td>Chest</td>
<td>0.2 ± 14.3^3</td>
<td>24.3 ± 3.7</td>
</tr>
<tr>
<td>Triceps</td>
<td>37.8 ± 14.0</td>
<td>13.4 ± 2.3</td>
</tr>
<tr>
<td>Forearm</td>
<td>74.9 ± 16.3^3</td>
<td>-13.7 ± 4.4^2</td>
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Values are means ± SE in W/m². Mean heart flow (h) differences were calculated as h in exercise minus h in rest. ^1,2,3,4,5,6 Significant differences between conditions with the matching number; ^a significant difference between Sh and H; ^b significant difference between H and K, $P < 0.05$.

The present study showed that the interpretation of internal body temperature response during immersion at different immersion levels may vary according to the sites of measurement for internal temperature. Furthermore, we observed that the immersion level did not correspond to fall of internal body temperatures nor to the magnitude of M.

The trend of internal body temperature responses from two sites during immersion was in good agreement, as significant correlations were noted between the absolute $T_{re}$ and $T_{es}$ values (Table 2). Also, when we compared the magnitude of change in $T_{re}$ and $T_{es}$ during each immersion, we observed a close parallelism between the temperatures. These analyses show that $T_{re}$ and $T_{es}$ reflect each other regardless of the water temperatures and depths. However, the observation of a lesser magnitude of change in $T_{es}$ than in $T_{re}$ during cold-water immersion deeper than the hip (Table 1 and Fig. 2) suggests that $T_{es}$ does not fluctuate as widely as $T_{re}$ during cold-water immersion. In many conditions, $T_{es}$ maintained its baseline value, whereas $T_{re}$ decreased significantly (Fig. 2).

One reason for a greater drop of $T_{re}$ could be the different locations of the rectum and the esophagus within the body. Thus $T_{re}$ appears to respond more closely to the magnitude of thermal stress in the lower body than $T_{es}$. For example, we demonstrated that $T_{re}$

![Fig. 3. Mean body heat flow at 15°C (A) and 25°C (B) water (see Fig. 1 for symbols). † Significantly different between exercise (E) and rest (R); ^a, ^b, and ^c: significantly different between shoulder group (Sh) and hip group (H), between H and knee group (K), and between K and Sh, respectively, during R or E; $P < 0.05$.](http://jap.physiology.org/)

Downloaded from http://jap.physiology.org/ by 10.220.32.2 on July 10, 2017
at rest was reduced from its baseline value in 15°C water at knee- and hip-level immersions, whereas Tes showed no change. Furthermore, Tes at rest was not affected by 25°C water at any immersion level, whereas Tre was significantly lowered in the same conditions (Fig. 2). We speculate that this difference in response was due to the distance between the lower limbs and rectum, compared with the esophagus. This would augment conductive heat transfer as well as cause a stronger influence of convective heat exchange by returning venous blood in the rectal region.

It could be argued that, if the conductive heat transfer in the body influences changes of internal temperature, then Tre and Tes should change to the same degree during whole body immersion. However, our data indicate that the magnitude of Tre drop during both water temperatures at the shoulder-level immersion was still larger than that of Tes. Possibly a blood volume shift from the periphery to the thoracic region during the shoulder-level immersion conserved heat inside the thorax, whereas the pelvic area did not reflect this redistribution of blood (17), thus causing a smaller fluctuation of Tes.

During exercise, the magnitude of changes of the two internal temperatures was fairly consistent with the resting state. In air, Kolka et al. (11) observed no difference in changes of Tre and Tes from rest to steady-state cycling at an intensity similar to that of the present study. Sagawa et al. (19) also reported that the two internal temperatures were not different while exercising at diverse intensities during immersions at about thermoneutral temperatures. When our subjects could maintain thermal balance, such as exercise at the knee-level immersion, we also observed no differences in the two temperatures. When maintenance of the internal temperature was not steady (approximately greater than ±0.005°C/min), however, the magnitude of change in Tre was always greater than Tes during exercise.

Most research has documented that exercise in cold water helps maintain internal body temperatures, although this is not always consistent (8, 16, 22) depend-

**Fig. 4.** Fractional heat flow of individual measurement site to total body heat flow at 15°C (A) and 25°C (B) water.

†Significantly different between E and R at P < 0.05; a, b, and c: significantly different between Sh and H, between H and K, and between K and Sh, respectively, during R or E; P < 0.05.

**Fig. 5.** Metabolic heat production at 15°C (A) and 25°C (B) water (see Fig. 1 for symbols). *Significantly different from control-air value (min 0); †significantly different between E and R; a, b, and c: significantly different between Sh and H, between H and K, and between K and Sh, respectively, during R or E; P < 0.05.
ing on the exercise intensity (7, 15, 27) and mode of exercise (5, 27). In this study, light-intensity cycling exercise did not prevent $T_{re}$ and $T_{er}$ from falling during 15°C water immersion to depth greater than knee level. In both water temperatures, however, cycling while immersed to the knee raised both internal temperatures compared with rest. If we assume that resting in water at knee depth has little effect on internal temperatures, then exercise appears to have little merit to further maintain body thermal balance, at least in water as cold as 15°C. Light exercise may not be adequate to prevent internal temperatures from falling with immersion greater than knee depth in 15 and 25°C water. However, $T_{re}$ was higher during exercise than at rest at all levels in 25°C water.

When we subtracted the average $h$ of each measuring site during rest from the exercise counterpart (Table 3), we considered the calculated value as the extra heat loss caused by factors other than the conductive component of heat transfer. Presumably, these could be the combined effect of a high convective heat transfer due to water turbulence at the body surface and a reduced peripheral vasoconstriction during exercise. We observed a large $h$ difference between exercise and rest for the lower body regardless of water temperature, suggesting that heat loss in the lower body can be greatly magnified by leg cycling, which is consistent with our previous observations (26).

In that study, we observed that $h$ in the chest area was higher for leg cycling than in rest and postulated that this could be due to greater blood flow in that region (3, 28). In contrast, we observed no differences of $h$ in the chest area between rest and exercise. The discrepancy is due to higher resting metabolic rate during immersions in the present subjects than the previous subjects (26), suggesting a higher cold stimulus during immersions in the present study. This may be possible because shivering could take place largely in the trunk region, as the blood flow was already heightened in that region so that exercise did not increase the existing level of $h$ (8).

Examination of the relative contribution of each body region to total body $h$, regardless of water temperature or activity level (Fig. 4), showed that the thigh site was the major location for heat loss when immersed at the hip level. At the shoulder-level immersion in all conditions, the combined fractional values for thigh and trunk regions contributed between 59 and 66% of total body heat loss, and this agrees with previous studies (4, 8, 29). The heat loss value for the arms was not more than 25% of the total $h$ during immersion, and the arms have the smallest surface area of all body regions; thus the least heat is lost from the arms than from any other body regions. Honig et al. (10) reported that the regional heat flux was the highest in the abdomen and was lower in the lower leg and arm areas. Such data on regional heat loss during cold-water immersion are of practical importance in that the trunk and the thigh have to be well protected to prevent major heat loss during occupational and military operations in cold water deeper than hip level (Table 3).

The $M$ in the present study did not appear to be closely related to the cutaneous thermal stimulus. Resting immersion up to the hip level minimally increased heat production, whereas immersion to the shoulder induced severalfold increase in heat production despite only a doubling of the body surface area in contact with the water (Fig. 5). It is possible that the summation of the cutaneous cold stimulus driving heat production may be much higher than simple mathematical addition of the skin surface area stimulated, thus providing a greater afferent thermal input to the hypothalamic thermoregulatory center. Alternatively, additional thermal input could arise from the core because of the lower temperatures during the shoulder compared with the hip exposures. In contrast to $M$, the amount of $h$ was fairly proportional to the area of body surface exposed to the water. This imbalance between heat loss and production, aforementioned, may explain the responses of internal temperature. It is certain that a water level exists for which a balance between body heat loss and production can be well established, hence maintaining internal temperature. In the present study, it could be a level between the knee and hip in 15°C water, and the hip in 25°C water. Thus immersion greater than these levels caused a fall of internal temperatures.

The increase in heat production induced by exercise was much smaller with immersion to the shoulder than to the hip or knee. It is noteworthy that heat production during rest at shoulder immersion of 15°C had reached the level of heat production during exercise in hip and knee immersions (Fig. 5). The high initial level of heat production during rest in cold water at shoulder level may cause a smaller increment of heat production from rest to exercise at this immersion level. Thus the increase in metabolic rate during exercise does not appear to be due to water resistance and mechanical inefficiency while immersed at shoulder level. Instead, the level of $M$ in cold water is achieved by muscular contraction involved in both shivering and exercise. However, the muscle groups involved in shivering and exercise are somewhat different, and some portion of these muscle fibers could be active for both shivering and exercise. Craig and Dvorak (7) suggested that exercise and shivering can occur at the same time. Hayward and Keatinge (8) also reported that individuals who produced relatively little increase in heat production by exercise were those who had already achieved the largest metabolic response at rest from shivering. This suggests that, during immersion to the shoulder at 15°C, a relatively large number of muscle groups are contracting for both shivering and exercise at the same time, leading to a summation of heat production that is less than in the other two water levels.

During exercise in 25°C water, total heat production at the three immersion levels was the same, although during rest it was higher for the shoulder-level immersion. Under this condition, exercise may have superimposed the shivering thermogenesis that occurred during rest. Regardless of the resting value of heat production, exercise resulted in a level of heat produc-
tion appropriate to the exercise intensity. This intensity blunted the decrease in $T_{re}$ shown during rest, although it did not maintain $T_{re}$ at the baseline level during shoulder-level immersion. Thus, when the level of heat production by exercise was not influenced by the cold stimulus, exercise blunted the reduction of $T_{re}$.

We conclude that caution is required in determining thermal balance in humans by means of a single-site internal body temperature during rest and exercise at various depths of cold-water immersion. For instance, $T_{re}$ fell during rest for all water immersions and also during light exercise while the subjects were immersed deeper than knee level in 15°C and deeper than hip level in 25°C water. In contrast, $T_{re}$ dropped only in exposure at 15°C water at hip and shoulder levels. Generally, the failure to maintain internal temperatures at these depths of immersion was due to the seemingly insufficient thermal drive for metabolic heat generation from the lower body (primarily the legs), hence compensating heat loss during rest. Compared with rest, exercise seemed to be beneficial for maintaining internal body temperature only when the amount of extra heat generated was additive to the resting level of heat production.

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