Physiological and metabolic responses to a hill walk

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Humphreys, D. P. M. Maclaren, and T. Reilly.** Physiological and metabolic responses to a hill walk. *J Appl Physiol* 92: 179–187, 2002.—The physiological and metabolic demands of hill walking have not been studied systematically in the field despite the potentially deleterious physiological consequences of activity sustained over an entire day. On separate occasions, 13 subjects completed a self-paced hill walk over 12 km, consisting of a range of gradients and terrain typical of a mountainous walk. During the hill walk, continuous measurements of rectal (T_{re}) and skin (T_{sk}) temperatures and of respiratory gas exchange were made to calculate the total energy expenditure. Blood samples, for the analysis of metabolites and hormones, were taken before breakfast and lunch and immediately after the hill walk. During the first 5 km of the walk (100- to 902-m elevation), T_{re} increased (36.9 ± 0.2 to $38.5 \pm 0.4°C$) with a subsequent decrease in mean T_{sk} from this time point. T_{re} decreased by ~1.0°C during a 30-min stop for lunch, and it continued to decrease a further 0.5°C after walking recommenced. The total energy intake from both breakfast and lunch [5.6 ± 0.7 (SE) MJ] was lower than the energy expended [14.5 ± 0.5 (SE) MJ; $P < 0.001$] during the 12-km hill walk. Despite the difference in energy intake and expenditure, blood glucose concentration was maintained. The major source of energy was an enhanced fat oxidation, probably from adipose tissue lipolysis reflected in high plasma nonesterified fatty acid concentrations. The major observations were the varying thermoregulatory responses and the negative energy balance incurred during the hill walk. It is concluded that recreational hill walking can constitute a significant metabolic and thermoregulatory strain on participants.

energy balance; thermal regulation; field study

THE PROLONGED DURATION OF a typical hill walk places exceptional demands on the participants. The specific demands of hill walking incorporate activity of varying intensity and duration, both of which are influenced by factors such as the physical fitness of the participant, dietary intake, backpack weight, environmental weather conditions, and severity of the terrain. Besides, hill walkers can be caught unexpectedly and unprepared when rain and wind accompany outdoor activities in cool weather. Decreased thermal insulation of wet clothing presents a serious challenge to body temperature regulation, which can be compounded by fatigue associated with prolonged exercise such as hill walking (33, 36, 38, 42).

The problem of wet-cold hypothermia is recognized by search-and-rescue organizations worldwide. Nevertheless, their ability to design educational material concerning this hazard is hindered by lack of knowledge of the physiological and psychological responses (42). The information that is available derives from the pioneering work of Pugh (36–38), supplemented by anecdotal descriptions of exposure incidents (23, 25, 36, 41).

Pugh (37) proposed that maintaining an oxygen uptake ($\dot{V}O_2$) of 2–2.5 l/min or 50–60% maximum oxygen uptake ($\dot{V}O_{2\,max}$) would offset heat loss and combat the debilitating effects of the cold, wet, and windy environment. Although these observations were based on only three subjects, recent work by Weller et al. (45) supported Pugh's postulate. Both experiments were based in an environmental chamber, and subjects exercised on a cycle ergometer and treadmill, respectively. Pugh (37) and Weller et al. (45) showed that, when exercise metabolism is reduced, the increase in shivering may be insufficient to prevent a decrease in deep body temperature. Weller et al. (45) reported that rectal temperature (T_{re}) and the metabolic responses to an initial 120-min phase of exercise at ~60% of peak $\dot{V}O_2$ ($\dot{V}O_{2\,peak}$) were not influenced by the cold stress of a wet and windy environment. However, during a subsequent 240-min phase of exercise at 30% $\dot{V}O_{2\,peak}$, T_{re} was lowered by 0.6°C, whereas the following were elevated: $\dot{V}O_2$ (25%), the proportion of carbohydrate (CHO) oxidized, and the venous concentrations of lactate, glucose, norepinephrine, and epinephrine.

The studies reviewed have been limited to simulated conditions. Consequently the influence of a "typical" day's hill walk on a range of physiological and metabolic variables, in the field, has not been established. Given such limitations, the aim of the present study was to investigate selected responses to a typical hill

walking event to gauge the overall physiological and metabolic strain. The field conditions would likely impose additional stresses not encountered during simulated conditions, such as stoppage of activity for fluid and food intake (transiently altering the balance between heat production and heat dissipation), in conjunction with varying terrain and weather conditions. Furthermore, we aimed to quantify both the energy cost of such activities and relevant responses that are important in the safety of hill walkers, such as the potential thermal stress, impaired psychomotor performance, and the ability to maintain glycemia. This type of study may be important in adding to the mostly anecdotal information regarding exposure and recreational activities. Because of the continuously changing intensity of activity, it is unlikely that individuals will be able to operate at or above 50–60% $\dot{V}O_{2\,max}$, the $\dot{V}O_2$ "cutoff" point described by Pugh (37) for combating heat loss during a hill walk. Although Pugh's postulate may have an element of truth, it would depend on factors such as favorable ambient temperature, the clothing worn, terrain, and physiological capabilities of the participants. The first hypothesis, therefore, is that the $\dot{V}O_2$ cutoff is not a realistic component of hill walking. Second, it was hypothesized that a seemingly "normal" hill walk in possible adverse, but not uncommon, conditions leads to a significant physiological, psychomotor, and metabolic stress on the body.

METHODS

Subjects

Thirteen subjects (11 men and 2 women) participated in this study, which was reviewed and approved by the Human Ethics Committee of Liverpool John Moores University. The subjects gave written consent to participate in the study after they had been fully informed of the nature, purpose, and possible risks associated with the study. The physical characteristics of the subjects are shown in Table 1. The majority of the subjects were active and experienced hill walkers. Experiments were conducted from January through March. Body density and percentage of body fat (%fat) were estimated from skinfold thicknesses over the biceps, triceps, and subscapular and suprailiac areas (14). Fitness level was established by using a continuous incremental treadmill running test to exhaustion (3). A plateau in the $\dot{V}O_2$-to-work relationship was reached in only four subjects; therefore, the highest aerobic power was expressed as $\dot{V}O_{2\,peak}$ and not as $\dot{V}O_{2\,max}$.

Protocol and Procedures

On separate occasions, subjects completed a 12-km (8 mile) hill walk. The course varied in elevation from 100 to 902 m above sea level and consisted of a range of gradients and terrain typical of a mountainous hill walk. A caravan was used as a temporary field laboratory and for living accommodation, and was located at the start and end of the hill walk. Subjects woke each morning between 0500 and 0530 and completed the preliminary experiments before the hill walk (Fig. 1). Self-paced walking began each day between 0700 and 0800. Before the walk and on its completion, subjects weighed themselves nude. Subjects were permitted fluid and food ad libitum. They selected their own food and fluids for the walk, which were preweighed before the walk. The energy gained from CHO, fat, and protein was subsequently determined by using standardized food tables (30). After initial weighing, the participants inserted a rectal temperature probe to a depth of 10 cm beyond the anal sphincter. Skin temperature (T_{sk}) was assessed by the placement of temperature thermistors on the chest, forearm, thigh, and shin. Thermistors and the rectal probe were connected to a data logger (Squirrel meter 1000, Grant Instruments, Cambridge, UK) that recorded data every 6 min. On the walk, a rest period of ~1–3 min was allowed every time thermal measurements were made, and 30 min were allowed for lunch (Fig. 1). During the hill walk, respiratory gas-exchange measures were obtained with a portable telemetry system (Metamax, Cortex Biophsik, Borsdorf, Germany). All subjects carried a lightweight waterproof backpack that contained the Metamax system and thermal logger to allow continuous recording of respiratory gas exchange and T_{re} and T_{sk}, respectively. The loaded pack weighed 9.5 kg, which is consistent with a hill-walking scenario.

Measurements and Analysis

Temperature and heart rate. T_{re} and T_{sk} were monitored continuously and recorded every 6-min with the data logging system. Heart rate (HR) was recorded by means of short-range radiotelemetry (PE3000 Sports Tester, Polar Electro, Kempele, Finland) every minute and were subsequently averaged over 5-min blocks. Mean T_{sk} ($\bar{T}_{sk}$) was estimated by the formula of Ramanathan (39): $\bar{T}_{sk}$ (°C) = 0.3(chest) + 0.3(arm) + 0.2(thigh) + 0.2(shin). Mean body temperature ($\bar{T}_b$) was estimated by the method of calculation used by Bittel (6): $\bar{T}_b = x \cdot T_{re} + (1 - x) \cdot \bar{T}_{sk}$, where x represents the cold weighting coefficient of 0.67. During one of the experiments, the data-logging system malfunctioned. Furthermore, one subject was not willing to use a rectal probe, and therefore the T_{re} data were based on 11 subjects and the $\bar{T}_{sk}$ data were based on 10 subjects.

Environmental measurements. Environmental air, dry, and wet bulb temperatures and velocity were recorded with a digital sling psychrometer thermohygrometer and a kestrel vane anemometer, respectively. Wind chill index was calculated from the air temperature and velocity by the equation of Nishi and Gagge (32): $K_o = (33 - T_a)(10V^{0.5} - V + 10.45)$, where K_o is the cooling power of the environment (kcal·m^{-2}·h^{-1}), T_a is the ambient temperature (°C), and V represents the air velocity (m/s).

Table 1. *Physical characteristics of the subjects*

	Age, yr	Mass, kg	Height, m	BMI, kg/m^2	Body Surface Area, m^2	Body Fat, %	$\dot{V}O_{2\,peak}$, ml·kg^{-1}·min^{-1}
Mean ± SE	25.6 ± 1.9	72.5 ± 2.9	1.8 ± 0.03	22.7 ± 1.1	1.9 ± 0.05	17.2 ± 2.4	58.9 ± 2.1
Range	18–32	55–82	1.7–1.9	18.3–26.7	1.6–2.16	9.9–30.4	47.7–67.0

Values are for 13 subjects. BMI, body mass index; $\dot{V}O_{2\,peak}$, peak oxygen uptake.
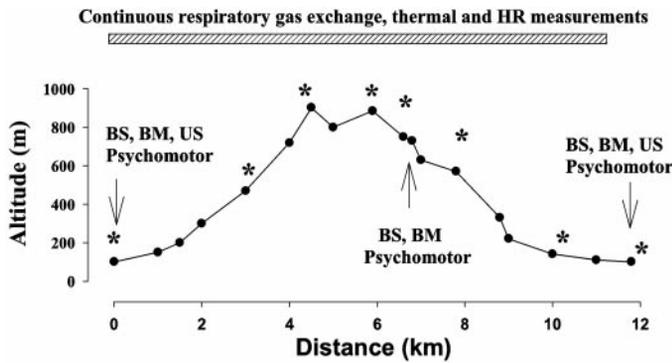
Fig. 1. Illustrated profile of the hill walk and associated measurements. HR, heart rate; BS, blood sample; BM, nude body mass; US, urine osmolality; Psychomotor, profile of mood state, rating of perceived exertion, reaction time, and grip strength measurements. *Windchill index measurement.

Thermal balance. All thermal balance data (rates) are expressed in units of watts per square meter. The rate of heat gained or lost (heat debt) from the body mass ($\pm S$) was computed from the equation of Burton (9): $\pm S = \Delta T_b \cdot mass \cdot c_{ti} \cdot SA^{-1}$, where ΔT_b is the change in T_b during each exercise period (from the preceding resting value to the end of the exercise period), c_{ti} is the average specific heat of the body tissues (1.29 $W \cdot kg^{-1} \cdot °C^{-1}$), and SA is the body surface area (m^2). The thermal balance was calculated and averaged every 2 km of the walk.

Indirect calorimetry. Continuous assessment of respiratory gas exchange was performed by the use of a portable telemetry system. Signals from the Metamax system were logged and subsequently retrieved at the end of the hill walk. This procedure allowed for continuous monitoring of $\dot{V}O_2$, ventilation, and respiratory exchange ratio. The percent contributions of the CHO and fat oxidation were estimated from nonprotein (NP) $\dot{V}O_2$ and respiratory exchange ratio (RER) data with the use of the following formulas: %CHO = [(RER$_{NP}$ − 0.707)/(1 − 0.707)] and %fat = 100 − %CHO. It was assumed that protein oxidation contributed 12.5% of energy expenditure at rest and that exercise did not alter this relative rate of protein utilization (45). The respiratory quotients of CHO, fat, and protein were taken as 1.00, 0.707, and 0.81, respectively. Oxidation rates (g/min) were estimated for CHO, fat, and protein, assuming 0.829, 2.019, and 0.966 liters of oxygen were consumed per gram of substrate oxidized (28), respectively. During the hill walk, CHO and fat oxidization rates were calculated and averaged over 10-min blocks at predetermined points in accordance with the other measurements. Total oxidation rates were then averaged for the whole hill walk. Energy expenditure was calculated from the averaged $\dot{V}O_2$ and CO_2 production from the whole walk by using the formulas of Elia and Livesey (15). Before use, the Metamax system was calibrated using both calibrated gas and ambient air. The volume transducer was calibrated using a 3-liter syringe. To decrease any error, the system was recalibrated during the hill walk when the subjects stopped for lunch. Because of technical problems during three of the walks, the respiratory gas exchange data were based on 10 subjects.

Psychomotor measurements. The Profile of Mood State (POMS) was measured using 65 ratings each on a 5-point rating scale. The scales are factored into six mood scores: depression/dejection, tension/anger, anger/hostility, confusion/bewilderment, fatigue/inertia, and vigor/activity (31). In addition, the subjects were asked to rate their overall ratings of perceived exertion (RPE) on a 6–20 scale (8) from the start

of the walk until the lunch stop, and from the lunch stop until the completion of the walk. Reaction time (cognitive function) tests (Hick's law) (1-, 2-, 4-, and 8-choice reaction time for a finger response) were assessed on a laptop computer before, during, and after the walk. Subjects were fully familiarized with the use of the equipment. Grip strength (motor function) was assessed by means of a handgrip dynamometer (Takei, Narragansett, Japan).

Blood and urine sampling and analysis. Blood samples were obtained from subjects in a semireclined position before, during, and immediately on completion of the walk as illustrated in Fig. 1. The venous blood samples (5 ml) were drawn from a superficial forearm vein with minimum stasis, then immediately placed in a vacuum flask containing ice. From the blood samples, serum was separated rapidly at ~4°C and frozen for later determination of serum nonesterified fatty acids (NEFA) and triacylglycerol (TAG) concentrations by enzymatic methods. In addition, a portion of the whole blood was immediately deproteinized with perchloric acid (7% wt/vol) in preparation for whole blood glycerol, lactate, 3-hydroxybutyrate (3-OHB), and glucose determination by enzymatic methods. All enzymatic methods were adapted to a Monarch centrifugal analyzer (Instrumentation Laboratory, Warrington, UK). Serum insulin concentrations were determined with a double-antibody radioimmunoassay (Pharmacia and Upjohn, Milton Keynes, UK). Serum cortisol concentrations were determined by using a solid-phase radioimmunoassay (Diagnostic Products, Llanberis, Wales, UK). Some of the uncoagulated blood was also used for the measurement of hemoglobin and packed cell volume (conventional microhematocrit method). Plasma volume changes were calculated from changes in hemoglobin and packed cell volume relative to initial resting values as described by Dill and Costill (12).

Urine was collected during the rest day before the hill walk, in which subjects performed no exercise, and during the hill walk at the following times: 0800–13:00, 1301–1800, and 1801–2000. From these collections, a 5-ml mixed sample was removed. Urine epinephrine, norepinephrine, creatinine, and dopamine concentrations were then analyzed by using high-performance liquid chromatography with electrochemical detection (in-house method, Dept. of Clinical Chemistry, The Royal University Hospital, Liverpool, UK). Index of dehydration was determined in triplicate using urine osmolality determined by freezing-point depression (model 3300 Advanced Microosmometer, Vitech Scientific, West Sussex, UK). For the urine osmolality, a 5-ml sample was produced after the first void of the day, and then from the first sample after the walk.

Statistical analysis. Variables are presented as means ± SE. Data were initially tested for normality, before being analyzed by repeated-measures ANOVA. The ANOVA results were corrected by the Huynh-Feldt ϵ-adjusted degrees of freedom when the violation to sphericity was minimal (>0.75), and the Greenhouse-Geisser correction was used when sphericity was violated (<0.75) and significant condition and condition-time interactions were identified (16). Post hoc tests (honestly significantly different) were performed to isolate any significant differences. Student's paired t-tests ascertained between-condition differences when a variable was measured once. Statistical significance was set at $P \leq 0.05$ for all statistical tests.

RESULTS

Exercise Duration

All subjects completed the 12-km hill walk. The mean (range) duration for the hill walk was 348 (245–

490) min. The differences in the time to complete the walk were due mainly to variations in weather conditions and terrain. Both cold, wet, and windy weather and deep snow underfoot led to an increased time to complete the hill walk.

Energy Balance

Energy intake and energy expenditure during the hill walk are given in Table 2. Total energy intake was lower than total energy expended during the hill walk in all subjects. CHO, fat, and protein comprised 65, 25, and 10%, respectively of all food consumed, in contrast to 47, 42, and 11%, respectively, of fuels oxidized. The energy intake from both CHO and fat was lower than the amount oxidized ($P < 0.001$), leading to the lower energy intake relative to expenditure ($P < 0.001$). The relatively high energy expenditure of 14.5 ± 0.5 MJ reflects the high energetic cost of hill walking, even when pursued over a relatively short duration. The negative energy balance is also shown by a decrease (72 ± 2 to 70 ± 2 kg; $P < 0.05$) in nude body mass as a consequence of the walk.

Thermoregulatory and Environmental Data

The mean (range) of the recorded environmental data for air velocity, air temperature, and wind chill index was 2.8 (0.1–10.4) m/s, 6.4 (−1.3–13.2)°C, and 520 (176–1,239) kcal·m^{-2}·h^{-1}, respectively. These figures highlight the variability in the weather conditions over the period of testing. Five of the walks were completed in cold, wet, and windy weather. The surface conditions on the walks tended to vary with the weather. Snow and ice were regularly encountered, along with high winds, as reflected by a high windchill index; these factors represent walking in very demanding climatic conditions.

The rise in T_{re}, illustrated in Fig. 2*C*, is a typical response during both exercise and the initial stages of cooling because of peripheral vasoconstriction decreasing the return of cooled blood from the periphery. Also reflected at this point were the apparent decreases in T_{sk} (Fig. 3*A*). T_b was maintained relatively well during the hill walk, until the stop for lunch at midwalk (Fig. 2*A*). A loss in $\bar{T}_b$ was evident at this point, before a subsequent rise when walking commenced again. Figure 3 illustrates an apparent temperature "afterdrop." This drop was reflected in a further decrease in T_{re} after walking recommenced. T_{sk} showed a typical rise during the 30-min rest at the midpoint of the walk, followed by a subsequent decrease when walking com-

menced (Fig. 3). Thermal balance demonstrated an initial decrease during the first 2-km walk, before gaining a positive balance (Fig. 2*B*). A marked negative balance ($−356 \pm 23$ W·m^2) was observed during the lunch stop and for the subsequent 2 km after this, before gaining a positive balance again.

During the ~30-min stop at midwalk, three subjects showed a pronounced shivering response after ~15 min of rest. T_{re} fell ~1.0°C from the level observed during the prelunch walking. Before the lunch stop, two of these subjects showed early signs of exposure; symptoms included stumbling, withdrawal from voluntary conversation, and slowing down in pace. Decreases in thermal balance were also observed at this time. The majority of the subjects complained of feeling "very cold" and wanting "to speed up" during the period after the lunch stop: these subjective impressions usually lasted ~15–45 min, depending on the weather conditions.

Psychomotor performance. The POMS profile showed an expected increase in tension and confusion before the walk ($P < 0.05$) and an increase in fatigue ($P < 0.05$) postwalk relative to both before and at midwalk. Overall RPE from the start of the walk to the lunch stop and to the final part of the walk was 15 ± 2 and 13 ± 3, respectively. There was a small decrease in grip strength (45.4 ± 2.7 to 43.5 ± 2.8 kg/m^2) from prewalk to postwalk ($P < 0.01$). Any changes in reaction time were less evident. The only significant changes in reaction time were evident in "one-finger" reaction time ($P < 0.01$) and in the recorded errors (4 finger) ($P < 0.05$, not shown), both after completion of the walk. However, the normal circadian variation of an accelerated reaction time from morning to afternoon was clearly not evident (not shown).

Respiratory gas exchange and HR responses. During the first ~5 km of ascent, RER increased from 0.82 ± 0.03 at base to 0.89 ± 0.02. During the descent, RER gradually fell to $<0.84 \pm 0.02$ for the final 5 km of the walk (Fig. 4*A*). RER changes are reflected in the oxidation rates of CHO and fat shown in Fig. 4*B*. During ascent, both CHO and fat oxidation increased. After the first 4 km, CHO oxidation decreased for the duration of the walk, with fat oxidation remaining elevated (Fig. 5). Increases in the $\dot{V}O_2$ and HR were evident during the rise in altitude over the first 4.5 km of the hill walk (Fig. 5, *D* and *C*). From ~3 km until the descent of the hill walk (~6 km), subjects were operating at ~50% $\dot{V}O_{2\,peak}$ with an average HR of 148 ± 8 beats/min; during the descent, this value fell to ~25–

Table 2. *Total energy, CHO, fat, and protein intake vs. total energy expenditure, CHO, fat, and protein oxidation during the hill walk*

EI, MJ	EE, MJ	CHO, g	CHO$_{ox}$, g	Fat, g	Fat$_{ox}$, g	P, g	P$_{ox}$, g
5.6 ± 0.7	14.5 ± 0.5†	232 ± 30	432 ± 16†	37 ± 4	162 ± 6†	41 ± 4	95*

Values are means $\pm$ SE for 10 subjects. EI, energy intake; EE, energy expenditure; CHO, Fat, and P, carbohydrate, fat, and protein intake, respectively; CHO$_{ox}$, Fat$_{ox}$, P$_{ox}$, amount of carbohydrate, fat, and protein oxidized. *It was assumed that P$_{ox}$ contributed 12.5% of energy expenditure at rest and that exercise did not alter this relative rate of protein utilization. †Significant differences between total EI, CHO, and Fat compared with total EE, CHO$_{ox}$, and Fat$_{ox}$ during the hill walk: $P \leq 0.001$ for expenditure and oxidation vs. intake.
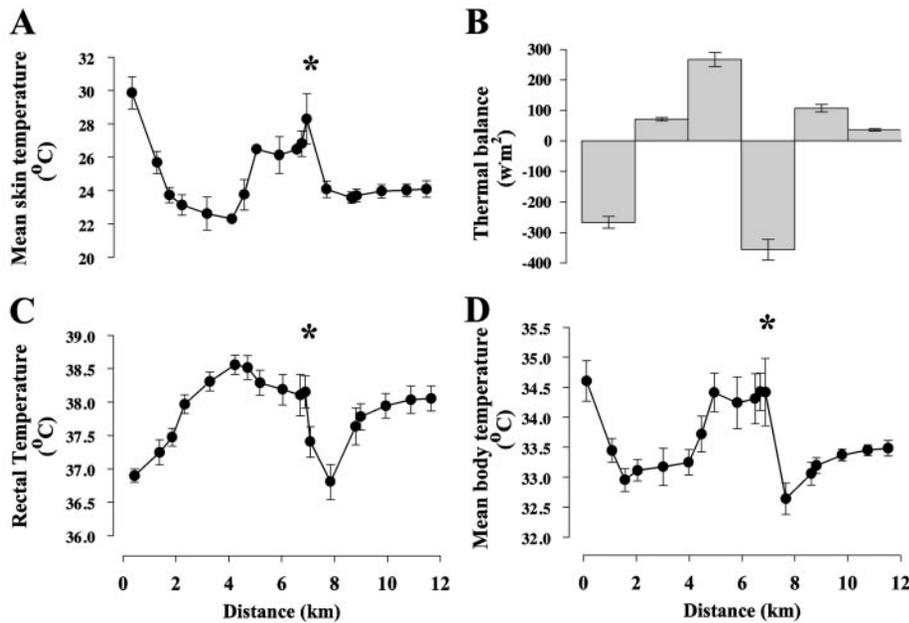
Fig. 2. Thermoregulatory responses during the hill walk. Values are means ± SE for 11 subjects. *A*: mean skin temperature. *B*: thermal balance. *C*: rectal temperature. *D*: mean body temperature. *Point at which a 30-min rest was taken for lunch.

40% of $\dot{V}O_{2\,peak}$ with HR averaging 126 ± 5 beats/min (Fig. 5, *D* and *C*).

Blood and urine constituents

There were no significant changes in plasma volume during the walk. Consequently, circulating concentrations have not been corrected for hemoconcentration. Table 3 gives concentrations of the blood constituents. The energy metabolites 3-OHB, lactate, glycerol, and NEFA increased from prewalk to midwalk ($P < 0.001$). In contrast, there was no change in TAG concentra-

tions. Insulin increased significantly, whereas cortisol decreased significantly ($P < 0.01$) postwalk, relative to both prewalk and midwalk. Table 4 gives the concentrations of the urine catecholamine collections. Generally, the hill walk led to a marked elevation in urinary epinephrine and norepinephrine compared with the rest day. In addition, urine osmolality increased prewalk to postwalk (from 603 ± 86 to 744 ± 71 mosmol/kgH$_2$O; $P < 0.05$).

DISCUSSION

The main finding of this study was that a seemingly normal outdoor hill walk in adverse, but not uncom-
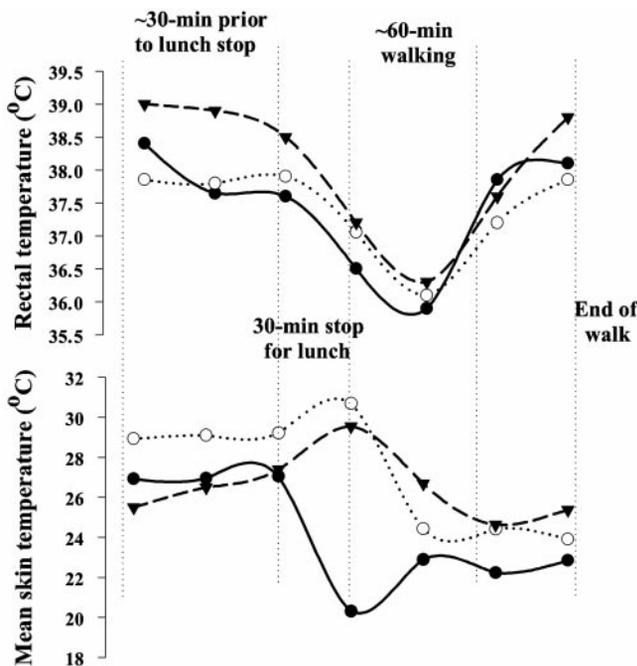

Fig. 3. Apparent temperature "afterdrop" that was evident in 3 subjects after the 30-min stop for lunch. Each line represents an individual subject.
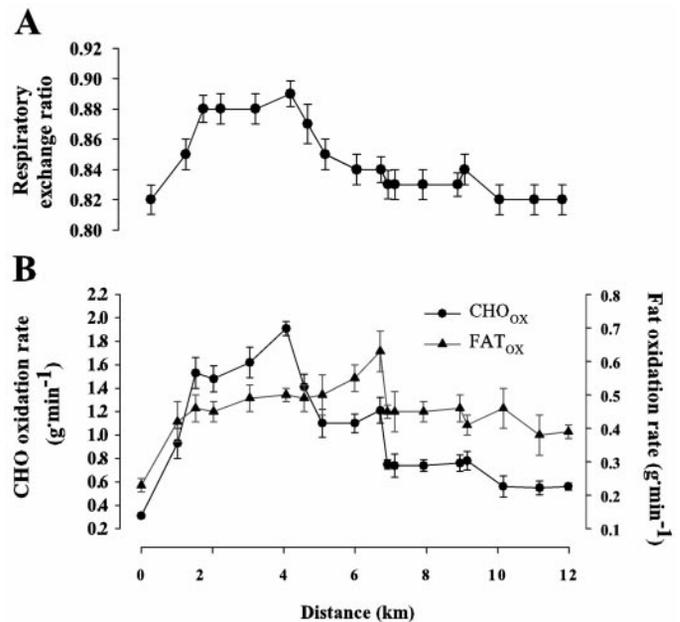

Fig. 4. Respiratory exchange ratio (*A*) and carbohydrate oxidation (CHO$_{ox}$) and fat oxidation (Fat$_{ox}$) rates (*B*) during the hill walk. Values are means ± SE for 11 subjects.
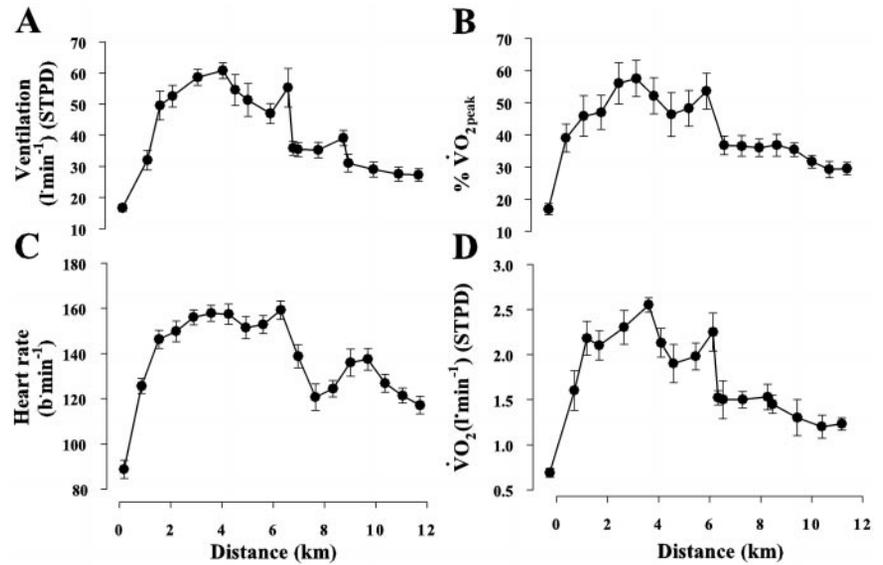
Fig. 5. Respiratory gas exchange and heart rate results from the hill walk. *A*: ventilation. *B*: maximal oxygen uptake ($\dot{V}O_{2 peak}$). *C*: heart rate. *D*: oxygen uptake ($\dot{V}O_2$).

mon, conditions led to a significant physiological stress on the body. Despite these stresses, which included dehydration, high thermal stress, and marked negative energy balance, subjects demonstrated only slight impairment in some of the measured psychomotor tests throughout the walk. Furthermore, the hill walk significantly altered the hormonal and metabolic milieu. Despite the large difference in energy intake and expenditure, a normal blood glucose level was maintained. The major source of energy, in the monitored walk, was an enhanced fat oxidation probably from adipose tissue lipolysis.

Physiological Responses

Pugh (37) described a $\dot{V}O_2$ cutoff point, above which individuals exercising in a cold, wet, and windy environment would not experience any influence on the physiological responses to exercise, i.e., drop in core temperature, mental impairment, extreme fatigue, and exhaustion. Below this point, there would be an obligatory increase in energy expenditure and subnormal T_{re} and muscle temperatures. Weller et al. (45) suggested that the cutoff point is likely to depend on factors, such as clothing insulation, body morphology, mass, and body fatness (43), and may account for the random nature of the hypothermic casualties described by Pugh (35, 37). The present observations highlight the variability in $\dot{V}O_2$ in response to the hill walk, which is likely to depend on such factors as terrain,

gradient, weather condition, backpack weight, exercise intensity, preceding diet, and thermal stress. It was only during the high-intensity part of the walk that subjects reached this cutoff point. This cutoff point was clearly variable. Because the hill walkers in this study walked at their own pace, it could be cautiously concluded that hill walkers do not consistently operate at, or above, this cutoff level.

Weller et al. (45, 46) demonstrated heat loss was greater in low-intensity ($\sim 30\% \dot{V}O_{2 peak}$) than high-intensity ($\sim 60\% \dot{V}O_{2 peak}$) walking, illustrating how the rate of heat production during high-intensity exercise will offset heat loss to the environment more effectively than low-intensity exercise. This observation has important implications for hill walking in that, during the low-intensity phase of a hill walk (e.g., walking downhill, navigation, and so on), an increased heat loss relative to heat production may be experienced. The factors already mentioned, along with individual variation in effective cold stress under given environmental conditions, may lead to a compromise in the ability to operate safely in the mountainous environment.

The observations of the present study regarding the thermal stresses involved in a hill walking event have provided some novel results. The results show generally higher values for the T_{re} profile than described in previous studies (42, 45, 46); this increase is most likely due to the elevated thermal insulation from the protective clothes worn by the hill walkers, causing a

Table 3. *Whole blood and serum constituents before, during, and after the hill walk*

	Lactate, mmol/l	Glucose, mmol/l	Glycerol, μmol/l	NEFA, μmol/l	TAG, μmol/l	3-OHB, μmol/l	Insulin, mU/l	Cortisol, nmol/l
Prewalk	0.85 ± 0.1	4.8 ± 0.1	93 ± 10	455 ± 83	957 ± 73	65 ± 32	6.7 ± 0.9	683 ± 45
Midwalk	$1.5 \pm 0.2^*$	4.7 ± 0.1	$262 \pm 24†$	$1,757 \pm 144†$	989 ± 49	332 ± 68	4.8 ± 0.7	627 ± 96
Postwalk	0.78 ± 0.1	5.1 ± 0.2	133 ± 24	$868 \pm 164‡$	$1,073 \pm 110$	$89 \pm 68§$	$12 \pm 2‡$	$326 \pm 50‡$

Values are means $\pm$ SE for 13 subjects. NEFA, nonesterified fatty acids; TAG, triacylglycerol; 3-OHB, 3-hydroxybutyrate. *Significant differences between prewalk and midwalk, $P < 0.001$. †Significant differences midwalk, relative to both prewalk and postwalk; $P < 0.001$. Significant differences between prewalk and postwalk: ‡$P < 0.01$; §$P < 0.001$.

Table 4. *Urinary catecholamine concentration during a rest day and monitored hill walk*

	Rest			Exercise		
	0800–1300	1301–1800	1801–2000	0800–1300	1301–1800	1801–2000
NE/Ct, nmol/mmol	27 ± 3	25 ± 2	2 ± 2	43 ± 11	43 ± 11†	26 ± 3†
Epi/Ct, nmol/mmol	4 ± 1	4 ± 1	5 ± 1	11 ± 4*†	8 ± 2	5 ± 1
Dop/Ct, nmol/mmol	156 ± 17	134 ± 11	176 ± 22	143 ± 22	163 ± 37	209 ± 86
NE, nmol/l	232 ± 29	293 ± 51	124 ± 22	583 ± 165	737 ± 264†	294 ± 48†
Epi, nmol/l	32 ± 6	50 ± 18	34 ± 11	186 ± 92†	144 ± 62	55 ± 8
Dop, nmol/l	$1,406 \pm 109$	$1,603 \pm 304$	$1,090 \pm 160$	$1,882 \pm 348$	$2,621 \pm 844$	$1,669 \pm 309$
Ct, mmol/l	10 ± 1	12 ± 2	7 ± 2	14 ± 2	15 ± 2	12 ± 2

Values are means $\pm$ SE for 10 subjects. NE/CT, norepinephrine/creatinine; Epi/Ct, epinephrine/creatinine; Dop/Ct, dopamine/creatinine. *Significantly different from exercise as a function of time (0800–1300 vs. 1801–2000), $P < 0.05$. †Significantly different from rest as a function of time, $P < 0.05$.

decrease in heat loss, which will subsequently increase T_{re}. The maintenance of normal core temperature during cold stress depends on the subject's ability to generate enough heat to offset heat loss to the environment (33, 46). This clearly was not a problem for the hill walkers because of high levels of prolonged exercise intensity.

When the subjects stopped for lunch and measurements midwalk for ~30 min, the exercise hyperthermia was canceled out by the decreased heat production and increased heat loss through conduction and radiation. The initial physiological responses to cold exposure to maintain core temperature in the cold are peripheral vasoconstriction to reduce heat loss and shivering to generate heat. Although shivering was not quantified directly, pronounced shivering was noted in four of the subjects. Once peripheral vasoconstriction is maximized, core temperature can only be maintained by an increased heat production, i.e., shivering, which is thought to be the major contributor to the cold-induced increase in heat production (13). The core temperature continued to fall after subjects began walking after lunch. This temperature afterdrop has been reported in a number of cold-water-immersion studies (17, 33) but, to our knowledge, has not been reported in circumstances such as those of the present study. Even though T_{re} did not drop below 36°C, this afterdrop may describe the reason for hill walkers slipping into the first stages of hypothermia after stopping for a rest. The suggested mechanisms for the afterdrop are at present subject to controversy (10, 17, 27, 44). The extent of this afterdrop was also reflected by the high negative thermal balance (-356 ± 23 W·m^2). Weller et al. (45) reported similar values for thermal balance after 240–360 min of walking in a simulated cold, wet, and windy environment with subjects wearing a minimum of clothing. The high negative thermal balance highlights the thermal stress placed on the human body, even when apparently prepared for the prevailing weather conditions

One possible explanation for this continued drop in T_{re} may be the decrease in exercise intensity (and hence metabolic heat production) after lunch when the subjects were walking downhill. Studies of cold-water immersion have shown T_{re} to continue to fall after immediate removal from cold water, even when sub-

jects are actively rewarmed (27). The extent to which this afterdrop can be limited by an increase in exercise intensity in this scenario merits further research.

Psychomotor Response

The unremarkable changes in the psychomotor tests demonstrate that, despite serious physiological stress, the subjects demonstrated normal motor control during the walk. The small decrease in grip strength suggests that, over the monitored walk, motor function was near normal, despite potential cooling of the peripheral tissues.

Energy Balance

The recorded energy expenditure of 14.5 MJ highlights the high energetic cost of the 12-km hill walk and is comparable to the 12-MJ energy expenditure in the studies of Greenhaff et al. (18) and Maughan et al. (29). These latter studies were based on a flat 37-km walk, which corresponded to operating at 17% of $\dot{V}O_{2 \text{ max}}$, with unrestricted access to either a mixed or CHO diet, respectively. In contrast, subjects in the present study operated at ~50% of $\dot{V}O_{2 \text{ max}}$ during the first 5-km on the predominately uphill section and at ~30% during the final 7-km, which was on the downhill section of the walk. This suggests that the main determinant of energy expenditure, in a hill walk is the relative difficulty of the walk, in terms of the gradient and terrain, both of which will contribute to a greater level of exercise intensity. Additionally, Maughan et al. demonstrated that a weight loss of 2 kg over their 4-day walk was only apparent in the group who had a low-CHO intake but was not observed in the group ingesting a high-CHO diet. They concluded that the loss of body weight was a consequence of the gradual use of the hepatic and muscle glycogen stores and loss of associated water. In the present study over 1 day, the weight loss also averaged 2 kg, with subjects consuming a mixed diet. The normal whole body muscle glycogen pool amounts to some 400 g (21). Water is stored in association with this glycogen in a ratio of ~3–4 g water/g glycogen (5, 34), suggesting that the observed body weight loss of 2 kg in the present study may reflect a small decrease in whole body glycogen level. Supporting this postulated decrease in whole

body glycogen was an observed negative CHO balance of 200 g. In addition, this negative CHO balance of 200 g would equate to an ~800-g loss of body water, suggesting a high element of dehydration, which was also reflected by the increased urine osmolality concentrations. The fundamental difference in the relative intensities of the walk, compared with that of Maughan et al., may largely explain the magnitude of the weight loss in the present study. However, subjects in the studies described (18, 19) had unrestricted access to food, whereas, in the present study, they supplied their own food that they considered appropriate for the conditions. The unrestricted food may have attenuated any potential negative energy balance in the aforementioned studies. In the present study, the negative energy balance, the failure to provide enough fuel for the exercise duration and intensity, could well have led to compromises in both physiological and psychological functioning if the duration were more prolonged. This suggestion generates important considerations for the hill walker with regard to nutrient intake both before and during the walk. For example, because the subjects were clearly in negative energy balance, a suggestion is that they should take more food and/or foods with higher energy content to help prevent this from occurring and provide a measure of protection if the walk becomes unexpectedly prolonged.

Metabolic Responses

The measurements made at the midpoint of the walk showed an enhanced lipolysis, demonstrated by an almost fourfold increase in NEFA concentrations accompanied by high glycerol and 3-OHB concentrations. Fatty acids delivered from adipose tissue are the predominant fuel for sustained exercise at moderate intensity (2, 11, 24). There is usually a surge in plasma NEFA concentrations shortly after exercise, presumed to reflect a continued high rate of lipolysis when muscle NEFA uptake has suddenly diminished (22), and this may have been responsible for some of the elevation in NEFA concentration observed. The stimulus for lipolysis during exercise is mainly adrenergic (4), reinforced by decreased insulin concentrations. It is likely that the former stimulus was greater in our subjects than in many exercise studies because of the adverse conditions. Even though large variations were present in urine catecholamine concentrations, the results clearly indicate a general stress response to the hill walk compared with the prior day.

In contrast, NEFA, glycerol, and 3-OHB concentrations were considerably lower at the end of the walk than midway. The food intake midwalk is likely to have influenced the pattern of lipid mobilization during the final part of the walk. Ahlborg and Felig (1) and Krzentowski et al. (26) showed that CHO feeding before or during mild-intensity, prolonged exercise decreased the amount of energy derived from fat oxidation and increased proportionally the amount of energy-derived blood glucose. However, in the present study, the decreased NEFA, glycerol,

and 3-OHB concentrations postwalk coincided with no evident decreases in fat oxidation assessed by indirect calorimetry. This maintained fat oxidation might be accounted for by fatty acids derived from the body's intramuscular stores (40). The relatively high circulating plasma insulin levels recorded at the end of the walk (~12 mU/l) would be expected to lead to a decrease in adipose tissue lipolysis, whereas intramuscular lipoysis is not so readily inhibited by insulin (7, 19).

Hypoglycemia, which would affect both fatigue and the shivering response (20), was not observed in this study at any time. The data indicate that the liver was able to meet glucose requirements by a combination of glycogenolysis and gluconeogenesis, supplemented by the midwalk carbohydrate intake.

In summary, the pattern of substrate mobilization and utilization is likely to vary according to the intensity and duration of the walk, level of fitness, environmental conditions and preceding diet of the participant. It is apparent that the energy expenditure during the hill walk exceeded energy intake, apparent in both total CHO and fat oxidation rates for the walk. The large energy expenditure observed served to highlight the high energetic cost of such hill-walking events, even when completed over a relatively short duration. The observations generate important implications for hill walkers with regard to nutritional strategies for preventing some of the potential detrimental effects of operating at a marked negative energy balance. The negative energy balance may lead to a compromise in physiological function and safety if activity is performed over a prolonged period. Nevertheless, despite the physiological stress and the difference between energy intake and expenditure, blood glucose was maintained. The major source of energy, in the monitored hill walk, was an enhanced fat oxidation probably from adipose tissue lipolysis.

It is evident that more research on this topic is desirable. Future research should extend the findings of this study into hill-walking events over a longer duration. Furthermore, there is little in the literature with respect to repetitive high-intensity hill walks completed over 1–2 wk. Finally, the optimal fluid and nutritional strategies need to be quantified for activity of this form.

REFERENCES

1. **Ahlborg G and Felig P.** Influence of glucose ingestion on fuel-hormone response during prolonged exercise. *J Appl Physiol* 41: 683–688, 1976.
2. **Ahlborg G, Felig P, Hagenfeldt L, Hendler R, and Wahren J.** Substrate turnover during prolonged exercise in man: splanchnic and leg metabolism of glucose, free fatty acids, and amino acids. *J Clin Invest 53*: 1080–1090, 1974.

3. **American College of Sports Medicine.** *Graded Exercise Testing and Exercise Prescription*. Philadelphia, PA: Lea & Febiger, 1986.

4. **Arner P, Kriegholm E, and Bolinder J.** Adrenergic regulation of lipolysis in situ at rest and during exercise. *J Clin Invest* 85: 893–898, 1990.

5. **Bergström J and Hultman E.** Nutrition for maximal sports performance. *JAMA* 221: 999–1006, 1972.

6. **Bittel JHM.** Heat debt as an index for cold adaptation in men. *J Appl Physiol* 62: 1627–1634, 1987.

7. **Bolinder J, Kerckhoffs DA, Moberg E, Hagström-Toft E, and Arner P.** Rates of skeletal muscle and adipose tissue glycerol release in nonobese and obese subjects. *Diabetes* 49: 797–808, 2000.

8. **Borg GAV.** Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med* 2: 92–98, 1970.

9. **Burton AC.** Human calorimetry. II. The average temperature of the tissues of the body. *J Nutr* 9: 264–280, 1935.

10. **Collins KJ, Easton JC, and Exton-Smith AN.** Body temperature afterdrop: a physical or physiological phenomenon? *J Physiol (Lond)* 382: 72–73, 1982.

11. **Coyle EF.** Substrate utilization during exercise in active people. *Am J Clin Nutr* 61: S968–S979, 1995.

12. **Dill DB and Costill DL.** Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J Appl Physiol* 37: 247–248, 1974.

13. **Doubt TJ.** Physiology of exercise in the cold. *Sports Med* 11: 367–381, 1991.

14. **Durnin JW and Womersley J.** Body fat assessed from total body density and its estimation from skin-fold thickness measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr* 323: 77–97, 1974.

15. **Elia M and Livesey G.** Energy expenditure and fuel selections in biological systems: the theory and practice of calculations based on indirect calorimetry and tracer methods. In: *Metabolic Control of Eating, Energy Expenditure and the Bioenergetics of Obesity. World Review of Nutrition and Dietetics,* edited by Simopoulos AP. Basel: Karger, 1992, vol. 70, p. 68–131.

16. **Field A.** *Discovering Statistics Using SPSS for Windows.* Wilshire, UK: Cromwell, 2000.

17. **Golden FS and Hervey GR.** The mechanism of the after-drop following immersion hypothermia in pigs. *J Physiol (Lond)* 227: 35–36, 1977.

18. **Greenhaff PL, McCormick K, and Maughan RJ.** The metabolic response to prolonged walking in fed and fasted men. *Eur J Appl Physiol* 56: 115–119, 1987.

19. **Hagström-Toft E, Thörne A, Reynisdottir S, Moberg E, Rössner S, Bolinder J, and Arner P.** Evidence for a major role of skeletal muscle lipolysis in the regulation of lipid oxidation during caloric restriction in vivo. *Diabetes* 50: 1604–1611, 2001.

20. **Haight JS and Keatinge WR.** Failure of thermoregulation in the cold during hypoglycaemia induced by exercise and ethanol. *J Physiol (Lond)* 229: 87–97, 1973.

21. **Hedman R.** The available glycogen in man and the connection between the rate of oxygen uptake and carbohydrate storage. *Acta Physiol Scand* 40: 305–321, 1957.

22. **Hodgetts V, Coppack SW, Frayn KN, and Hockaday TD.** Factors controlling fat mobilization from human subcutaneous adipose tissue during exercise. *J Appl Physiol* 71: 445–451, 1991.

23. **Hunter WC.** Accidental hypothermia, parts I, II and III. *Northwest Med* 68: 569–573, 735–739, 837–844, 1968.

24. **Keins B, Essen-Gustavsson B, Christen NJ, and Saltin B.** Skeletal muscle substrate utilization during submaximal exercise in man: effect of endurance training. *J Physiol (Lond)* 496: 459–478, 1993.

25. **Kreider RB.** Physiological considerations in ultra-endurance performance. *Int J Sport Nutr* 1: 3–27, 1991.

26. **Krzentowski CT, Jandrain B, Pirnay F, Mosora F, Lacroix M, Luyckx AS, and Lefebvre PJ.** Availability of glucose given orally during exercise. *J Appl Physiol* 56: 315–320, 1984.

27. **Lloyd LE.** *Hypothermia and Cold Stress*. Worcester, MA: Billing and Sons, 1986.

28. **Lusk G.** *The Elements of the Science of Nutrition* (3rd ed.). Philadelphia, PA: Saunders, 1923.

29. **Maughan RJ, Greenhalf PL, Gleeson M, Fenn CE, and Leiper JB.** Carbohydrate intake and metabolism during walking. *Eur J Appl Physiol* 56: 583–591, 1987.

30. **McCance RA, Widdowson EM, and Holland B.** *McCance and Widdowson's the Composition of Foods (*5th ed.). New York: Springer-Verlag, 1991.

31. **McNair DM, Lorr M, and Droppleman LF.** *Edits Manual For The Profile Of Mood States*. San Diego, CA: Educational and Industrial Testing Service, 1992.

32. **Nishi Y and Gagge AP.** A psychometric chart for graphical predication of comfort and heat tolerance. *ASHRAE Trans* 80: 115–125, 1977.

33. **Noakes TD.** Exercise and the cold. *Ergonomics* 43: 1461–1479, 2000.

34. **Olsson KE and Stalin B.** Variation in total body water with muscle glycogen changes in man. *Acta Physiol Scand* 80: 11–18, 1970.

35. **Pugh LGCE.** Deaths from exposure on Four Inns Walking Competition, March 14–15, 1964. *Lancet* 1: 1281–1286, 1964.

36. **Pugh LGCE.** Clothing insulation and accidental hypothermia in youth. *Nature* 209: 1281–1286, 1966.

37. **Pugh LGCE.** Accidental hypothermia in walkers, climbers, and campers: report to the Medical Commission on Accident Prevention. *Br Med J* 1: 123–129, 1966.

38. **Pugh LGCE.** Cold stress and muscular exercise, with special reference to accidental hypothermia. *Br Med J* 2: 333–337, 1967.

39. **Ramanathan NL.** A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 19: 531–533, 1964.

40. **Romijn JA, Coyle EF, Sidossis LS, Gastaldlli A, Horowitz JF, Endert E, and Wolfe RR.** Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. *Am J Physiol Endocrinol Metab* 265: E380–E391, 1993.

41. **Strang PJH.** Death due to exposure to cold in the New Zealand mountains. *NZ Med J* 69: 4–11, 1969.

42. **Thompson RL and Hayward JS.d** Wet-cold exposure and hypothermia: thermal and metabolic responses to prolonged exercise in the rain. *J Appl Physiol* 81: 1128–1137, 1996.

43. **Toner MM and McArdle WD.** Physiological adjustments of man to the cold. In: *Human Performance Physiological and Environmental Medicine at Terrestrial Extremes*, edited by Pandolf K, Sawka M, and Gonzalez K. Indianapolis, IN: Benchmark, 1989, p. 361–399.

44. **Webb P.** Afterdrop of body temperature during rewarming: an alternative explanation. *J Appl Physiol* 60: 385–390, 1986.

45. **Weller AS, Millard CE, Stroud MA, Greenhaff PL, and MacDonald IA.** Physiological responses to a cold, wet, and windy environment during prolonged intermittent walking. *Am J Physiol Regulatory Integrative Comp Physiol* 272: R226–R233, 1997.

46. **Weller AS, Millard CE, Stroud MA, Greenhaff PL, and MacDonald IA.** Physiological responses to cold stress during prolonged intermittent low- and high-intensity walking. *Am J Physiol Regulatory Integrative Comp Physiol* 272: R2025–R2033, 1997.