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HEAT STRAIN AND WORK TOLERANCE TIMES WITH VARYING LEVELS OF CANADIAN FORCES NBC PROTECTIVE CLOTHING, AMBIENT TEMPERATURE, PHYSICAL WORK INTENSITY, AND WORK/REST SCHEDULES

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EXECUTIVE SUMMARY

Canadian Forces personnel must be able to sustain operations in an environment contaminated with nuclear, biological and/or chemical (NBC) agents. Clothing has been designed that protects the individual from a hostile NBC environment. This clothing, however, impairs body heat loss. The degree of impairment is magnified if metabolic heat production is increased and/or environmental temperature increases. The purpose of the present study, therefore, was to examine the effects of environmental temperature and metabolic rate on soldiers' physical work tolerance times (WTT) while wearing various levels of NBC clothing.

Twenty-three male soldiers were allocated to exercise at either a light (walking at 4 $km \cdot h^{-1}$ and lifting 10 kg boxes) or heavy metabolic rate (4.8 $km \cdot h^{-1}$ up a slight grade and lifting 20 kg boxes) in an environmental chamber that controlled ambient conditions at either a cool 18°C or hot 30°C temperature. Subjects were tested wearing three levels of protective clothing: their regular combat fatigues (Low); fatigues and the NBC overgarment (Med); fatigues, NBC overgarment, rubber gloves and boots, and protective respirator (High). WTT was defined as the time until body temperature increased to 39.3°C (normal being 37°C), heart rate reached 95% of an individual's maximum (~ 190 beats/min with resting values being ~ 70 beats/min), dizziness or nausea precluded further exercise or 5 hours had elapsed. During the continuous exercise trials, subjects walked on a motorized treadmill for 55 min of every other hour. Between treadmill walks, subjects performed a 60 min lifting task (two 30 min periods each consisting of 25 min exercise followed by 5 min of rest). The lifting task consisted of carrying a known weight (10 or 20 kg) a distance of 3 m and lifting the weight up (or down) to a height of 1.6 m every 10 s. Subjects exercised in pairs throughout each clothing trial and during the lifting task they alternated between the positive (lifting up) or negative (carrying down) work phases of the task every 5 min. During the hot environmental temperature trials, 8 subjects (four in each of the light and heavy work schedules) performed an additional three clothing experiments using a discontinuous (longer rest intervals intervened between the walking and the lifting tasks) rather than a continuous schedule.

WTT was not impaired by the different levels of protective clothing in the cool environment while the soldiers performed light physical work (average WTT was close to 280 min). For the light work in the hot environment WTT was significantly reduced when soldiers wore the High level of protection (~ 85 min vs 4 hours or longer for the Med and Low levels of protection). With the heavy work schedule in the cool environment WTT was reduced to 4 hours for Med and 1 hour for the High level of protection. Finally, in the hot environment with the heavy work schedule WTT was progressively reduced for the Low (~ 3 hours), Med (~ 1 hour) and High (~ 30 min) levels of NBC protective clothing. For both the Med and High levels of protection in the hot environment a curvilinear relationship was found between WTT and the average metabolic rate of the continuous or intermittent work schedules. When the inverse of WTT was plotted against the metabolic rate a strong linear relationship was observed. These relationships allow one to estimate WTT for the Med and High levels of protective clothing if the metabolic rate of a particular work task is known and to suggest work/rest schedules that may prolong WTT.

ABSTRACT

This study examined the effects of environmental temperature and metabolic rate on soldiers' work tolerance time (WTT) while wearing various levels of nuclear, biological and chemical (NBC) defence protective clothing. Twenty-three unacclimatized males (23 ± 3 y, 76 ± 8 kg, 1.77 ± 0.08 m) were assigned to exercise at either a light (walking 1.11 $m \cdot s^{-1}$ 0% grade, alternating with lifting 10 kg) or heavy metabolic rate (walking 1.33 $m \cdot s^{-1}$ 7.5% grade, alternating with lifting 20 kg) in an environmental chamber at either 18°C, 50% R.H. (cool) or 30°C, 50% R.H. (hot). Subjects were tested wearing three levels of clothing protection: combat fatigues (Low); fatigues and a semi-permeable NBC overgarment (Med); fatigues and NBC overgarment, gloves, boots and respirator (High). WTT was the time until rectal temperature (T_{re}) reached 39.3°C, heart rate reached 95% maximum, dizziness or nausea precluded further exercise, or 5 h had elapsed. During the hot trial, 8 subjects (light (N=4) and heavy exercise (N=4)) performed an additional three clothing trials using an intermittent rather than a continuous work schedule. During the light and cool trials (N=5), the levels of protective clothing did not impair WTT (277 ± 47 min). For the light and hot experiments (N=6), WTT was significantly impaired with the High level of protection (82.7 ± 10.6 min) and T_{re} increased 1.3 ± 0.3 $°C \cdot h^{-1}$. With the heavy and cool condition (N=6), WTT was reduced with the Med (240.5 ± 73.8 min, T_{re} increased 0.5 ± 0.2$°C \cdot h^{-1}$) and High (56.7 ± 17.9 min, T_{re} increased 1.8 ± 0.5$°C \cdot h^{-1}$) levels of protection. Finally, during the heavy and hot trials (N=6), WTT was progressively impaired for the Low (172.5 ± 52.8 min, T_{re} increased 0.8 ± 0.3 $°C \cdot h^{-1}$), Med (65.8 ± 18.2 min, T_{re} increased 2.0 ± 0.5$°C \cdot h^{-1}$) and High (34.0 ± 9.7 min, T_{re} increased 2.6 ± 0.5$°C \cdot h^{-1}$) levels of protection. In the hot environment, the inverse of WTT was directly proportional to the average metabolic rate ($\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)) for both the Med ($WTT^{-1} = 0.00129\dot{V}O_2 - 0.0109$, r = 0.9) and High ($WTT^{-1} = 0.00167\dot{V}O_2 - 0.0068$, r = 0.9) levels of protection. If the metabolic rate of a task is known, these relationships can be used to calculate work to rest schedules that may prolong work time in the Med or High levels of NBC protective clothing.

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1.0 INTRODUCTION

The Canadian Forces (CF) has a requirement to be prepared to operate in a nuclear, biologically, and/or chemically (NBC) contaminated environment in the event of war. To protect personnel working in this environment from the effects of contaminating agents an individual protective ensemble (IPE) has been developed which consists of a facial mask/respirator, a clothing coverall, overboots and gloves. Depending on the likelihood and severity of the perceived threat, either the coverall alone may be donned or the entire IPE may be donned so that no skin surface and no portion of the usual battle fatigue clothing is exposed to the environment. The components of the IPE are either semi-permeable or impermeable to moisture penetration; thus the ability to evaporate sweat from the skin surface is severely impaired. Since sweat evaporation is the major avenue by which humans dissipate body heat which otherwise accumulates during physical work in a hot environment, debilitating heat strain is the likely outcome of attempting to maintain normal work rates while wearing IPE. Such an effect is described in several documents and reports by our allies (see the review of relevant literature later in this report).

There are no data available which document the extent of heat strain in infantry personnel wearing Canadian Forces IPE. Thus the NDHQ Directorate of Nuclear, Biological and Chemical Coordination tasked the DCIEM Environmental Physiology Section to quantify the extent of heat strain in infantry personnel wearing various levels of IPE and working at routine work intensities.

1.1 Objectives

The aims of the research project carried out for this tasking were as follows:

1. to document the effects on work tolerance time of varying the level of CF IPE protection, ambient temperature, and work intensity in infantry personnel;

2. to evaluate the utility of converting continuous work schedules into intermittent work/rest schedules in order to prolong work tolerance time;

3. to establish general guidelines for commanders of infantry units which will enable the estimation of the duration of time during which a specific work intensity can be continuously maintained in medium or high levels of IPE protection before a significant number of heat casualties is incurred.

2.0 BACKGROUND AND REVIEW OF LITERATURE

2.1 Impairments Associated With Wearing IPE

By developing ingenious ways to block the passage of contaminated liquids, gases and particulate from contacting the unprotected human body, protective clothing has been rendered relatively impermeable to heat and water vapour. Some new materials have been introduced which are somewhat permeable to water vapour but heat dissipation from the body remains impeded. The problem of heat dissipation is compounded because most of this clothing is composed of multiple layers which trap air, a good insulator, and it is usually worn over normal combat clothing, trapping more air. This thermal insulation created by the layering of clothing restricts heat loss from the body of the wearer, specifically by limiting the evaporation of sweat. This poses two problems: firstly, the body's ability to dissipate metabolic heat is impaired; and secondly, the sweat buildup can actually reduce or destroy the garment's ability to protect against toxic vapour hazard by contaminating the charcoal layer in the suit.

Wearing IPE, especially in hot humid weather, has been shown to cause performance decrements and increase the time to complete a task. For example, Fine et al. (1) assessed the performance of soldiers in IPE (at 91°F (33°C), 61% R.H.) who were required to perform artillery-type tasks (eg. fire direction, communications, forward observation, etc.), none of which required intense physical exertion. The authors concluded that performance decrements could be expected to take place in as little as 3 hours in the field. In addition, the integrity of the protective clothing worn by some of the subjects had been compromised by sweat within 3 hours in spite of the absence of any physical activity.

Carter et al. (2) reported five heat related casualties among 195 field hospital personnel during a simulated chemical warfare scenario at a WBGT of 76-78°F (25°C). Personnel were dressed in full U.S. Army IPE during this exercise. Four of the five casualties occured during periods of heavy physical activity.

Rakaczky (3) calculated the time required to complete a variety of army unit tasks and indicated that the time would increase substantially when personnel were wearing full U.S. Army IPE, and that the time would be further increased as environmental temperature increased. The author concluded that the extent of performance degradation due to heat stress while wearing IPE was dependent on six factors: type and combination of environmental and protective ensembles worn; prevailing environmental conditions; duration during which a specific ensemble is worn; work intensity sustained; physical state of personnel; and the degree to which the unit is trained in wearing protective clothing.

In contrast to the above results, Posen et al. (4) found that wearing full U.S. Army IPE for up to 34 hours had little effect on performance of mechanized infantry squads. The tasks performed by these squads were relatively light, however, and environmental conditions were classified as moderate. Subjects wore only underwear under their IPE and were allowed to drink plenty of water. They were also more accustomed to wearing full IPE than is normal for U.S. troops.

Avellini (5) evaluated two different NBC IPEs, the British two-piece Mk III "permeable" and the Norwegian one-piece "semi-permeable" suits, and found that the British suit, which allowed some sweat evaporation, was superior in terms of reducing the heat stress. These suits were tested at temperatures ranging from 22.2 to 48.9°C. In each case, subjects wearing the Norwegian suits had higher heart rates, rectal temperatures (T_{re}) and, in all cases except the 22.2°C temperature condition, a decreased work tolerance time compared with the personnel wearing the British Mk III uniform. Tests in both IPEs, however, resulted in higher heart rates, T_{re} and, in most cases, decreased work tolerance times when compared to tests where only standard combat clothing was worn. Work levels in this experiment were quite light (i.e., subjects alternated walking for 25 minutes on a treadmill at 1.34 $m \cdot s^{-1}$ with a 5 minute rest period for 3 hours. Work rates averaged ~170 $W \cdot m^{-2}$ or ~280 $kcal \cdot h^{-1}$ (assuming a body surface area of ~ 1.9 m^2). Similar results have been observed with chemical protective clothing in an industrial setting (6, 7).

Bergh and Danielsson (8) reported a positive heat imbalance of about 200 W in subjects wearing three different types of NBC suits, both permeable and impermeable. The subjects walked at 2.9 $km \cdot h^{-1}$ while carrying a 19 kg backpack for two 25 minute exercise bouts with a 5 minute intervening rest period. The temperature during this experiment was 20°C with a relative humidity of 25%. The heat accumulation resulted in a steadily increasing heart rate which reached an average of 170 b·min^{-1} by the end of the experiment. Similar results were observed by Duggan (9) who found that the cost of stepping up and down on a stool 0.31 m high was increased by about 8% when wearing IPE compared to wearing combat fatigues alone. The author indicated that metabolic heat production at this level would quickly result in overheating.

Tilley et al. (10) studied the effect of two different environmental conditions (hot/humid and hot/dry) on Australian soldiers wearing combat clothes and various IPE ensembles. They found that soldiers wearing IPE lost significantly more water and had higher T_{re} than those wearing regular combat clothing. This was especially true when the IPE was worn at the highest protection level (hood, mask, boots, completely done up). The authors concluded that in hot/humid conditions (in this case 30°C, 60-65% R.H.) soldiers would be able to do little in daylight hours while wearing full IPE ensembles without incurring severe heat casualties. They suggested that in hot/dry conditions (in this case 35°C, 30-35% R.H.) soldiers would be able to sustain light activity while similarly dressed provided the commander was aware of the necessity of sufficient rest and water replenishment.

Thermal stress in NBC IPE is also evident in tank crews (4,11,12). For example, Toner et al. (12) found that crews dressed in IPE sitting in an XM-1 tank with the ventilators off and hatches closed ("silent watch") with an ambient temperature of 35°C (R.H. 25%) lost an average of of 1.7-2.1 L of water per hour on two separate days. Average heart rates for the crews on those days were 162 and 147 b·min^{-1}. The heat stress became so intolerable that the tests were terminated after 80 and 124 minutes respectively (maximum test length was 210 minutes). There was also a performance decrement noted in simulated fire missions on these two days with the most active crew members, i.e., the commander and gunner, being the most affected. Even on test days where the hatches were open and ventilators were operational, the subjects lost from 0.3 to 1.0 L of water per hour. This emphasizes the necessity for adequate water supply in these conditions.

2.2 Work Tolerance Times

Joy and Goldman (13) examined survival times (defined as a T_{re} of 39.5°C or heat exhaustion, inability to continue, etc.) of infantry units who were performing typical infantry-type tasks (eg. marching, attack, defence) while dressed in protective clothing. They found that the time required to produce a 50% casualty rate due to heat stress at a WBGT of 85 - 87°F (30°C) decreased in protective gear depending upon whether it was worn closed (done up with hood and gloves etc.) or open and as workload increased. Heat acclimatization had no effect on unit survival time in this study.

One solution to the problem of heat strain is to reduce the amount of work, and therefore heat production, done by personnel at any given time. The U.S. Army, for example, has developed work/rest schedules based on different environmental temperatures in order to give field commanders some guidelines for troops working in NBC gear. These schedules are included in a report by Rakaczky (3). Inspection of these tables suggests that as environmental temperature increases, the ratio of work to rest must decrease.

The temperatures given in the tables referred to above are dry bulb temperatures and do not account for humidity. Although such calculations may be appropriate for totally impermeable clothing, they do not apply to situations where less protective clothing is required. This has been criticized by Rich (14) who used a computer-mathematical model to analyse guidelines in use. He concluded that the current U.S. guidelines were inadequate for continuous work levels because of the omission of effects due to humidity. In his model, Rich used an arterial blood temperature of 39°C and/or an absolute body water loss of 3 qts (U.S.) as limiting cases for heat stress. His data indicated that with all workloads examined at low to moderate temperatures and low workloads at high temperatures (WBGT), water loss rather than arterial temperature may be the limiting factor. He also indicated that the work/rest ratios in use by the U.S. Army may be reasonable for relative humidities of 50% or less but that at a relative humidity of 80% they may be questionable, especially at higher temperatures. The author constructed a graph that predicts tolerance times for work at low, moderate and heavy workloads dependant on the effective temperature (a modified WBGT). The author stressed the importance of having an adequate supply of "clean" water in an NBC environment and the need for the field commanders to ensure that their troops are adequately hydrated.

Others have suggested that environmental conditions *per se* may not be the limiting factor in work tolerance in impermeable or semi-permeable clothing in certain circumstances. Goldman (15), for example, found that tolerance time for continuous work decreased in subjects wearing IPE compared with regular combat uniforms at temperatures above 75°F (24°C). However, tolerance times were similar while wearing IPE within the temperature range of 75-95°F (24-35°C). The author suggested that at temperatures of 75°F and above, environmental factors such as temperature, humidity and solar radiation did not affect tolerance times. Rather, it appeared that the heat generated within the enclosed "capsule" of clothing was the limiting factor because of the inability to dissipate heat through evaporation. This conclusion was confirmed in several other reports (1,2,5,6,11,16-18). The suggestion is that during work, a microclimate is actually set up within the protective capsule of the overgarment and that once this has occurred, outside heat load will have very little, if any, effect on the person. In contrast, Wenger and Santee (19) observed a significant decrease in work tolerance time in subjects wearing different NBC fabrics at a temperature of 29.5°C when the relative humidity was 85% compared with 20%, even with a 5 $m{\cdot}s^{-1}$ wind.

It would appear from a physiological perspective that more work must be done to develop guidelines for field commanders who must deal with heat stress casualties in their troops. Such work has not yet been done for Canadian IPE. The present study was designed to address this issue.

3.0 METHODS

3.1 Subjects

Following approval from the Institute's Human Ethics Committee, twenty-three male soldiers (23 ± 3 y, 76 ± 8 kg, 1.77 ± 0.08 m) were recruited from 1 Canadian Brigade Group. They were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination to ensure that there were no medical contraindications to their participation in the experiments, they gave their informed consent prior to the first day of data collection.

3.2 Determination of Maximal Aerobic Power ($\dot{V}O_2max$)

The series of experiments in the climatic chamber was spread out over a seven to ten day period. In order to evaluate whether the experimental procedures *per se* caused an improved aerobic fitness level (which would confound our data interpretation), $\dot{V}O_2max$ was determined on a motor-driven treadmill using open circuit spirometry both before and after the series of experiments. Subjects walked initially for 3 min at 1.33 $m \cdot s^{-1}$ with 0% elevation. Thereafter, the treadmill grade was increased 2%$\cdot min^{-1}$ until subjects were walking at a 12% grade. Treadmill speed was then increased 0.44 $m \cdot s^{-1}$ each minute until the subject could no longer continue. $\dot{V}O_2max$ was defined as the highest oxygen consumption ($\dot{V}O_2$) value observed during the incremental test. Heart rate (HR) was monitored throughout the incremental test from bipolar chest electrodes and the value recorded at the end of the exercise test was considered to be the individual maximal heart rate.

3.3 Experimental Design

Subjects were allocated to exercise at either a light or heavy intensity. Half of the subjects within each intensity-group exercised at 18°C, 50% R.H. (cool) and the other half exercised at 30°C, 50% R.H. (hot). Those exercising at the light intensity walked at 1.11 $m \cdot s^{-1}$, 0% grade alternating with lifting 10 kg. Those subjects exercising at the heavy intensity walked at 1.33 $m \cdot s^{-1}$ with a 7.5% grade alternating with lifting 20 kg. The allocation of subjects to the various groups is shown in Table 1, as are the abbreviations used throughout this report to denote the various groups.

Each subject was tested wearing each of the following three levels of clothing protection, corresponding to the standard Canadian Forces "task-oriented protective postures" (TOPP):

(a) TOPP Low (TL), i.e. combat fatigues and webbing;

(b) TOPP Medium (TM), i.e. fatigues, webbing and a semi-permeable overgarment; and,

(c) TOPP High (TH), i.e. fatigues, webbing, overgarment, gloves, boots and respirator.

The order of wearing the various clothing configurations was assigned randomly. The detailed description and characteristics of the clothing can be found elsewhere (20).

Table 1. Subject allocations to either light (walking at 1.11 $m \cdot s^{-1}$, 0% grade alternating with lifting 10kg) or heavy exercise (walking at 1.33 $m \cdot s^{-1}$, 7.5% grade alternating with lifting 20kg) in either a cool (18°C, 50% R.H.) or hot (30°C, 50% R.H.) climatic chamber. In the hot environment some subjects performed both continuous and intermittent exercise.

Exercise	Light			Heavy		
Intensity	Continuous	Continuous	Intermittent	Continuous	Continuous	Intermittent
Temperature	Cool	Hot	Hot	Cool	Hot	Hot
# of Subjects	5	6	4	6	6	4
Abbreviation	18LC	30LC	30LI	18HC	30HC	30HI

3.3.1 Work Tolerance Time

Work tolerance time (WTT) for all trials was defined as the time until any of the following criteria first occurred: rectal temperature reached 39.3°C; heart rate remained at or above 95% of maximum for 3 min; dizziness or nausea precluded further exercise; or 5 h had elapsed.

3.3.2 Work Protocol

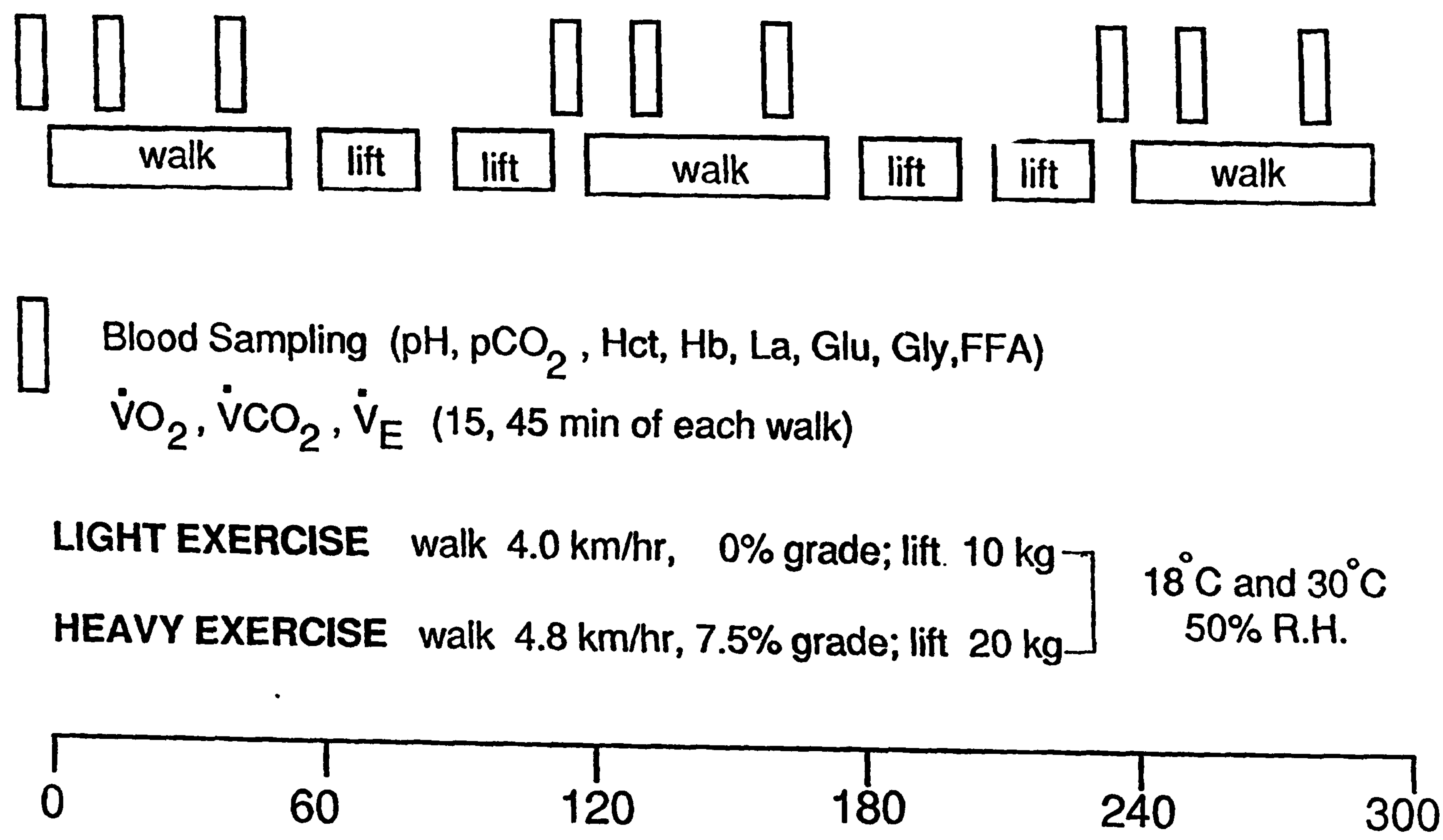
During the continuous exercise clothing trials, subjects walked on the treadmill for 55 min of every other hour. Between treadmill walks subjects performed a 60 min lifting task (two 30 min periods, each consisting of 25 min exercise followed by 5 min of rest) (see Figure 1). The lifting task consisted of carrying a known weight a distance of 3 m and lifting the weight up (or down) to a height of 1.6 m every 10 s. Subjects exercised in pairs throughout each clothing trial and during the lifting task they alternated between the positive and negative work phases of the task every 5 min (i.e. one subject lifted the weight and the other lowered it).

3.3.3 Continuous vs Intermittent Work Schedule

Four of the 6 subjects in both the light-hot and heavy-hot conditions performed an additional three clothing trials using an intermittent rather than a continuous work schedule. For the TL trials and for the TM trial with light exercise the work/rest schedule was 25 min exercise and 5 min rest. For the TM condition with heavy exercise and for the TH trials with light exercise the work/rest schedule was 20 min exercise and 10 min rest. Finally, for the TH trial with heavy exercise a 15 min work and 15 min rest schedule was implemented.

Figure 1. EXPERIMENTAL PROTOCOL

Nuclear, Biological and Chemical Defence Trial



3.4 Dressing and Weighing Procedures

At the beginning of each test day in the climatic chamber, subjects first inserted a rectal thermistor (Pharmaseal APC 400 Series) approximately 12 cm beyond the anal sphincter. They were then weighed nude on an electronic scale sensitive to the nearest 0.01 kg (Electroscale Model 921). To measure skin temperature, thermistors (Yellow Springs Instruments thermistor bead 4404) were taped to the following 12 sites: forehead, chest, upper back, lower back, forearm, wrist, abdomen, front thigh, rear thigh, calf, shin, and foot.

For HR measurements, a telemetry transmitter (SportTester) was clipped to an elasticized electrode belt around the chest; a recording/displaying HR receiver was taped to the outside of the clothing and recorded HR continuously for the duration of each trial. Subjects then dressed in their combat fatigues and boots.

Following this stage of the dress procedure, a 20-gauge flexible catheter (Vialon) was inserted into an antecubital vein and a 60 cm sampling line was connected to the catheter, taped to the forearm and to the sleeve of the fatigues or IPE overgarment. The line was flushed with 2 mL of saline and kept patent with a heparin (10 $I.U.\cdot mL^{-1}$) lock.

Approximately 10 min before entry into the chamber, subjects donned their IPE overgarment for the TM or TH trials. Standard issue webbing was worn over the fatigues or IPE overgarment. A solid-state data recorder for the twelve skin temperatures and T_{re} was carried on the webbing. T_{re} was continuously displayed on the recorder. Subjects also carried one canteen filled with cool water (approximately 1 L).

They were instructed to drink *ad libitum* from the canteen but the canteen would not be refilled. An extension tube fit to the fluid intake port of the C4 respirator allowed water intake during the TH trials. The canteen was weighed to the nearest 0.001 kg before and after each trial. Both nude and total dressed weight were recorded prior to entry into the chamber. For the TH trials the respirator and hood were donned 1 min before chamber entry. After the completion of each trial, dressed weight was recorded within 1 min after exit from the chamber and nude weight was recorded following a 10 min undress procedure. Any urine which was collected in bottles during the experiment was weighed to the nearest 0.001 kg.

Differences in nude and dressed weights before and after each trial were corrected for urine, blood, respiratory and metabolic weight losses (see below). Fluid loss was calculated as follows: pre-trial minus post trial nude weight (corrected) plus the weight of the water drunk during the trial. Evaporative sweat loss was calculated as the ratio of the difference in corrected dressed weight to fluid loss, and was expressed as a percentage.

Mean weighted skin temperature ($\overline{T}_{SK}$) was calculated from a 12-point weighted equation (21). If one or more of the skin thermistors came off the skin or broke during the trial, either a 7-point (22) or 3-point (23) weighted equation was used to calculate $\overline{T}_{SK}$. For a given subject the same equation was used across clothing trials for $\overline{T}_{SK}$ calulation.

3.5 Gas Exchange Analyses

During each treadmill walk, open-circuit spirometry was used to determine expired minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) during minutes 10-15 and 40-45. Values were averaged from a 2-min sampling period obtained for each subject. The CO_2 concentration in the environmental chamber was monitored throughout each trial with an ADC CO_2 analyzer. Inspired CO_2 values varied from 0.05 to 0.11%.

Subjects breathed through a low-resistance Hans-Rudolf respiratory valve during the TL and TM trials. When the respirator was worn during the TH trials, an adaptor was attached to the respirator which allowed expired air to be collected. Expired gases were directed into a 5 L mixing-box and through an Alpha Technologies VMM 110 Series Ventilation Module for the determination of $\dot{V}_E$. A sampling line directed dried gases from the mixing-box to S-3A O_2 and CD-3A CO_2 Ametek analyzers. The gas analyzers were calibrated before each collection period with a precision-analyzed gas while the ventilation module was calibrated with a syringe of known volume. After conversion of the analogue voltage outputs from the ventilation module and gas analyzers into digital signals (Hewlett-Packard 59313 A/D Converter) $\dot{V}_E$, $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated and printed on-line every 60 s using appropriate software on a Hewlett-Packard 9825A microcomputer.

Respiratory water loss was calculated using the $\dot{V}O_2$ measured during the treadmill walk and the equation presented by Mitchell et al. (24). Metabolic weight loss was calculated assuming an energy equivalent of 21 $kJ \cdot L^{-1} O_2$ consumed (a 0.1 kg weight loss would require ~3200 kJ of energy expenditure or the consumption of ~ 150 L of O_2).

3.6 Blood Sampling

Blood was sampled prior to entry into the chamber after the subject had been standing for 10 minutes following catheterization. Subsequent samples were taken, with the subject standing, immediately prior to each treadmill walk and while gas exchange was being measured (see Figure 1). During each sampling period, 2 mL of blood were collected into a heparinized plastic syringe. Fom this sample 1 mL of blood was used to determine hematocrit (Hct) with a microhematocrit centrifuge, and hemaglobin (Hb) concentration (Total Hemoglobin Assay, Sigma Chemical). The changes in hematocrit and hemaglobin values were used to calculate the percent change in plasma volume (25). The remaining blood was analyzed immediately for pH and pCO_2 corrected for T_{re} on an automated blood gas analyser (Corning pH/Blood Gas System, Model 168). From an additional 3 mL of blood, 200 µL were deproteinized in 2 mL of 0.4 $mol \cdot L^{-1}$ perchloric acid for subsequent glucose and lactate analyses (26) while the remaining sample volume was used for glycerol (27) and FFA (NEFA C assay, Wako, Yamagoochi, Japan) determinations. Weight loss due to blood sampling was calculated by using 1.055 $g \cdot mL^{-1}$ for the density of whole blood.

3.7 Statistics

Data are presented as mean values and standard error of the mean. Both a one-factor (clothing at each environmental temperature) and two-factor (clothing and continuous versus intermittent exercise) repeated measures analyses of variance (ANOVA) were used to analyze gas exchange, heart rate, T_{re}, $\overline{T}_{SK}$, blood metabolites and body weight changes at a given metabolic rate (light or heavy). Similarly, a two-factor (clothing and temperature) ANOVA was used to compare responses among subjects at a given metabolic rate. When a significant F-ratio (corrected for the repeated measures factor) was obtained, a Newman-Keuls post-hoc analysis was performed to isolate differences among treatment means. Correlation and regression analyses were performed to investigate the relationship between metabolic rate and work tolerance time for the different clothing configurations at 30°C. In addition, step-wise multiple regression techniques were used to identify variables that could explain individual differences in work tolerance time, rate of T_{re} change, rate of fluid loss or evaporative sweat loss at a given metabolic rate and chamber temperature. For all statistical analyses, the 0.05 level of significance was used.

4.0 RESULTS

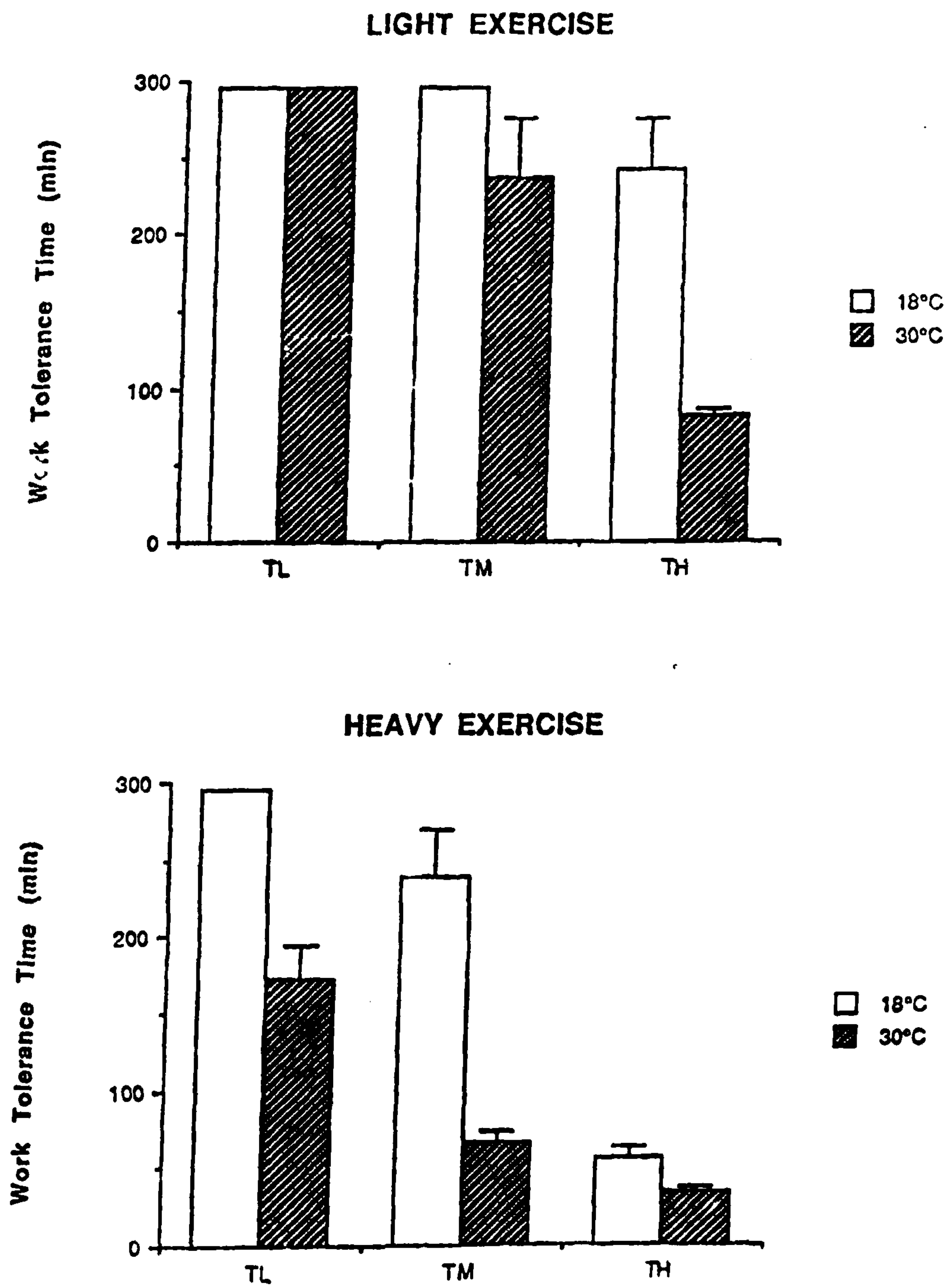
$\dot{V}O_2max$ was similar for subjects allocated to both light exercise groups (18LC, 45.5 ± 3.6 $mL \cdot kg^{-1} \cdot min^{-1}$; 30LC, 47.2 ± 2.4 $mL \cdot kg^{-1} \cdot min^{-1}$), or both heavy exercise groups (18HC, 51.6 ± 5.2 $mL \cdot kg^{-1} \cdot min^{-1}$; 30HC, 52.0 ± 4.4 $mL \cdot kg^{-1} \cdot min^{-1}$). $\dot{V}O_2max$ was unchanged for all groups following the series of experiments in the climatic chamber. Maximal heart rates were similar among all groups of subjects (190.0 ± 8.2, 190.5 ± 6.5, 184.0 ± 9.2 and 197.8 ± 9.1 $b \cdot min^{-1}$ for the 18LC, 30LC, 18HC and 30LC groups, respectively).

4.1 CONTINUOUS EXERCISE

4.1.1 Work Tolerance Time (WTT).

In 18LC, WTT was similar in all three levels of protective clothing (Figure 2). Although mean values for WTT were reduced in the TH trial, 3 of the 5 subjects completed the 5 h of exercise. In 30LC WTT was significantly reduced in TH (82.7 ± 10.6 min). In the 18HC trials, WTT was impaired in TM (240.5 ± 73.8 min) and TH (56.7 ± 17.9 min) levels of protection. Finally, in 30HC WTT was progressively reduced for

Figure 2. Work tolerance times during the light and heavy exercise trials at 18°C or 30°C while wearing TOPP Low (TL), Medium (TM) or High (TH) levels of protective clothing. Data are presented as means and standard errors of the mean.



the TL (172.5 ± 52.8 min), TM (65.8 ± 18.2 min) and TH (34.0 ± 9.7 min) levels of protective clothing (Figure 2). As shown in Figure 3, for both TL and TM levels of protection, WTT was reduced in 30HC compared with the other exercise and/or environmental conditions. For the TH level of protection, WTT was reduced during the hot environment or heavy exercise trials compared with the light exercise and cool condition (Figure 3). The various criteria used to establish WTT in the different experimental trials are shown in Table 2.

Table 2. Criteria used to determine work tolerance times.

Level of Protection	Light Exercise		Heavy Exercise	
	18°C	30°C	18°C	30°C
Low	5 h (5)	5 h (6)	5 h (6)	dizziness (3) T_{re} (2) HR (1)
Medium	5 h (5)	5 h (4) nausea (1) asked to come out (1)	5 h (3) T_{re} (3)	HR (3) T_{re} (3)
High	5 h (3) dizziness (2)	T_{re} (2) dizziness (3) HR (1)	HR (4) dizziness (2)	HR (3) dizziness (3)

numbers in parentheses refer to number of subjec.

4.1.2 Rectal Temperature.

The T_{re} at the beginning and end of each trial for each group is shown in Table 3. The rate of change in T_{re} is depicted in Figure 4. The rate of change ranged from 0.16°C·h^{-1} while wearing TL during light intensity work at 18°C to 2.61°C·h^{-1} while wearing TH during heavy intensity work at 30°C. For 18LC the rate of change was similar for all three levels of protection. For 30LC, however, all three levels of

Figure 3. Work tolerance times presented separately for the three levels of protective clothing during the light continuous (LC) or heavy continuous (HC) exercise trials at 18°C or 30°C.

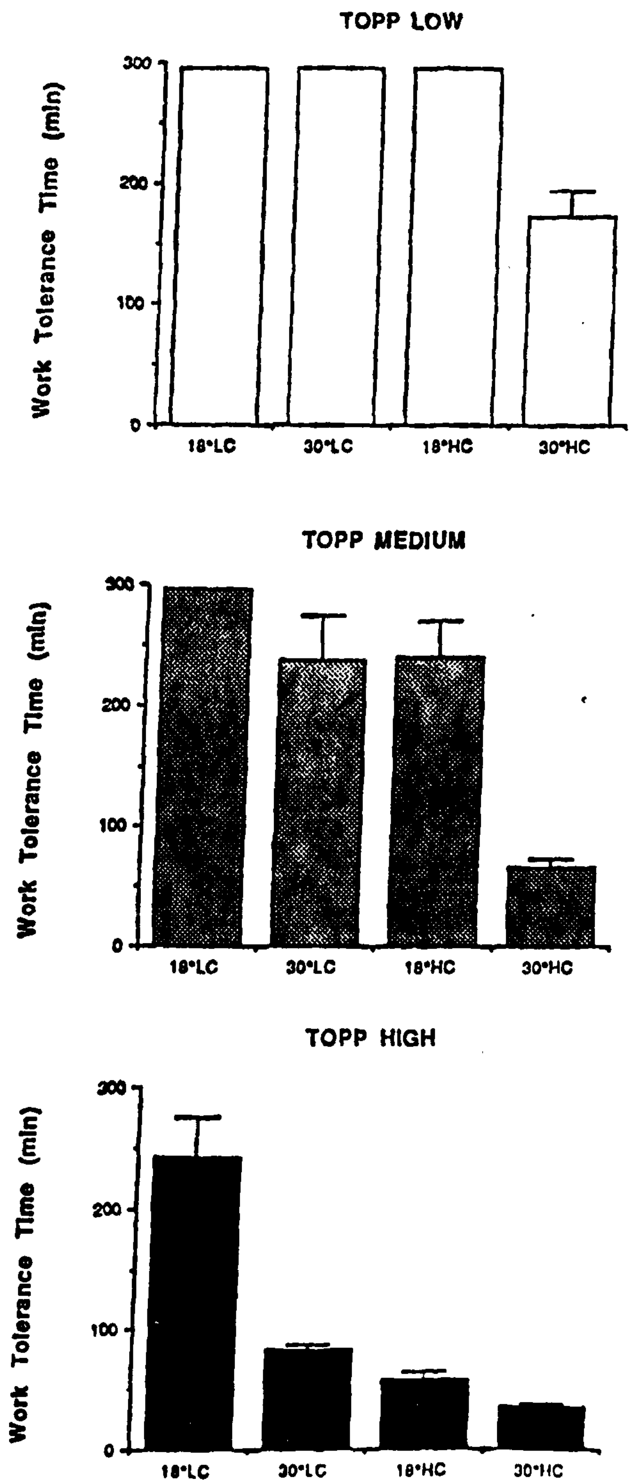


Table 3. Initial and final rectal temperatures.

Group		Level of Protection		
		TL	TM	TH
18LC	initial	36.79 (0.12)	36.90 (0.13)	37.01 (0.15)
	final	37.62 (0.13)	37.79 (0.07)	38.27 (0.15)
30LC	initial	37.03 (0.11)	36.97 (0.11)	37.22 (0.08)
	final	38.02 (0.07)	38.70 (0.22)	38.88 (0.12)
18HC	initial	36.90 (0.11)	37.15 (0.14)	36.91 (0.13)
	final	38.31 (0.04)	38.83 (0.21)	38.53 (0.13)
30HC	initial	36.84 (0.12)	36.95 (0.10)	36.86 (0.13)
	final	38.90 (0.07)	39.03 (0.11)	38.33 (0.16)

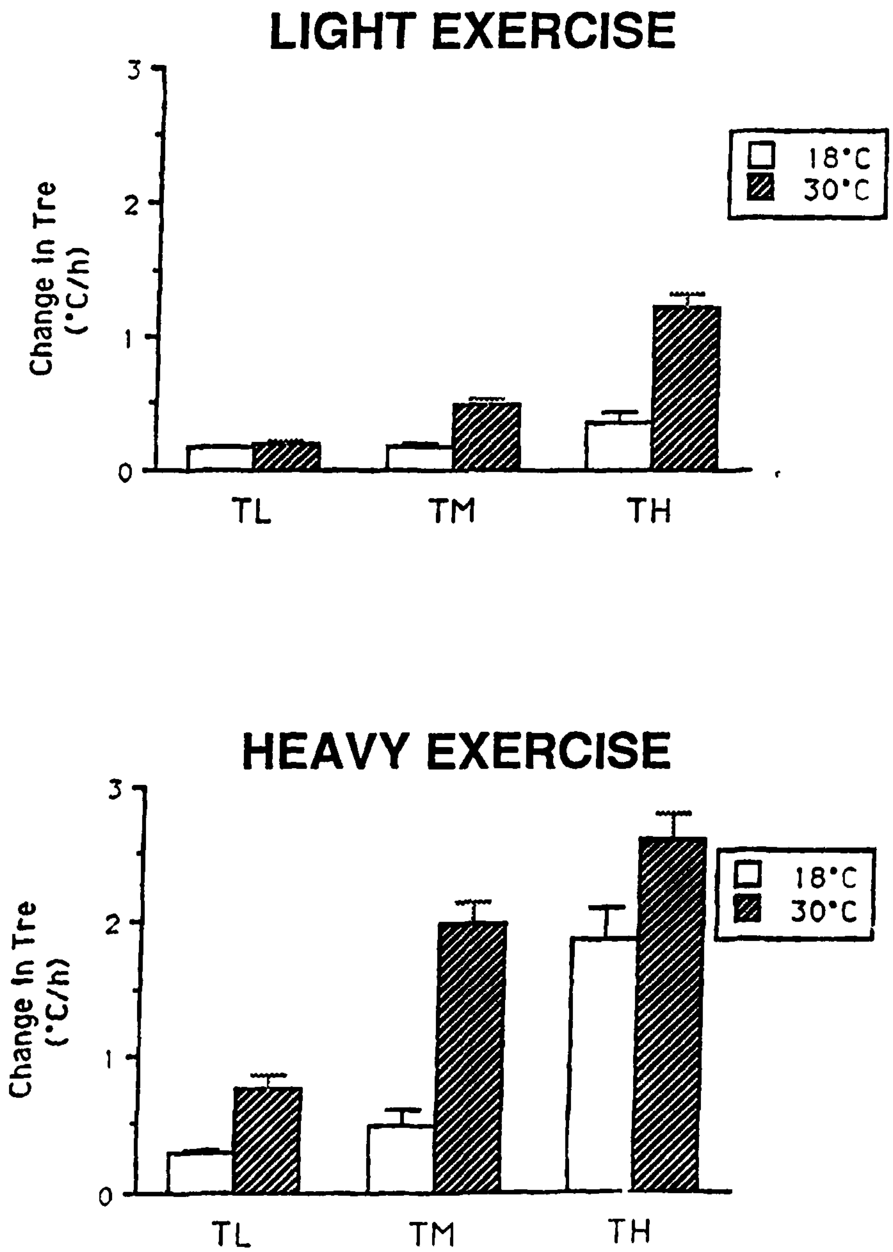
Values are mean (SEM)

Table 4. Initial and final mean skin temperatures.

Group		Level of Protection		
		TL	TM	TH
18LC	initial	32.79 (0.29)	33.65 (0.11)	33.63 (0.35)
	final	33.06 (0.29)	34.34 (0.37)	35.34 (0.35)
30LC	initial	34.37 (0.09)	34.79 (0.20)	35.17 (0.10)
	final	35.88 (0.12)	36.61 (0.24)	37.29 (0.15)
18HC	initial	32.82 (0.26)	34.31 (0.17)	34.09 (0.23)
	final	33.68 (0.32)	34.49 (0.38)	36.27 (0.12)
30HC	initial	34.39 (0.21)	34.81 (0.15)	34.84 (0.17)
	final	35.65 (0.19)	36.72 (0.30)	37.01 (0.09)

Values are mean (SEM)

Figure 4. Rate of rectal temperature change during light and heavy exercise at 18°C and 30°C while wearing TL, TM, and TH levels of protective clothing.



protection differed significantly from each other. For the heavy intensity groups (i.e., 18HC and 30HC) the rate of change in T_{re} for the cooler trials was significantly higher for TH compared with both TL and TM; for the warmer trials all three levels of protection differed significantly from each other.

4.1.3 Mean Skin Temperature.

The $\overline{T}_{SK}$ at the beginning and end of each trial for each group is shown in Table 4. The rate of change for the various groups is depicted in Figure 5a, and ranged from 0.05°C·h^{-1} while wearing TL for 18LC to 3.99°C·h^{-1} while wearing TH for 30HC. For the light intensity exercise the rate of change in $\overline{T}_{SK}$ was significantly greater in TH compared with both TM and TL at both temperatures. Likewise, for the heavy intensity work the rate of change at 18°C was also greater in TH than both TL and TM. At 30°C, however, all three trials were significantly different from each other (i.e., TH>TM>TL).

4.1.4 Gradient Between Skin and Rectal Temperature.

Another proposed indicator of impending heat-induced incapacitation is the convergence of skin and rectal temperature (17). As can be seen in Figure 5b, the gradient between $\overline{T}_{SK}$ and T_{re} decreased progressively in all groups with increasing levels of protection. This observation simply reemphasizes that the impaired evaporation of sweat from the skin surface results in a decreased rate of heat transfer from the body core to the surface and, therefore, a greater heat storage.

4.1.5 Gas Exchange.

$\dot{V}O_2$ averaged approximately 1.0 L·min^{-1} during the light exercise trials

Figure 5(a). Comparison of rate of mean skin temperature change in all groups while wearing TL, TM, and TH levels of protective clothing.

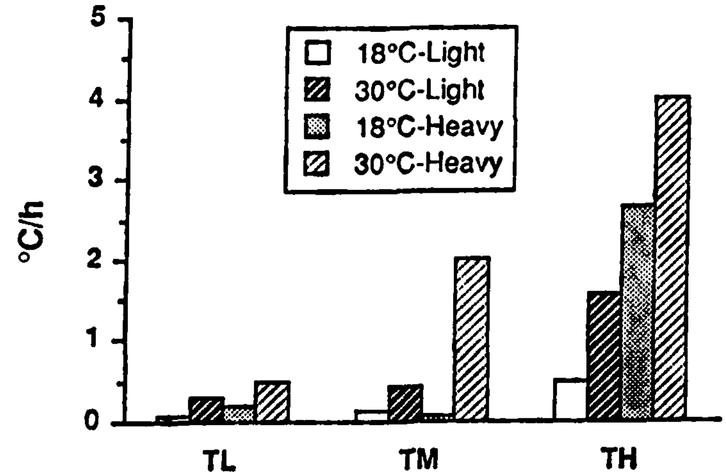
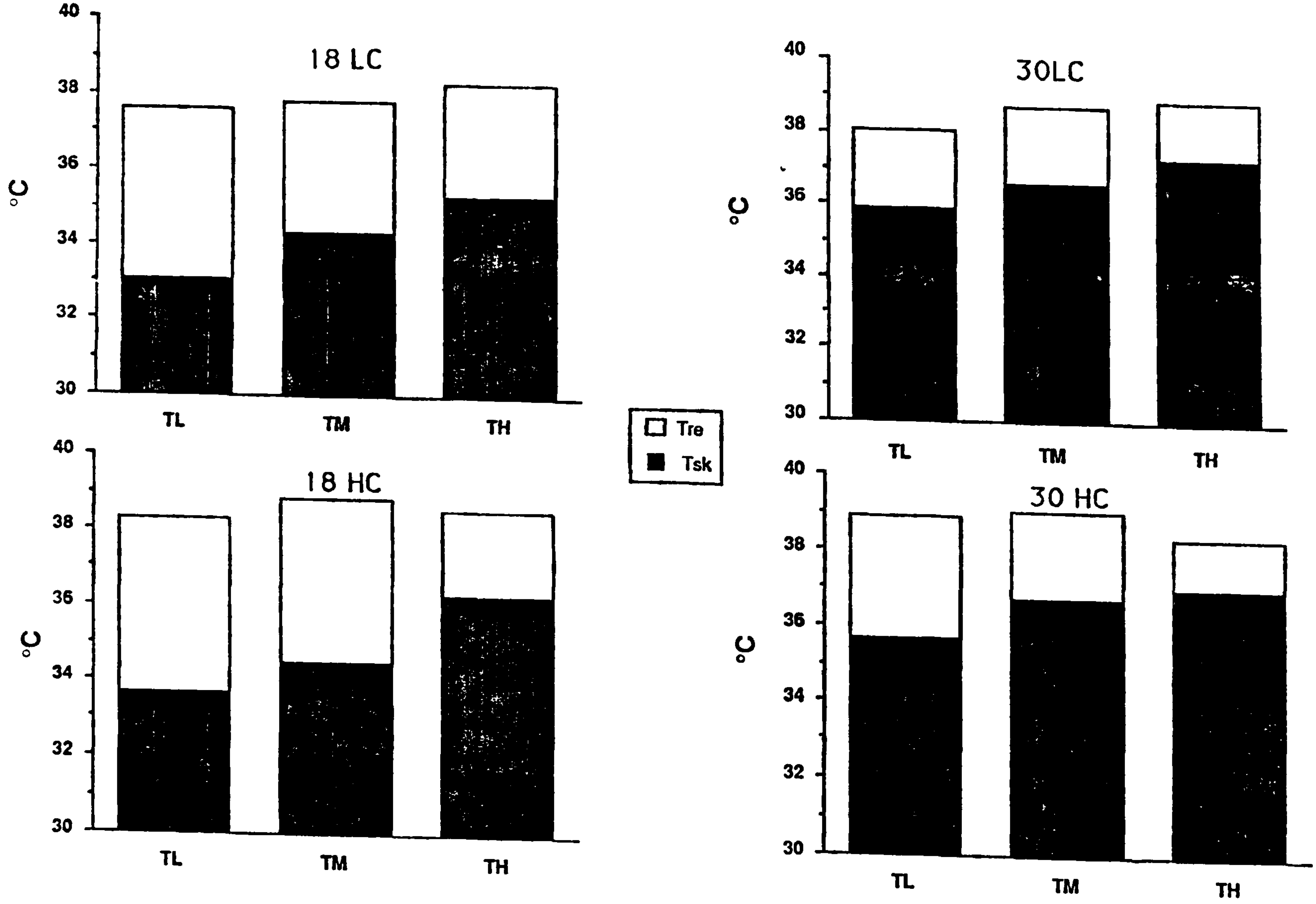


Figure 5(b). The gradient between mean skin (Tsk) and mean rectal (Tre) temperatures while wearing TL, TM, and TH levels of protective clothing for each group. 18LC = light continuous exercise at 18°C; 30LC = light continuous exercise at 30°C; 18HC = heavy continuous exercise at 18°C; 30HC = heavy continuous exercise at 30°C.



throughout the three treadmill walks (Tables 5 and 6). Due to the added weight of the full IPE $\dot{V}O_2$ (L·min^{-1}) was increased during the TH trials in both the cool and hot environments. Similarly, $\dot{V}_E$ did not change throughout the three treadmill walks wearing TL and TM for both 18LC and 30LC (Tables 5 and 6). $\dot{V}_E$ was significantly increased, however, during the TH trials for both chamber temperatures. For those 18LC subjects who completed the 5 h of exercise, $\dot{V}_E$ increased during the third treadmill walk in TH.

For the heavy exercise trials, $\dot{V}O_2$ averaged 1.6 to 1.8 L·min^{-1} (Tables 7 and 8). For those 18HC subjects who completed the 5 h of exercise $\dot{V}O_2$ did not change throughout the three treadmill walks for the TL and TM trials. Again, due to the added weight of the IPE $\dot{V}O_2$ was increased during the TH trials in both 18HC and 30HC. In 18HC $\dot{V}O_2$ increased significantly during the TH trial for the first treadmill walk. In 30HC $\dot{V}O_2$ was increased throughout the second treadmill walk for the TL condition. $\dot{V}_E$ was unchanged throughout the treadmill walks for the 18HC TL and TM trials, but $\dot{V}_E$ was higher for the TM level of protection (Tables 7 and 8). For both the cool and hot environments, $\dot{V}_E$ was significantly higher during the TH trials compared with the other levels of protection. In addition, $\dot{V}_E$ increased throughout the first treadmill walk for the TH trial in the 18HC. Similarly, $\dot{V}_E$ increased during the first treadmill walk in 30HC for both the TL and TM trials and continued to increase during the second treadmill walk for the TL level of protection.

4.1.6 Heart Rate (HR).

For the light exercise trials HR was significantly higher during the lifting task compared with the treadmill walks in both the cool and hot environments (Figure 6).

Table 5. Gas exchange measurements ($\dot{V}O_2$ and $\dot{V}_E$) during the three treadmill walks of the light exercise and cool (18°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Light Exercise 18°C		TREADMILL WALK 1		2		3	
Time (min)		15	45	15	45	15	45
		N = 5		N = 4		N = 3	
$\dot{V}O_2$ ($L{\cdot}min^{-1}$) (STPD)	Low	0.95	0.99	0.95	0.97	0.94	0.93
		(0.08)	(0.07)	(0.20)	(0.20)	(0.11)	(0.11)
	Medium	1.04	1.04	0.97	0.98	0.97	1.01
		(0.09)	(0.09)	(0.10)	(0.10)	(0.15)	(0.15)
	High	1.09	1.14	1.11	1.15	0.98	1.03
		(0.08)	(0.09)	(0.08)	(0.11)	(0.12)	(0.13)
$\dot{V}_E$ ($L{\cdot}min^{-1}$) (STPD)	Low	18.9	19.2	18.5	18.3	17.0	16.9
		(1.4)	(1.4)	(1.2)	(1.1)	(1.2)	(0.8)
	Medium	20.8	20.9	19.3	19.1	16.6	18.1
		(2.2)	(1.8)	(0.9)	(1.3)	(1.1)	(1.2)
	High	21.6	22.9	21.4	22.6	20.2	22.5
		(2.1)	(2.4)	(1.9)	(2.9)	(0.7)	(2.3)

Values are means (SEM)

Table 6. Gas exchange measurements ($\dot{V}O_2$ and $\dot{V}_E$) during the three treadmill walks of the light exercise and hot (30°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Light Exercise 30°C		TREADMILL WALK 1		2		3	
Time (min)		15	45	15	45	15	45
		N = 6		N = 5		N = 4	
$\dot{V}O_2$ ($L{\cdot}min^{-1}$) (STPD)	Low	0.95	0.92	0.95	0.95	0.95	1.05
		(0.04)	(0.04)	(0.03)	(0.05)	(0.07)	(0.08)
	Medium	0.95	0.94	1.01	1.04	0.98	0.99
		(0.04)	(0.05)	(0.06)	(0.06)	(0.06)	(0.07)
	High	1.11	1.13				
		(0.04)	(0.05)				
$\dot{V}_E$ ($L{\cdot}min^{-1}$) (STPD)	Low	21.0	20.4	21.1	19.9	21.8	23.4
		(1.0)	(1.1)	(1.1)	(1.4)	(2.6)	(4.0)
	Medium	21.8	21.9	22.5	24.5	25.9	27.5
		(1.0)	(1.5)	(1.6)	(2.5)	(3.6)	(6.9)
	High	23.7	26.1				
		(0.5)	(1.4)				

Values are means (SEM)

Table 7. Gas exchange measurements ($\dot{V}O_2$ and $\dot{V}_E$) during the three treadmill walks of the heavy exercise and cool (18°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Heavy Exercise 18°C		TREADMILL WALK 1		2		3	
Time (min)		15	45	15	45	15	45
		N = 5		N = 4		N = 3	
$\dot{V}O_2$ ($L \cdot min^{-1}$) (STPD)	Low	1.63 (0.10)	1.63 (0.11)	1.54 (0.07)	1.58 (0.09)	1.69 (0.09)	1.65 (0.08)
	Medium	1.76 (0.15)	1.80 (0.12)	1.78 (0.06)	1.77 (0.13)	1.73 (0.03)	1.68 (0.09)
	High	1.71 (0.08)	1.92 (0.12)				
$\dot{V}_E$ ($L \cdot min^{-1}$) (STPD)	Low	31.8 (2.5)	32.2 (2.7)	30.3 (0.9)	31.3 (1.2)	32.4 (0.9)	32.4 (0.1)
	Medium	36.6 (4.2)	37.8 (3.3)	36.7 (0.3)	36.6 (2.0)	36.5 (1.7)	37.7 (4.4)
	High	35.1 (2.5)	42.2 (4.5)				

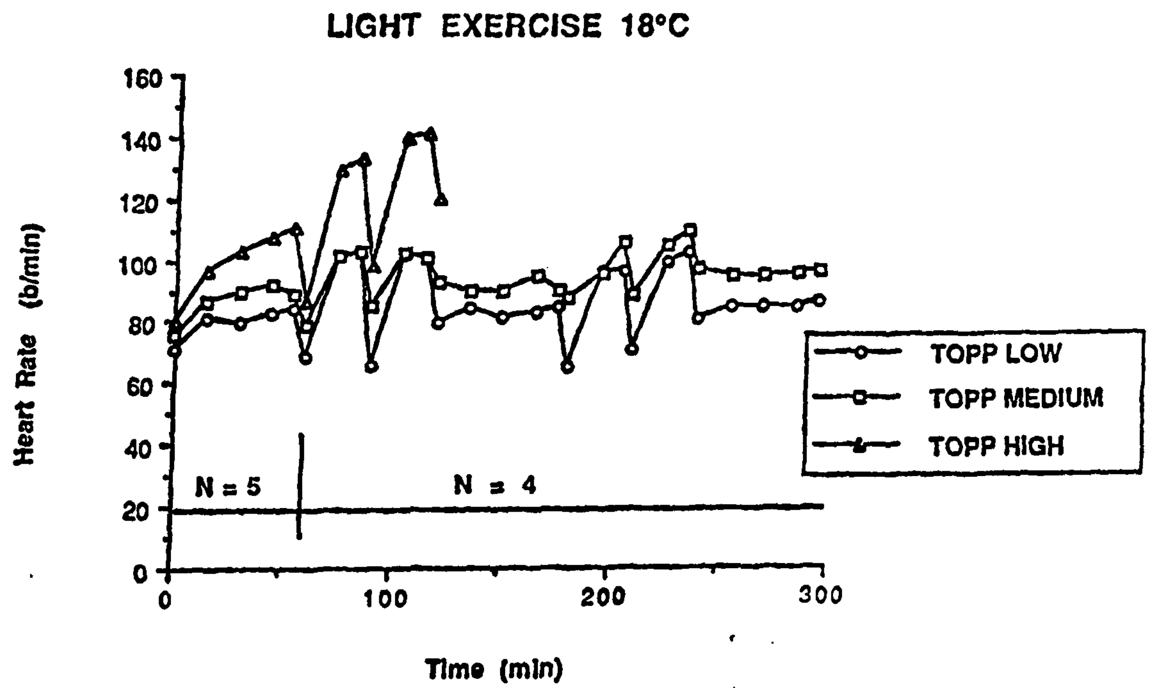
Values are means (SEM)

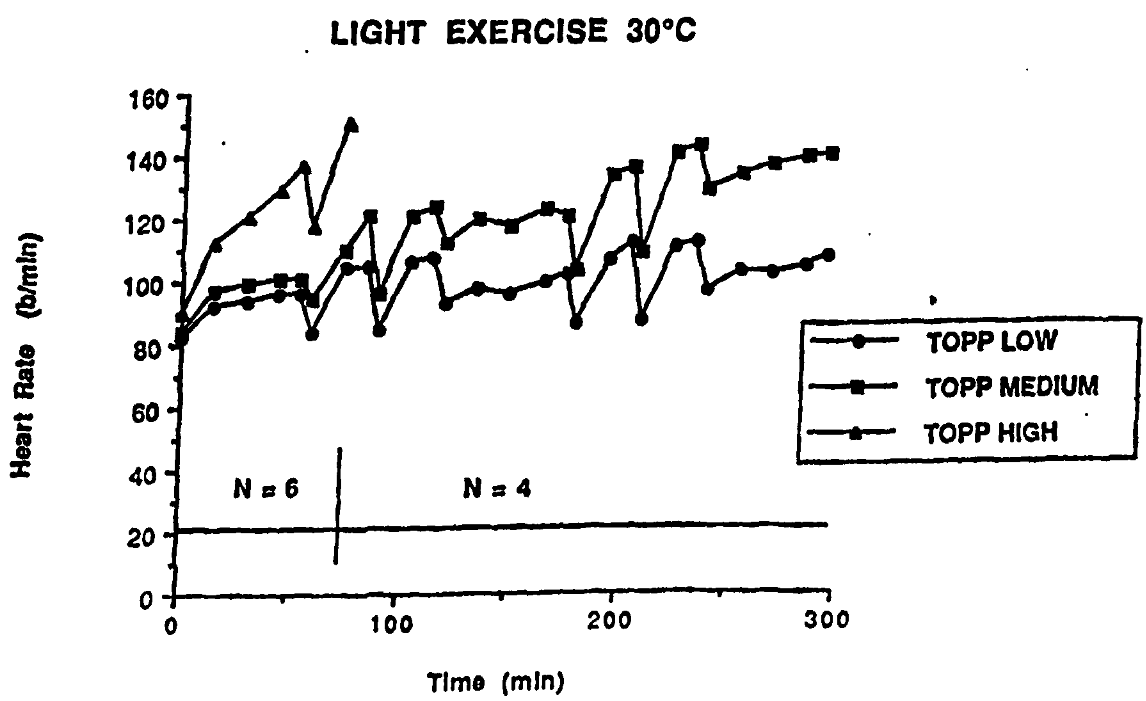
Table 8. Gas exchange measurements ($\dot{V}O_2$ and $\dot{V}_E$) during the three treadmill walks of the heavy exercise and hot (30°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Heavy Exercise 30°C		TREADMILL WALK 1		2		3	
Time (min)		15	45	15	45	15	45
		N = 6		N = 5			
$\dot{V}O_2$ ($L \cdot min^{-1}$) (STPD)	Low	1.65 (0.04)	1.68 (0.04)	1.82 (0.03)	1.88 (0.04)		
	Medium	1.72 (0.04)	1.77 (0.04)				
	High	1.90 (0.07)					
$\dot{V}_E$ ($L \cdot min^{-1}$) (STPD)	Low	35.0 (1.7)	37.2 (2.1)	40.5 (2.6)	49.3 (4.6)		
	Medium	37.2 (1.5)	41.1 (1.8)				
	High	40.6 (1.4)					

Values are means (SEM)

Figure 6. Heart rate responses during the light exercise trials at 18°C or 30°C.

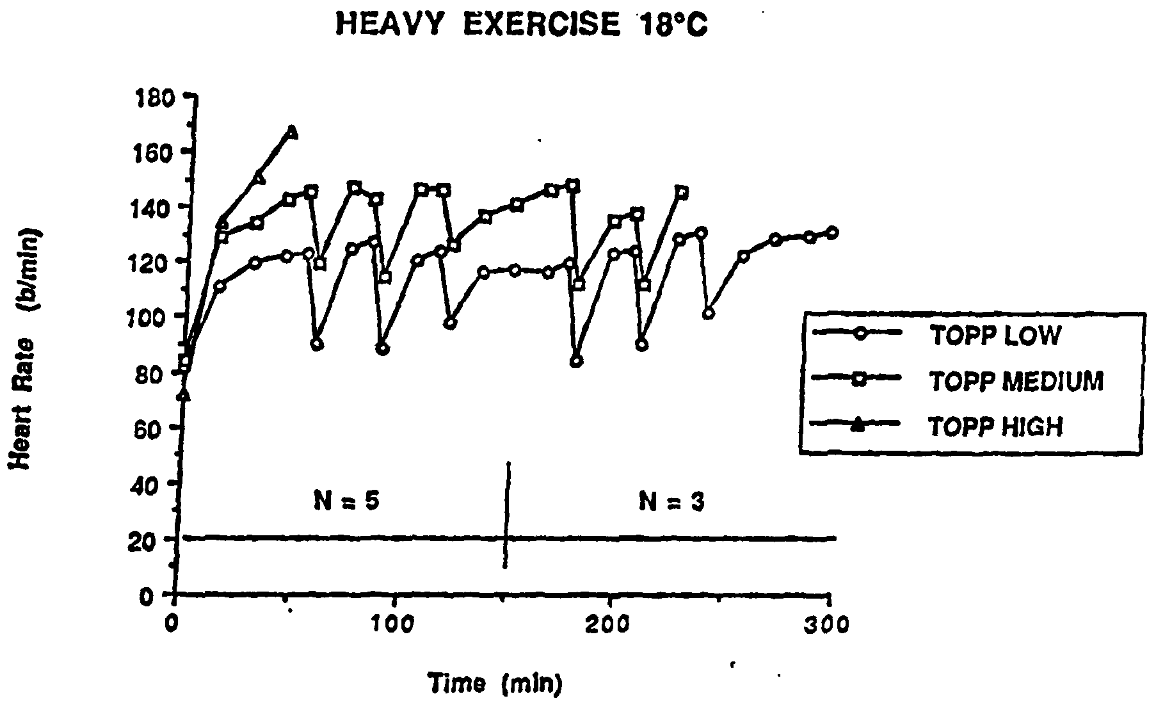


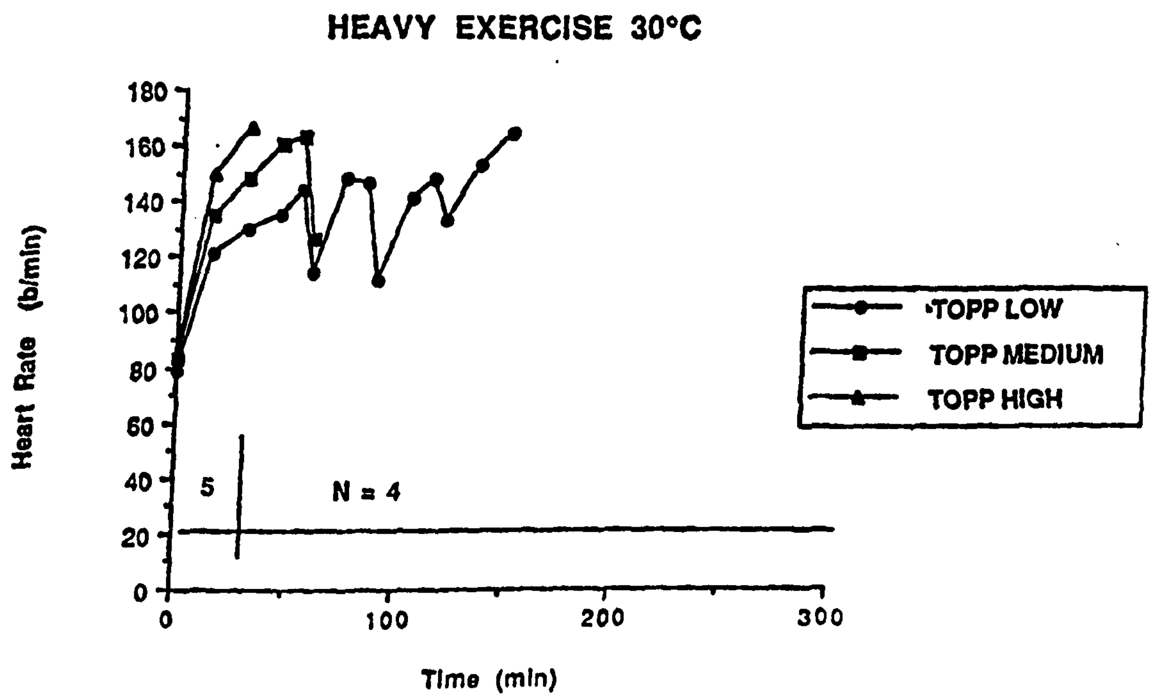


For the TL and TM levels of protection in 18LC HR was not different over the three treadmill walks or throughout the two lifting bouts. The HR response was increased during the TH level of protection in 18LC and HR continued to increase throughout the first treadmill walk and lifting task (Figure 6). During the periodic non-exercise periods HR recovered to similar levels for the TL and TM trials in 18LC whereas HR increased progressively during these non-exercise periods in the TH trial. Heart rates were higher in the hot environment compared with the cool environment for all levels of protective clothing. In addition, HR was significantly increased during the second and third treadmill walks and during the two lifting tasks for the TM condition compared with the TL level of protection. Heart rate increased at a faster rate during the TH trial. During the periodic non-exercise periods HR recovered to similar levels for the TL trial except after the second lifting bout. In contrast HR remained elevated after each lifting bout in the TM level of protection (Figure 6).

For the heavy exercise trials in the cool environment (i.e. 18HC), HR was higher and increased more throughout the treadmill walks for the TM level of protection compared with the TL trial (Figure 7). HR was significantly elevated for the TH trial compared with the other levels of protective clothing. During the non-exercise periods HR did not recover to the same extent at the end of each lifting task for both the TM and TL trials. Again, the HR response was higher in the hot environment for all levels of protective clothing (Figure 7). In addition HR continued to increase throughout the first treadmill walk for each level of protective clothing. Heart rates were significantly different among the three clothing trials. During the second treadmill walk HR was higher for the TL level of protection compared with the first treadmill

Figure 7. Heart rate responses during the heavy exercise trials at 18°C or 30°C.





walk. Heart rates did not recover to pre-exercise values during the non-exercise periods (Figure 7).

4.1.7 Plasma Volume Changes.

The changes in plasma volume were calculated relative to hematocrit and hemaglobin values obtained at the 15 min time point during the first treadmill walk. The reason they were not calculated relative to the pre-exercise values was in order to minimize the variation between trials in the degree of the venous blood arterialization. The mean changes in plasma volume for each group in each level of protective clothing are displayed in Table 9. In general the changes in plasma volume were not great enough to significantly affect the blood metabolite concentrations. Thus, the blood data have not been corrected for the plasma volume change.

Table 9. % change in plasma volume at end of each trial.

Group	Level of Protection		
	TL	TM	TH
18LC	9.3 (6.0)	5.8 (3.8)	-0.9 (2.5)
30LC	2.0 (1.0)	-4.6 (1.5)	-0.3 (1.6)
18HC	1.9 (1.0)	-3.6 (3.7)	-2.4 (1.6)
30HC	-2.4 (2.1)	-0.3 (1.4)	-0.2 (5.6)

Values are mean (SEM)

4.1.8 Acid-base data (pH and pCO_2).

The data for the continuous exercise trials are presented in Tables 10 to 13. The apparent increase in pH and decrease in pCO_2 during the first treadmill walk reflects the gradual arterialization of the venous blood sample due to the heating effects of the exercise, clothing and/or chamber temperature. As a result, data from before the first treadmill walk were not used in subsequent analyses. For the light exercise trials in the cool environment, pH and pCO_2 values were similar among the three levels of protective clothing for the three treadmill walks (Table 10). Similarly, acid-base data were unaffected by the light exercise in the hot environment for the three levels of protective clothing (Table 11). For the heavy exercise trials in the cool environment, pH and pCO_2 values were similar among the different levels of protective clothing and did not change throughout the treadmill walks (Table 12). For the heavy exercise in the hot environment a slight respiratory alkalosis was evident by the end of the second treadmill walk for the TL trial as pCO_2 decreased and pH increased. There were no other acid-base changes that were evident during the heavy exercise trials in the hot environment (Table 13).

4.1.9 FFA.

The mean values for the FFA concentrations are shown in Figures 8 and 9. For the light exercise groups, there was a similar response at both temperatures; they increased progressively during the three treadmill walks while wearing TL and TM. In TH blood samples were available for only the first treadmill walk, and only during the cool trial was there an increase. When comparing the effects of the various levels of protection in the light exercise groups, the change in FFA was greater in TM than TH

Table 10. Acid-base measurements (pH and pCO_2) during the three treadmill walks of the light exercise and cool (18°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Light Exercise 18°C		TREADMILL WALK 1			2			3		
Time (min)		0	15	45	0	15	45	0	15	45
		N = 4			N = 3			N = 3		
pH	Low	7.35 (0.01)	7.36 (0.01)	7.38 (0.01)	7.39 (0.01)	7.36 (0.03)	7.39 (0.01)	7.38 (0.01)	7.38 (0.02)	7.39 (0.01)
	Medium	7.34 (0.01)	7.36 (0.01)	7.38 (0.01)	7.37 (0.02)	7.39 (0.01)	7.39 (0.01)	7.40 (0.01)	7.39 (0.01)	7.39 (0.01)
	High	7.36 (0.01)	7.38 (0.01)	7.39 (0.01)						
pCO_2 (mmHg)	Low	48.1 (1.3)	47.2 (2.6)	43.7 (0.4)	43.9 (0.4)	43.7 (2.0)	42.5 (1.2)	41.4 (1.7)	45.2 (0.3)	41.4 (4.0)
	Medium	46.9 (3.3)	45.3 (0.8)	43.6 (1.2)	46.4 (4.8)	42.1 (1.4)	41.5 (2.0)	39.9 (2.7)	42.0 (1.5)	40.9 (2.2)
	High	47.9 (2.2)	45.3 (0.9)	42.6 (1.9)						

Values are means (SEM).

Table 11. Acid-base measurements (pH and pCO_2) during the three treadmill walks of the light exercise and hot (30°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Light Exercise 30°C		TREADMILL WALK 1			2			3		
Time (min)		0	15	45	0	15	45	0	15	45
		N = 6			N = 5			N = 4		
pH	Low	7.35 (0.01)	7.40 (0.01)	7.41 (0.01)	7.40 (0.01)	7.41 (0.01)	7.41 (0.01)	7.41 (0.02)	7.42 (0.01)	7.43 (0.01)
	Medium	7.38 (0.01)	7.38 (0.01)	7.40 (0.01)	7.42 (0.01)	7.41 (0.01)	7.41 (0.01)	7.41 (0.02)	7.42 (0.02)	7.43 (0.03)
	High	7.37 (0.01)	7.39 (0.01)	7.41 (0.01)						
pCO_2 (mmHg)	Low	42.4 (2.8)	40.7 (1.2)	39.1 (1.3)	39.7 (2.5)	38.0 (1.9)	38.4 (2.2)	39.1 (3.7)	37.0 (3.0)	35.8 (4.1)
	Medium	43.4 (2.3)	43.1 (1.6)	40.8 (1.2)	37.2 (1.9)	38.6 (1.8)	37.8 (1.9)	39.7 (3.1)	36.4 (2.9)	34.9 (4.1)
	High	44.9 (2.5)	41.5 (1.1)	38.4 (0.6)						

Values are means (SEM)

Table 12. Acid-base measurements (pH and pCO_2) during the three treadmill walks of the heavy exercise and cool (18°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Heavy Exercise 18°C		TREADMILL WALK								
		1			2			3		
Time (min)		0	15	45	0	15	45	0	15	45
			N = 4			N = 6			N = 6	
pH	Low	7.35 (0.01)	7.37 (0.01)	7.39 (0.01)	7.38 (0.01)	7.40 (0.01)	7.39 (0.01)	7.38 (0.01)	7.39 (0.01)	7.39 (0.01)
	Medium	7.36 (0.02)	7.38 (0.01)	7.40 (0.01)						
	High	7.37 (0.02)	7.38 (0.01)	7.41 (0.01)						
pCO_2 (mmHg)	Low	47.4 (2.8)	45.0 (2.2)	42.1 (0.9)	42.9 (3.0)	40.4 (1.1)	41.2 (1.1)	41.8 (2.7)	39.8 (1.3)	40.2 (0.9)
	Medium	48.1 (4.9)	43.1 (1.2)	40.0 (1.1)						
	High	48.3 (4.9)	44.1 (1.2)	39.1 (1.1)						

Values are means (SEM)

Table 13. Acid-base measurements (pH and pCO_2) during the three treadmill walks of the heavy exercise and hot (30°C) chamber trials while wearing the Low, Medium or High level of protective clothing.

Heavy Exercise 30°C		TREADMILL WALK								
		1			2			3		
Time (min)		0	15	45	0	15	45	0	15	45
			N = 5			N = 4				
pH	Low	7.34 (0.02)	7.37 (0.01)	7.39 (0.01)	7.39 (0.01)	7.39 (0.01)	7.42 (0.02)			
	Medium	7.35 (0.01)	7.38 (0.01)	7.40 (0.01)						
	High	7.35 (0.01)	7.37 (0.01)							
pCO_2 (mmHg)	Low	45.3 (1.9)	40.8 (0.7)	39.4 (1.3)	36.9 (1.6)	38.2 (1.5)	33.6 (1.1)			
	Medium	47.1 (2.4)	42.2 (1.1)	38.0 (1.0)						
	High	48.0 (2.8)	43.1 (0.3)							

Values are means (SEM)

Figure 8. FFA concentration during light exercise at 18°C and 30°C while wearing TL, TM and TH levels of protective clothing.

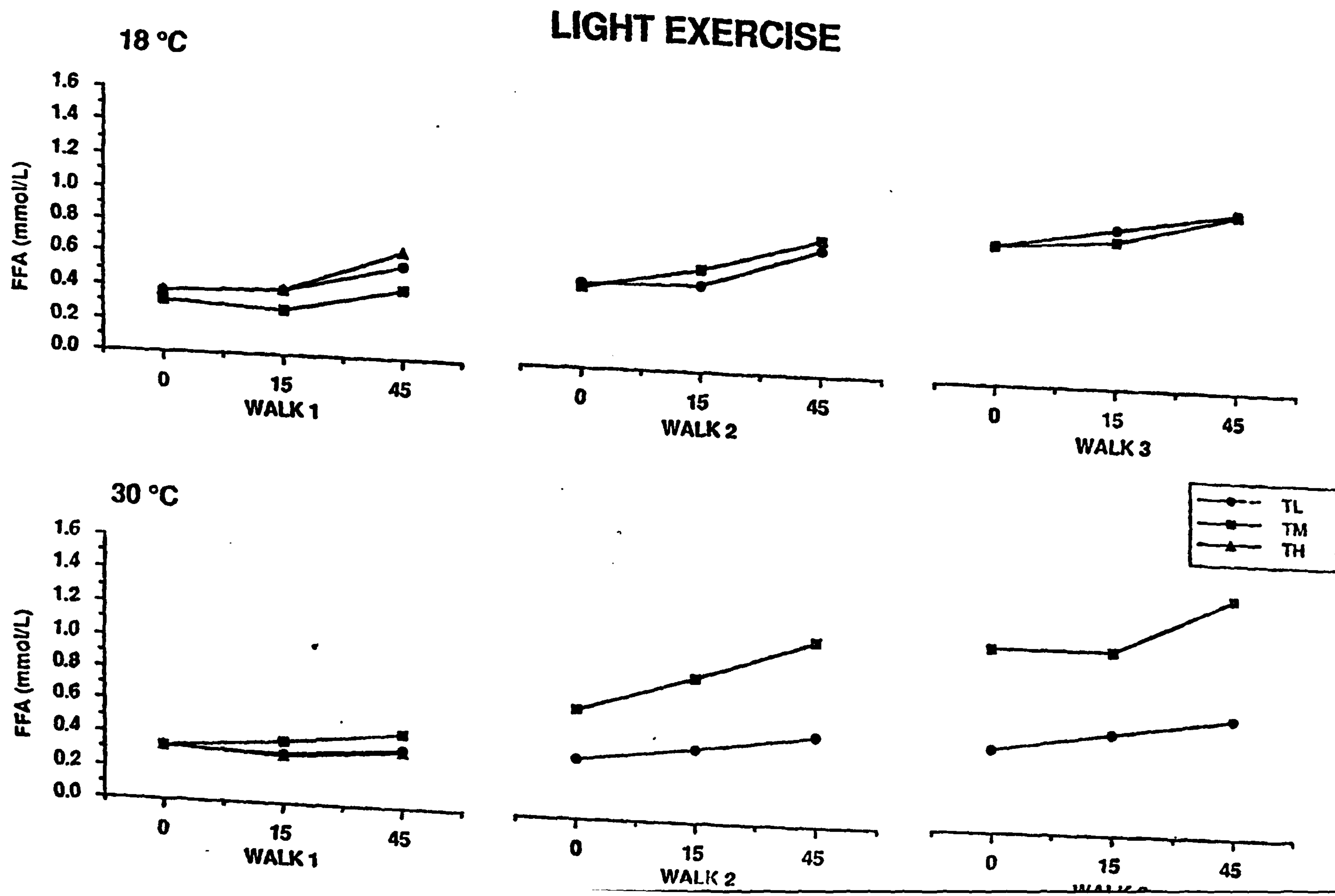
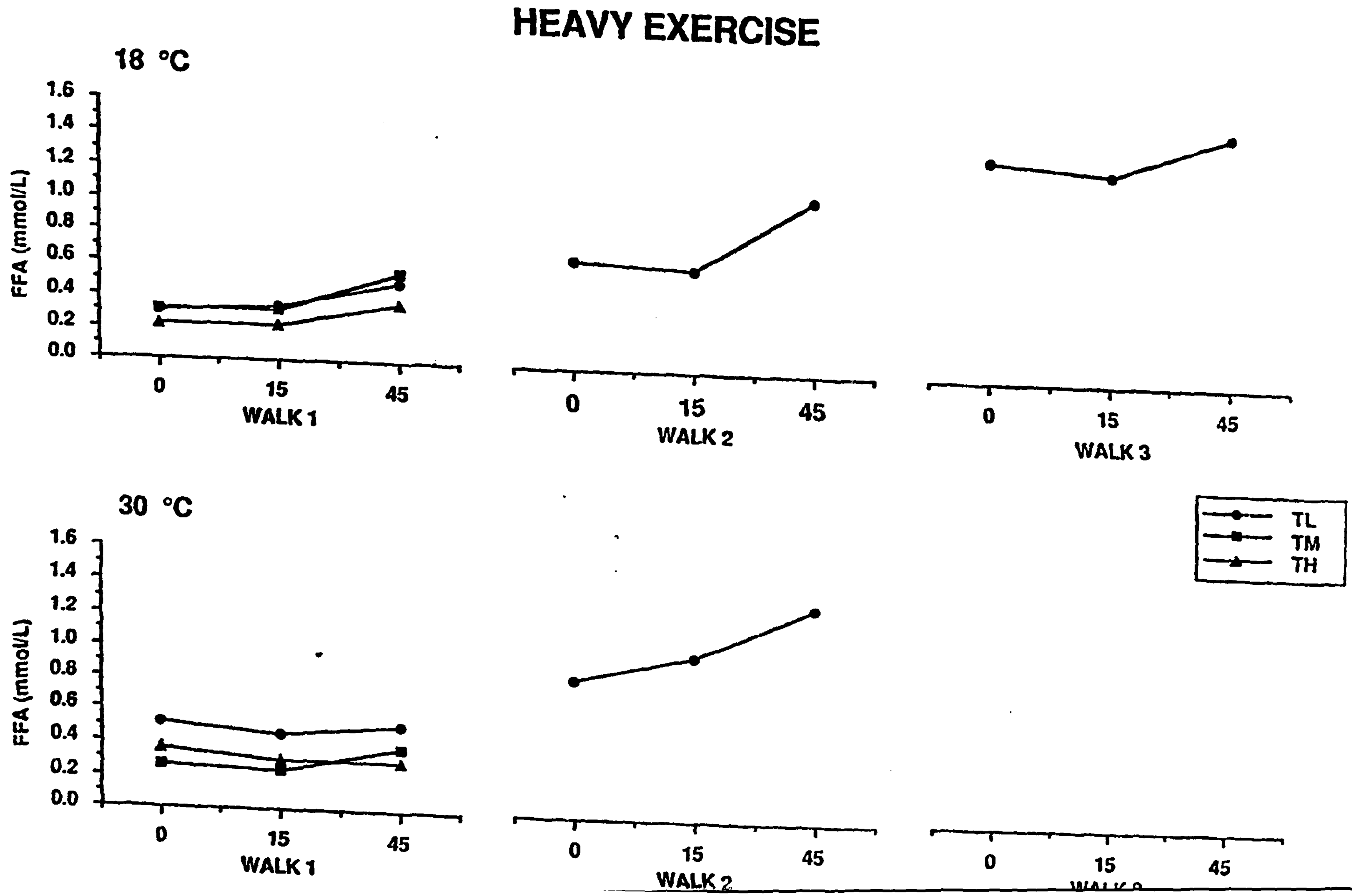


Figure 9. FFA concentration during heavy exercise at 18°C and 30°C while wearing TL, TM and TH levels of protective clothing.



at the warmer temperature. A similar pattern was evident for the heavy exercise groups except that the pattern of change in TH was similar at both temperatures. The effect of the different exercise intensities was significant only for the TL trials; i.e., there was a greater increase in FFA for the higher intensity groups at both temperatures. The TM and TH trials were probably too short in duration for a differential effect of exercise intensity to manifest itself. Therefore, when comparing the different levels of protection in the heavy exercise groups, the change in the TL FFA levels was greater than both TM and TH at both temperatures.

4.1.10 Glycerol.

The changes in glycerol concentration were similar to the FFA results (Figures 10 and 11). For the light exercise there were increases in glycerol concentrations at both temperatures for all three clothing conditions; in the warm trial the change in glycerol was greater in TM than in TH during the light exercise. For the heavy exercise groups there were also progressive increases in glycerol for all clothing groups at both temperatures; the increase was significantly greater at the warmer temperature for only the TL trial; and the change in glycerol was greater for TL than TH at both temperatures. Consistent with the FFA results, the higher intensity group had greater increases in glycerol than did the lighter intensity group while wearing TL at both temperatures, and in TM but only at the cooler temperature.

4.1.11 Glucose.

For the light exercise glucose changed only in the TL trial, decreasing similarly at both temperatures (Figure 12). In contrast, there was a significant increase in glucose for all levels of protection during the heavy exercise, which was similar for both

Figure 10. Glycerol concentration during light exercise at 18°C and 30°C while wearing TL, TM and TH levels of protective clothing.

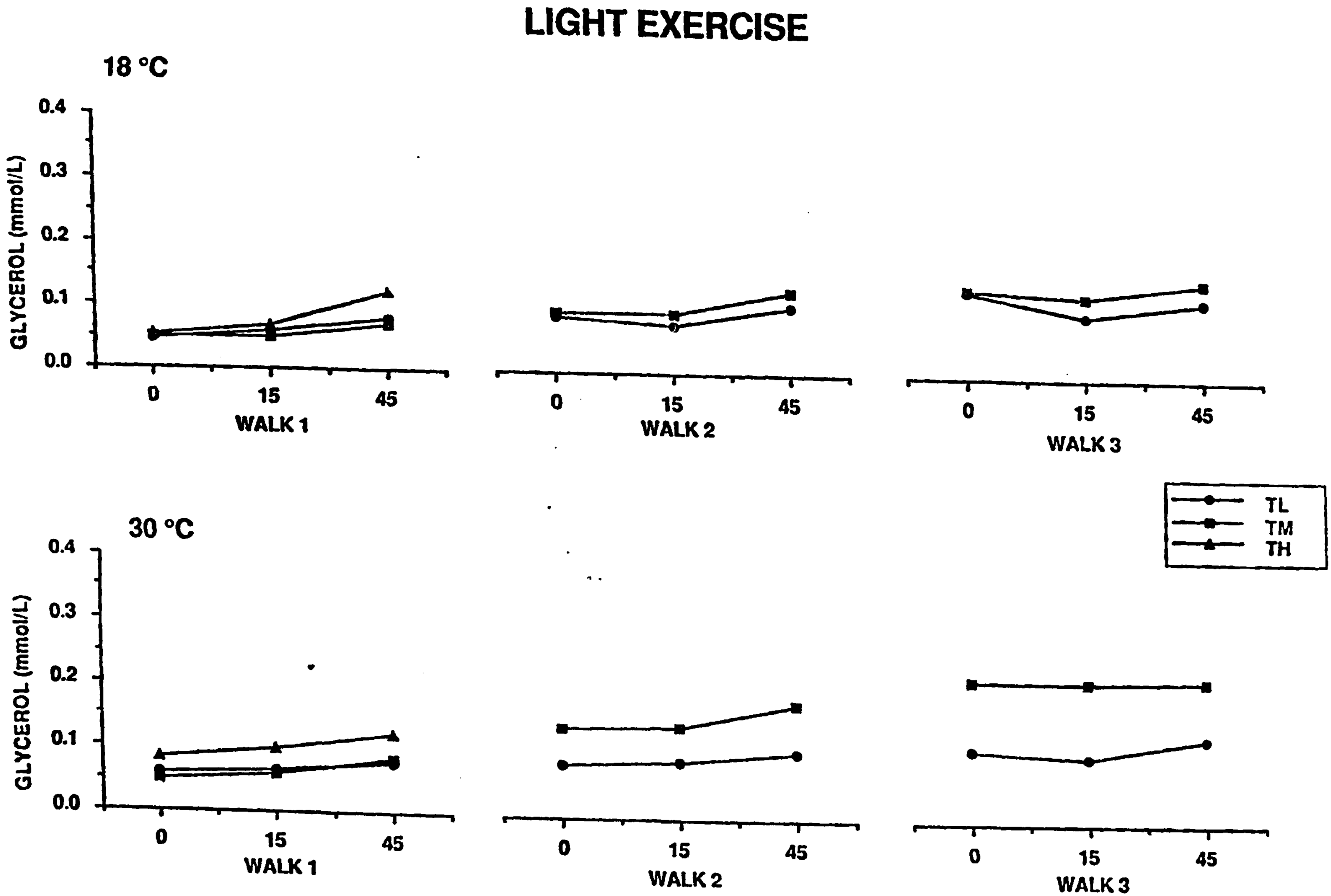


Figure 11. Glycerol concentration during heavy exercise at 18°C and 30°C while wearing TL, TM and TH levels of protective clothing.

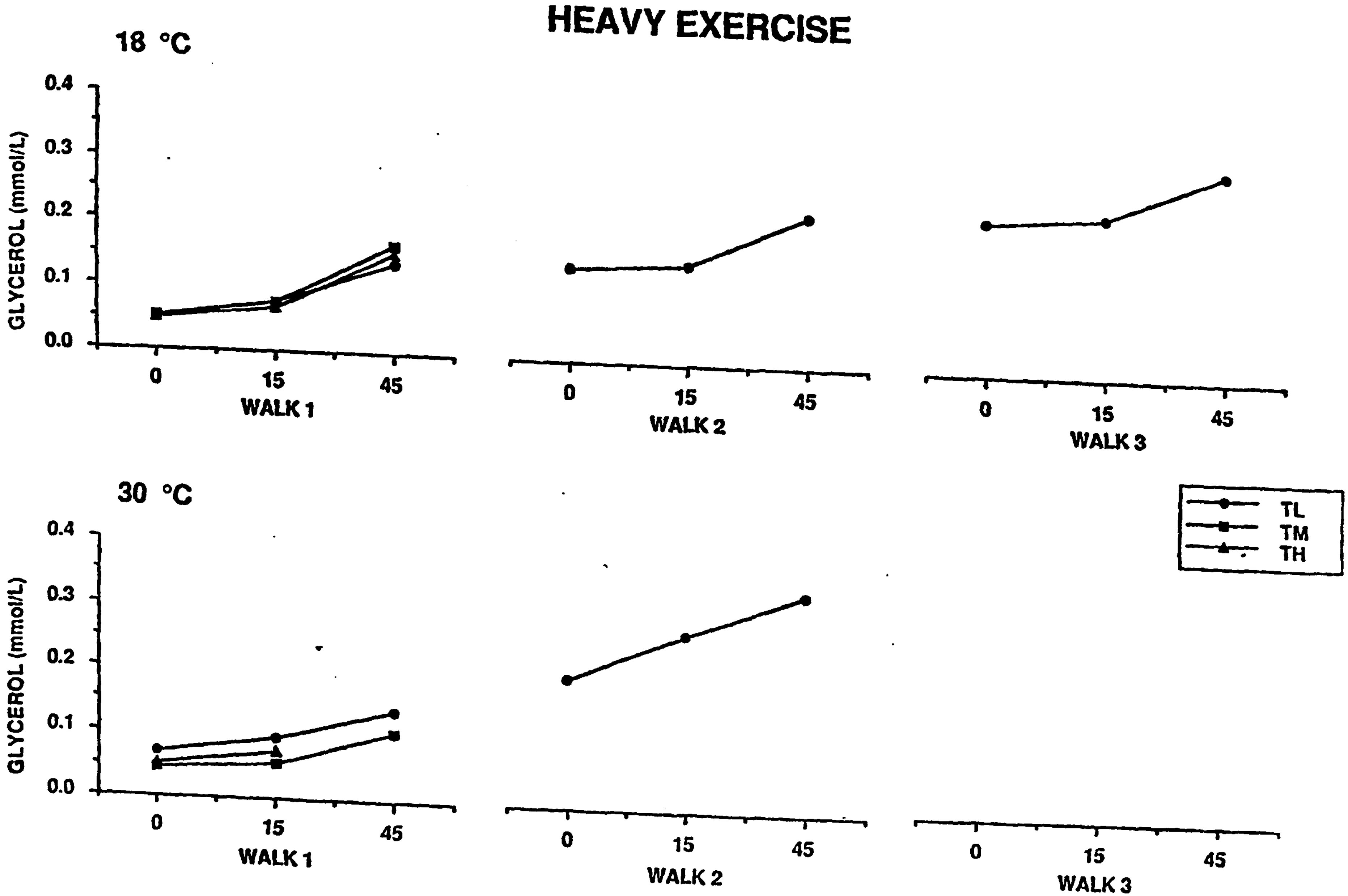


Figure 12. Glucose concentration during light exercise at 18°C and 30°C while wearing TL, TM and TH levels of protective clothing.

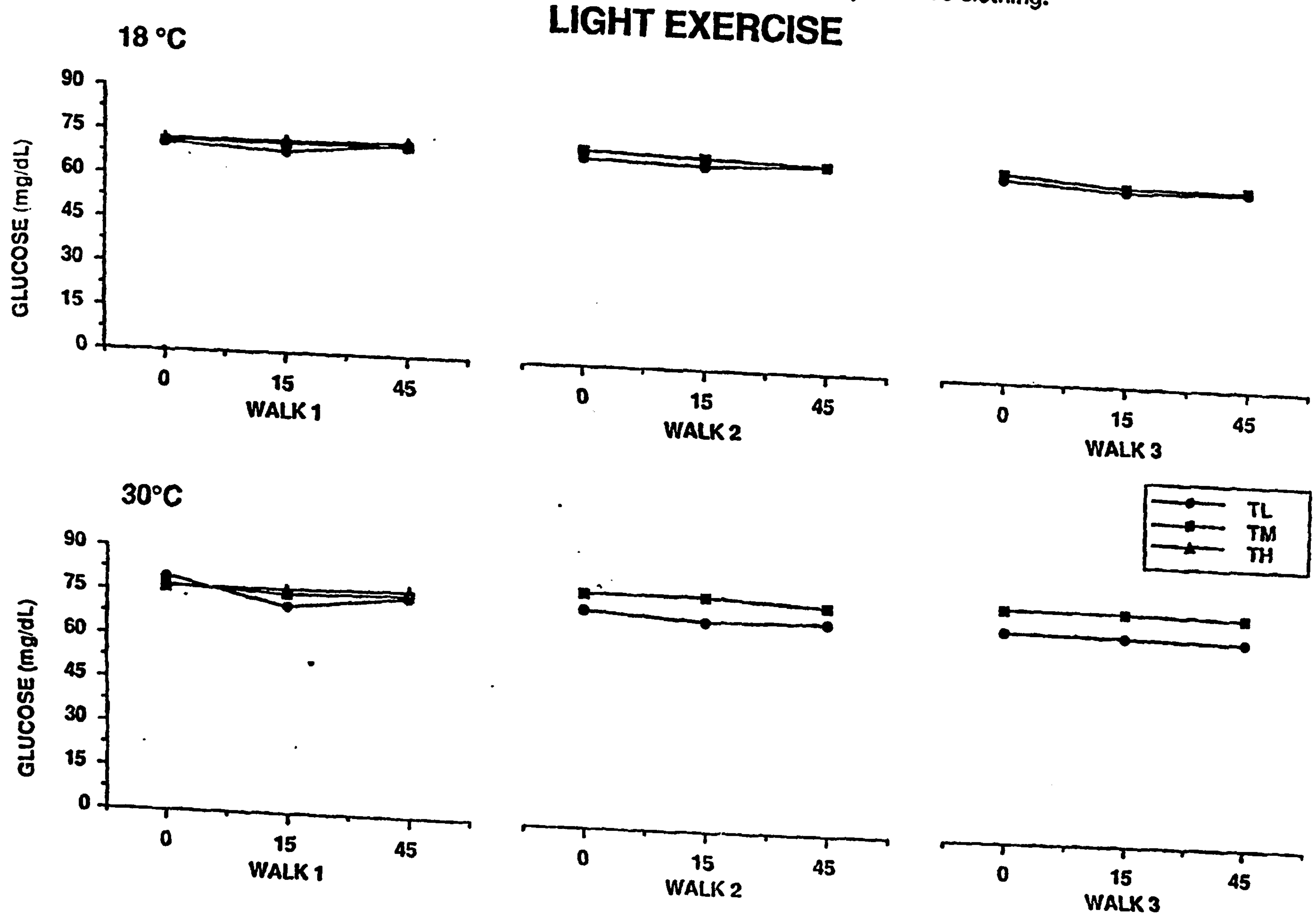
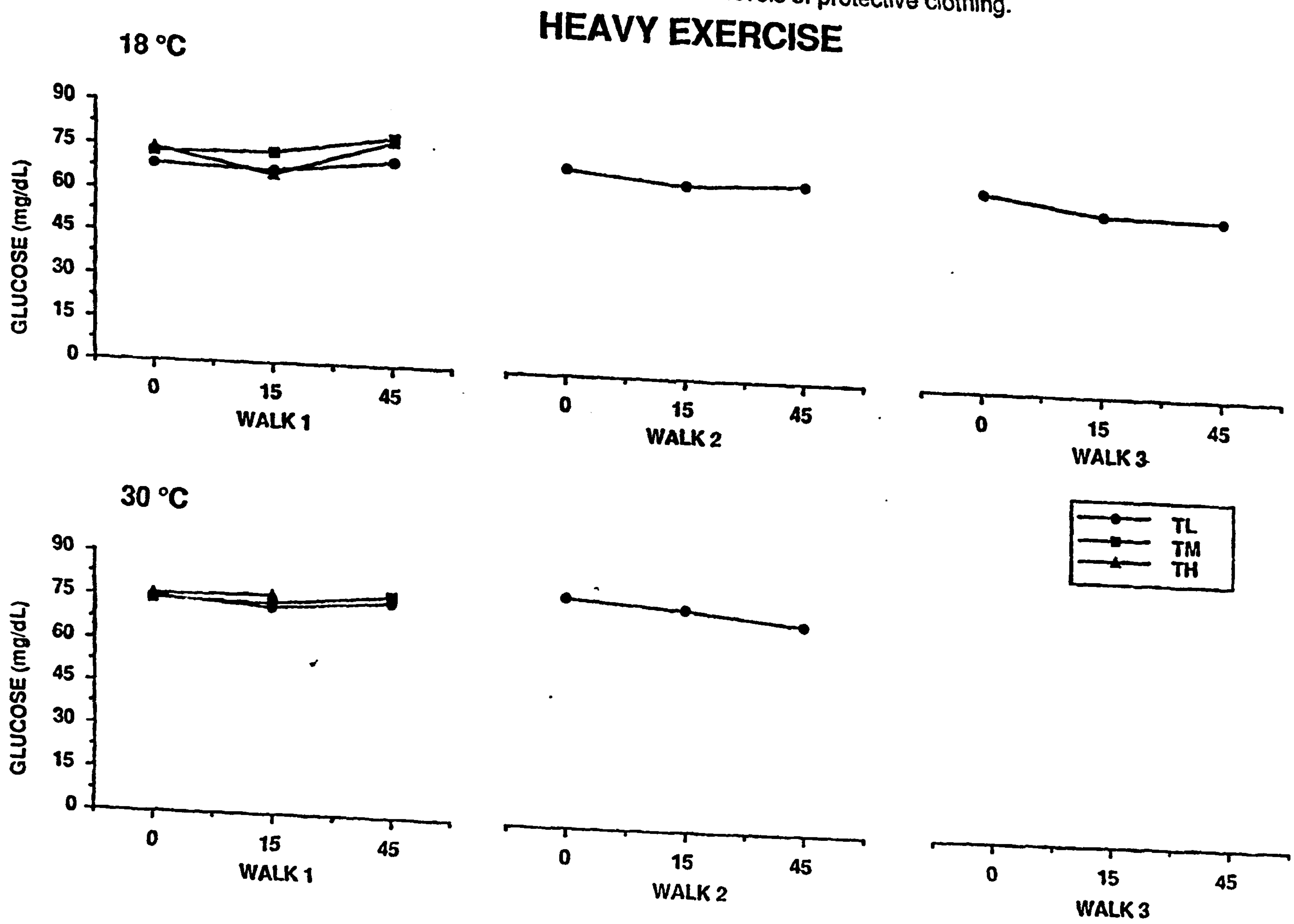


Figure 13. Glucose concentration during heavy exercise at 18°C and 30°C while wearing TL, TM and TH levels of protective clothing.



temperatures (Figure 13). For any given temperature and work intensity, the extent of the change in glucose was similar for all levels of protection.

4.1.12 Lactate.

The changes in blood lactate concentration were small but statistically significant. When evaluating the effect of temperature, for the light exercise groups (Figure 14), lactate decreased in the TL trial at both temperatures; in TM the decrease occurred only in the cooler trial; in TH there was a similar slight decrease at both temperatures. For the heavy exercise groups (Figure 15) there was a slightly, but significantly, greater increase at the warmer temperature. When comparing the exercise intensities, lactate decreased in TL to a greater extent in the lighter exercise group but only at the cooler temperature; otherwise the responses were similar at both intensities for the other levels of protection.

4.1.13 Rate of Fluid Loss and Evaporative Efficiency.

The rate of fluid loss was always significantly increased during the TH trials compared with the other levels of protective clothing (Figure 16). For the TL trials the rate of fluid loss was increased during the heavy exercise and hot environment compared with the cooler environments and/or lighter exercise trials (Figure 16). There was no difference in the rate of fluid loss for the TM level of protective clothing between the cool and hot environments for the light exercise or heavy exercise. A progressive increase in the rate of fluid loss was observed for the TM trials from the light exercise cool condition to the heavy exercise, hot condition (Figure 16). For the TH trials, the hot environment increased the rate of fluid loss with the light exercise whereas chamber temperature did not influence the rate of fluid loss with the heavy

Figure 14. Lactate concentration during light exercise at 18°C and 30°C while wearing TL, TM and TH levels of protective clothing.

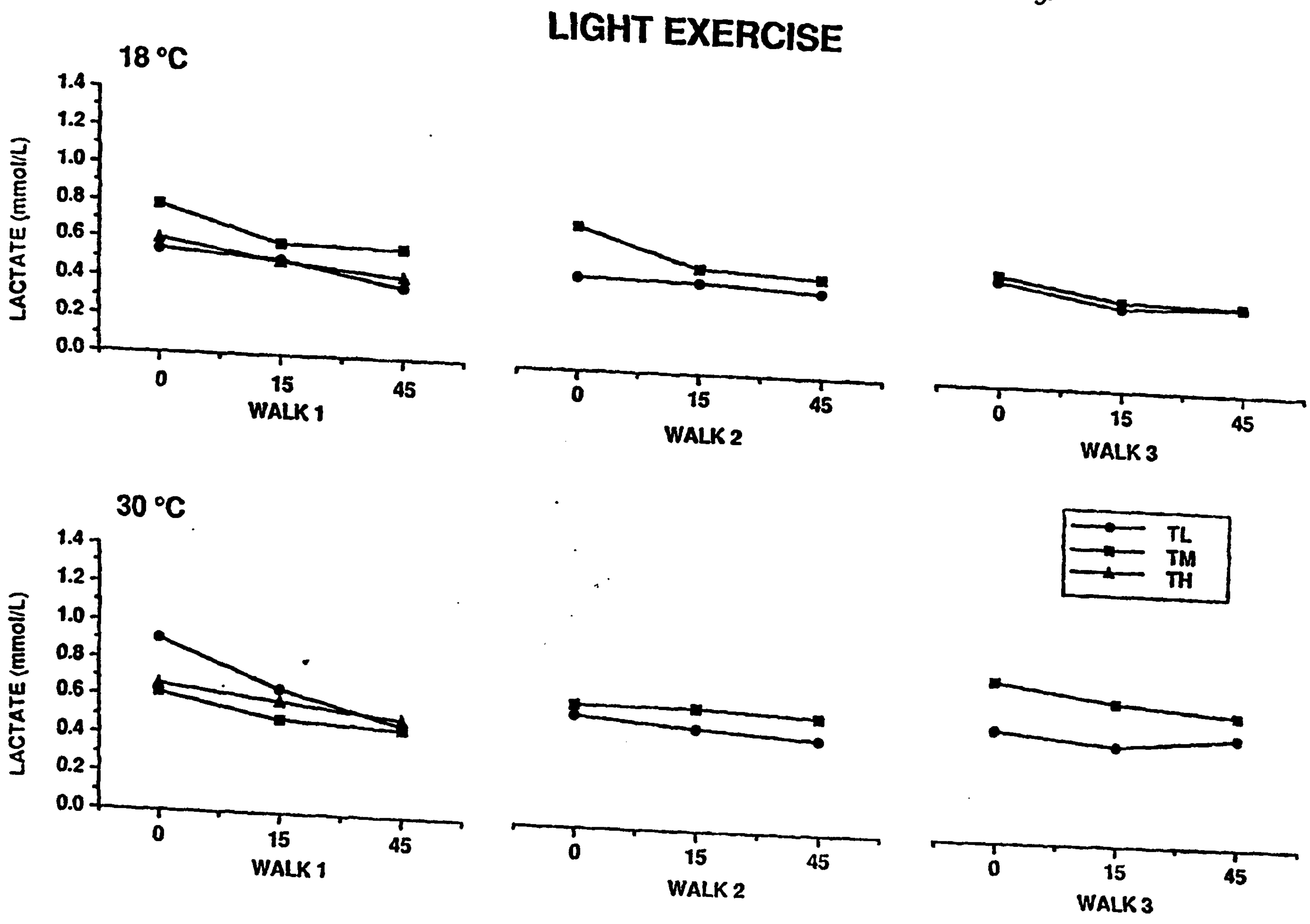


Figure 15. Lactate concentration during heavy exercise at 18°C and 30°C while wearing TL, TM, and TH levels of protective clothing.

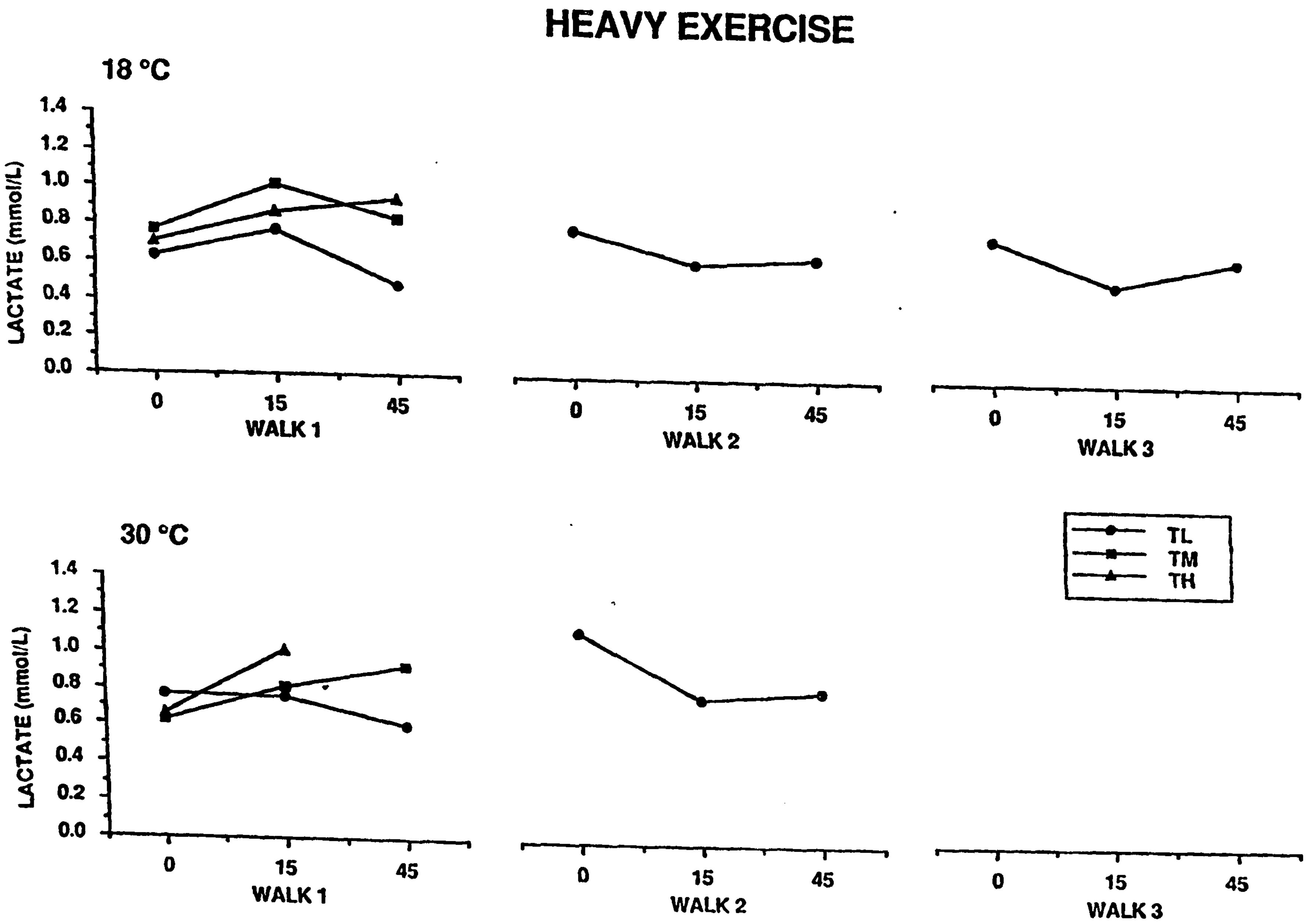


Figure 16. Rate of fluid loss during the light and heavy exercise trials at 18°C or 30°C while wearing TL, TM or TH levels of protective clothing.

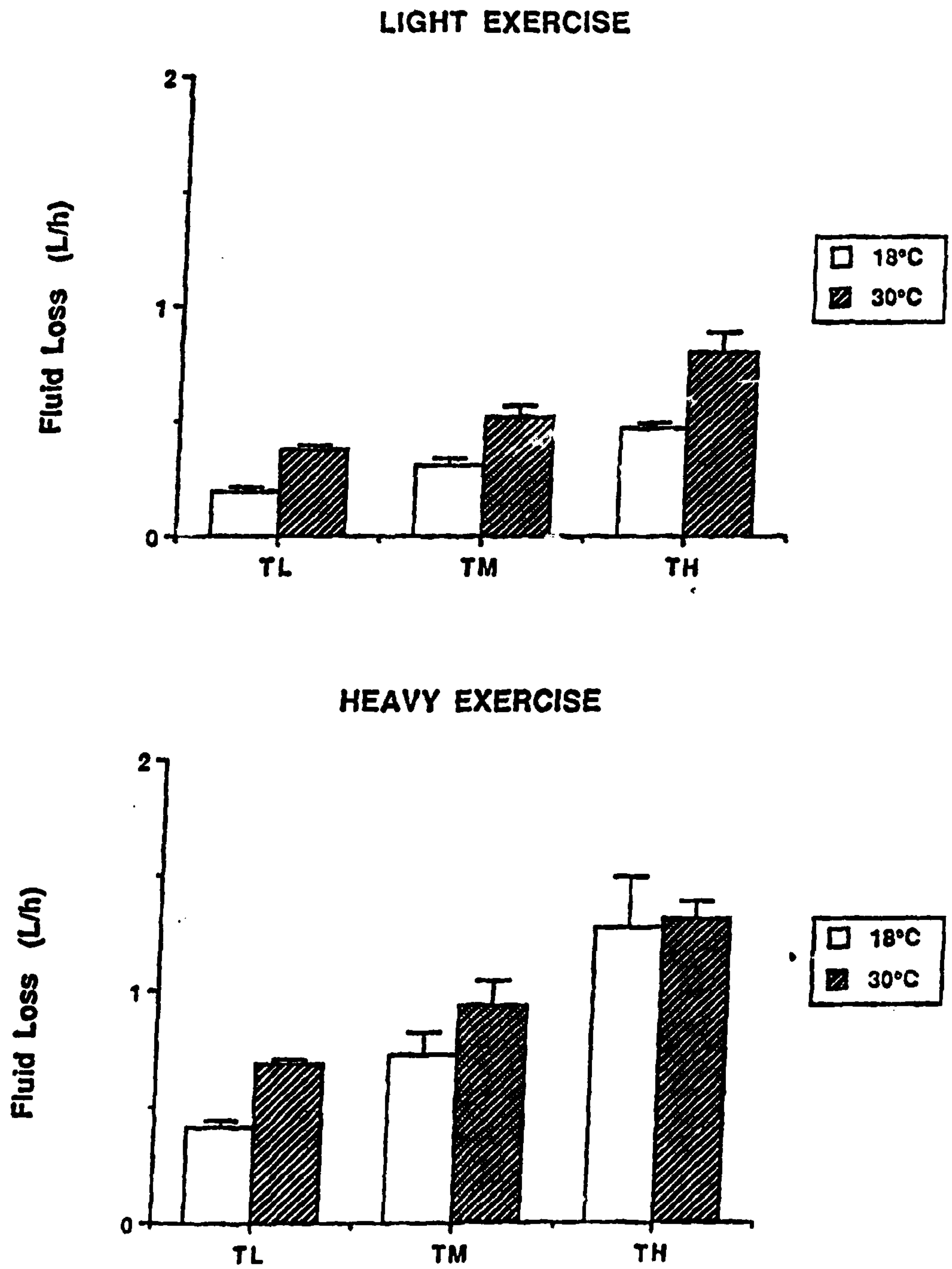
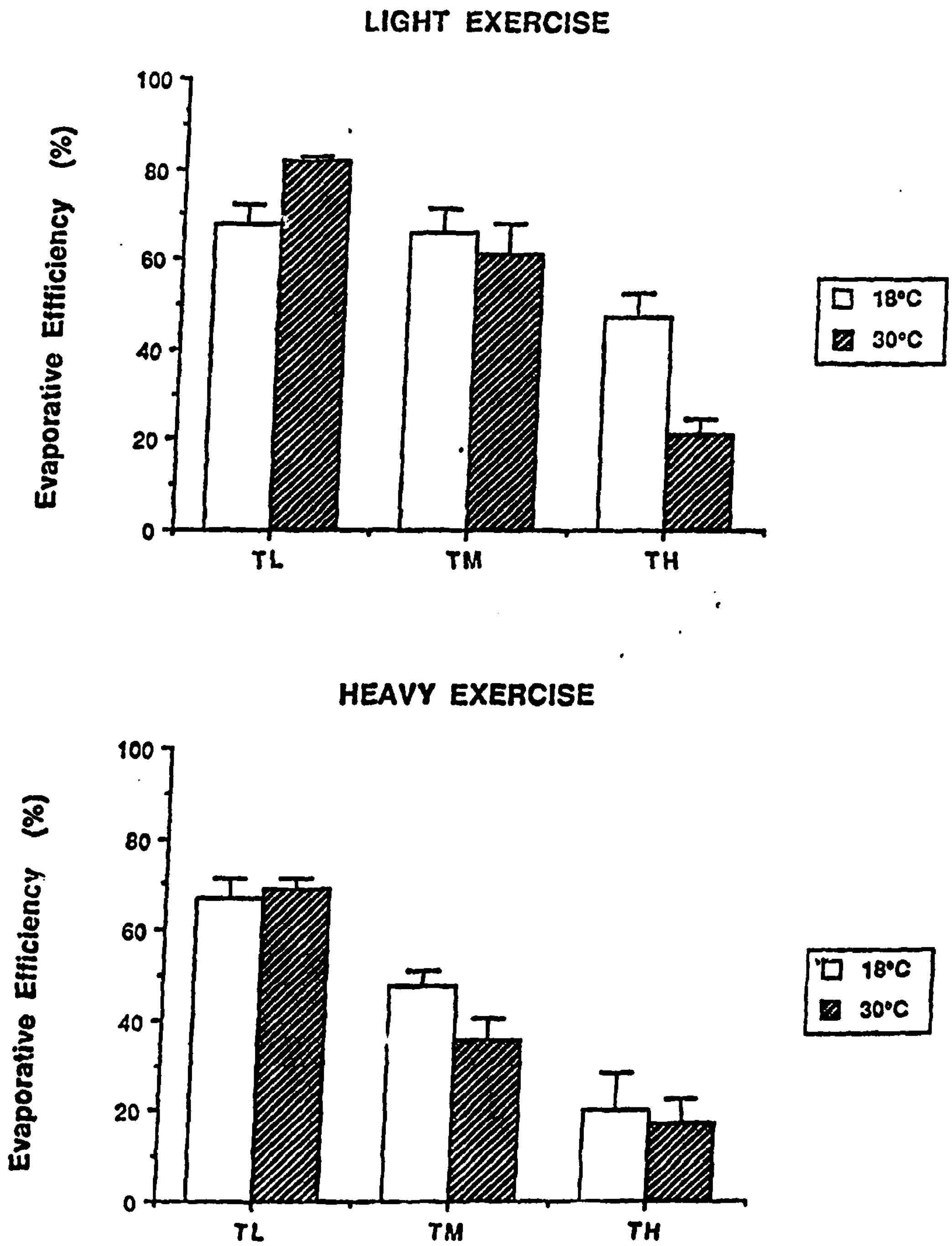


Figure 17. Evaporative efficiency during the light and heavy exercise trials at 18°C or 30°C while wearing TL, TM or TH levels of protective clothing.



exercise. The rate of fluid loss with the TH level of protection was increased during the heavy exercise (approximately 1.5 $L \cdot h^{-1}$) compared with the light exercise trials (Figure 16).

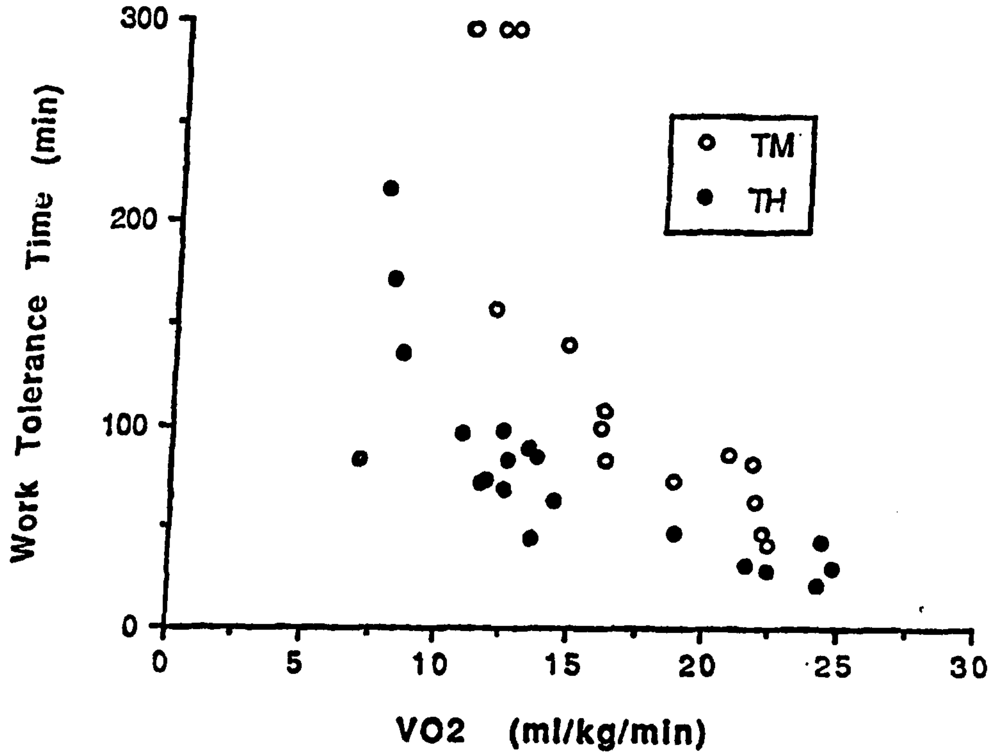
For each exercise condition and environmental temperature the evaporative efficiency was reduced while wearing the TH level of protective clothing (Figure 17). In addition, evaporative efficiency was reduced for the TM level of protection compared with TL for all exercise trials except the light exercise and cool chamber temperature (Figure 17). Evaporative efficiency averaged approximately 70% for the TL level of protection for all exercise trials (Figure 17). A progressive decrease in evaporative efficiency was observed for the TM level of protection from approximately 65% during the light exercise and cool environment to 35% during the heavy exercise and hot environment. Evaporative efficiency was reduced with the TH level of protection from approximately 45% during the light exercise and cool environment to 20% for the hot environment and/or heavy exercise conditions (Figure 17).

4.2 CONTINUOUS VS INTERMITTENT EXERCISE

4.2.1 Work Tolerance Time and Metabolic Rate.

For the intermittent exercise schedules and for the 5 min non-exercise periods during the continuous protocol an average metabolic rate was calculated assuming a resting $\dot{V}O_2$ of 4 $mL \cdot kg^{-1} \cdot min^{-1}$. The $\dot{V}O_2$ measured during the treadmill walk was used to represent the exercise metabolic rate throughout the 5 h. For both the TM and TH levels of clothing protection a decreasing curvilinear function described the relationship between WTT and average $\dot{V}O_2$ (Figure 18). When the inverse of WTT was

Figure 18. The relationship between the average metabolic rate (VO2) and work tolerance time during intermittent exercise at 30°C while wearing either TOPP Medium (TM) or TOPP High (TH) levels of protective clothing.



plotted against the average $\dot{V}O_2$ a strong relationship was observed for both the TM (r = 0.90, Figure 19) and TH (r = 0.90, Figure 20) levels of protection. These relationships depicted in Figures 19 and 20 suggest that at 30°C, WTT while wearing TM and TH can be predicted accurately with knowledge of the metabolic rate required for a specific activity. This relationship also means that WTT increases in direct proportion to the decrease in average metabolic rate for a specfic activity that is caused by inserting rest intervals of varying durations.

4.2.2 Rectal Temperature.

There was a significant effect of the level of protection on the rate of T_{re} change during both intermittent trials; the three levels differed significantly for both the light and heavy exercise groups (Figure 21). When the intermittent and continuous protocols were compared there was no difference between protocols for the TL trials for both the light and heavy exercise. While wearing TM there was a significant reduction in the rate of T_{re} change during the intermittent protocol, but only for the heavy exercise group. While wearing TH there was a significant reduction in the rate of T_{re} change during the intermittent protocol for both the light and heavy exercise group; this reduction was most marked in the high intensity group where there was a difference of almost 1 $°C \cdot h^{-1}$ between the continuous ($2.55°C \cdot h^{-1}$) and the intermittent ($1.50°C \cdot h^{-1}$) protocols.

4.2.3 Mean Skin Temperature.

During the light intensity work the rate of change in $\bar{T}_{SK}$ was greater in TH than both TM and TL (Figure 22). During the heavier intensity work, however, TH and TM rates of $\bar{T}_{SK}$ change were similar but were both greater than in TL. When the

Figure 19. Inverse of work tolerance time plotted against the average metabolic rate for TOPP Medium and 30°C.

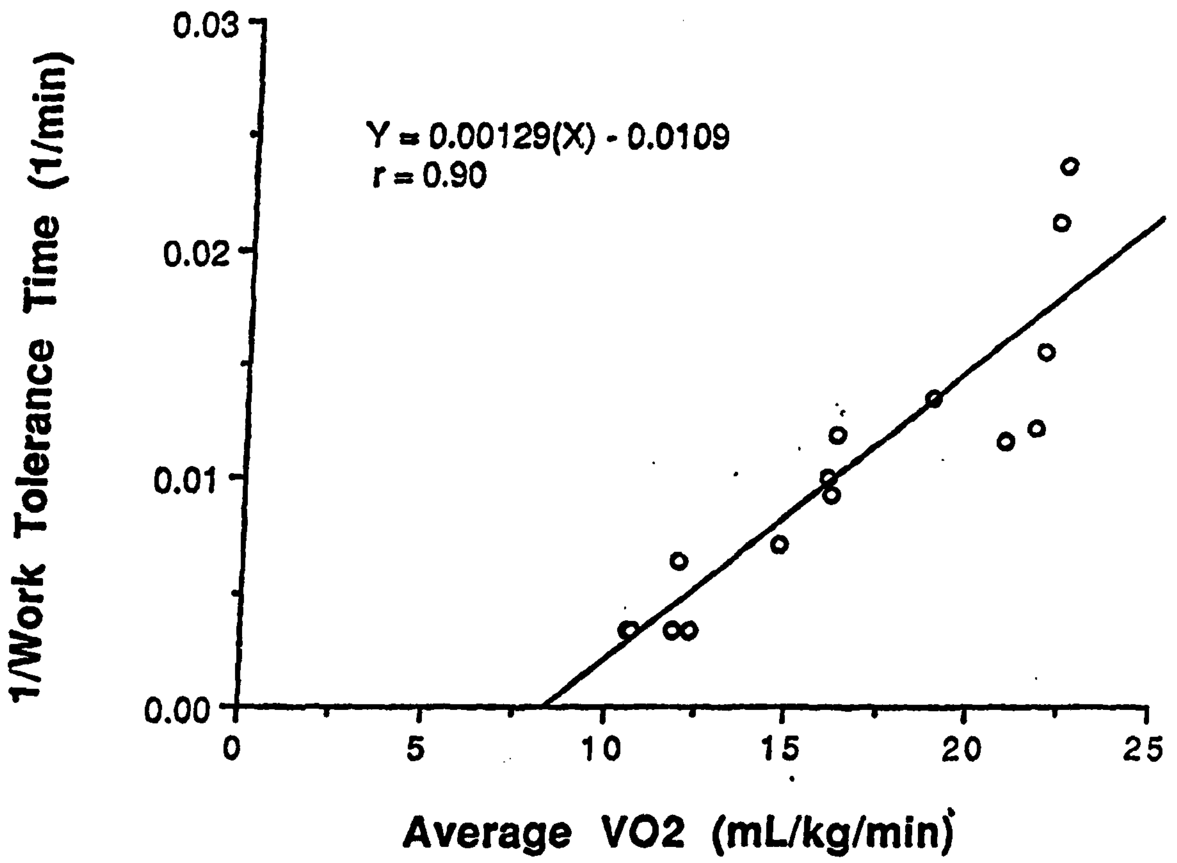


Figure 20. Inverse of work tolerance time plotted against the average metabolic rate for TOPP High and 30°C.

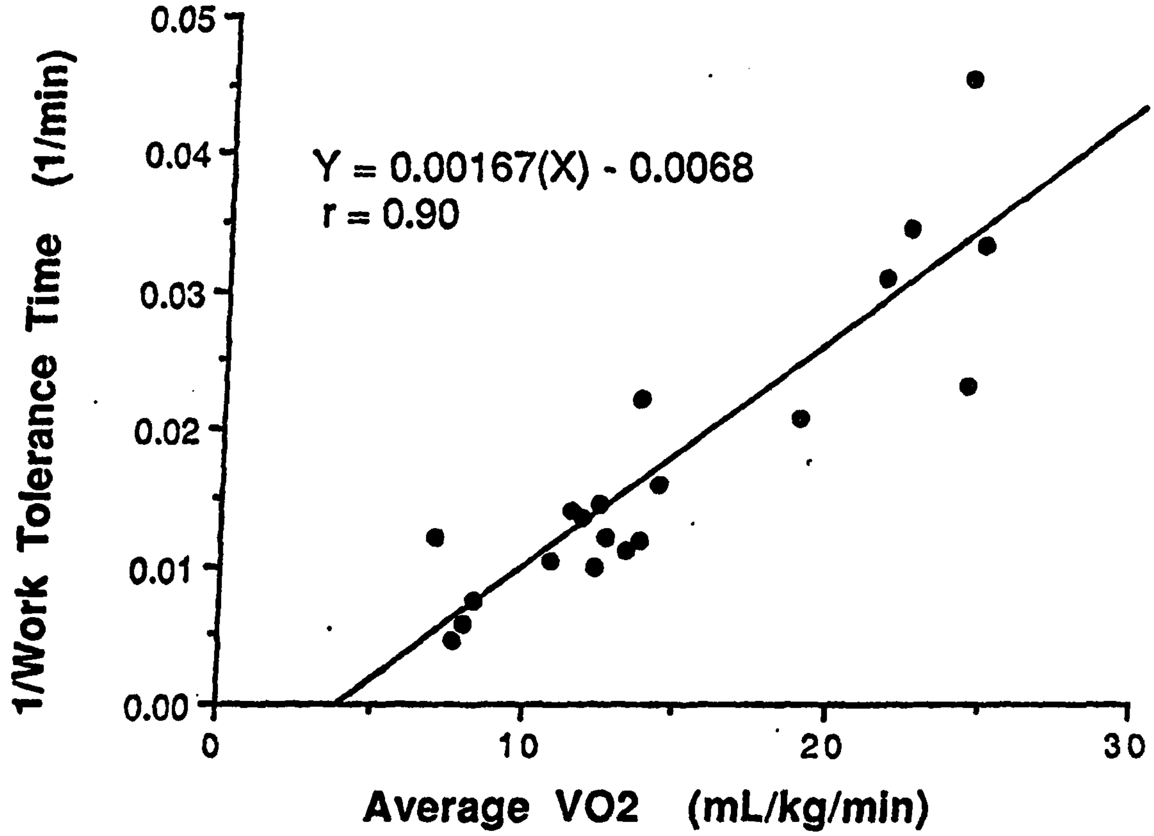


Figure 21. Comparison of the rate of rectal temperature change during light and heavy exercise performed either continuously or intermittently while wearing TL, TM and TH levels of protective clothing at 30°C.

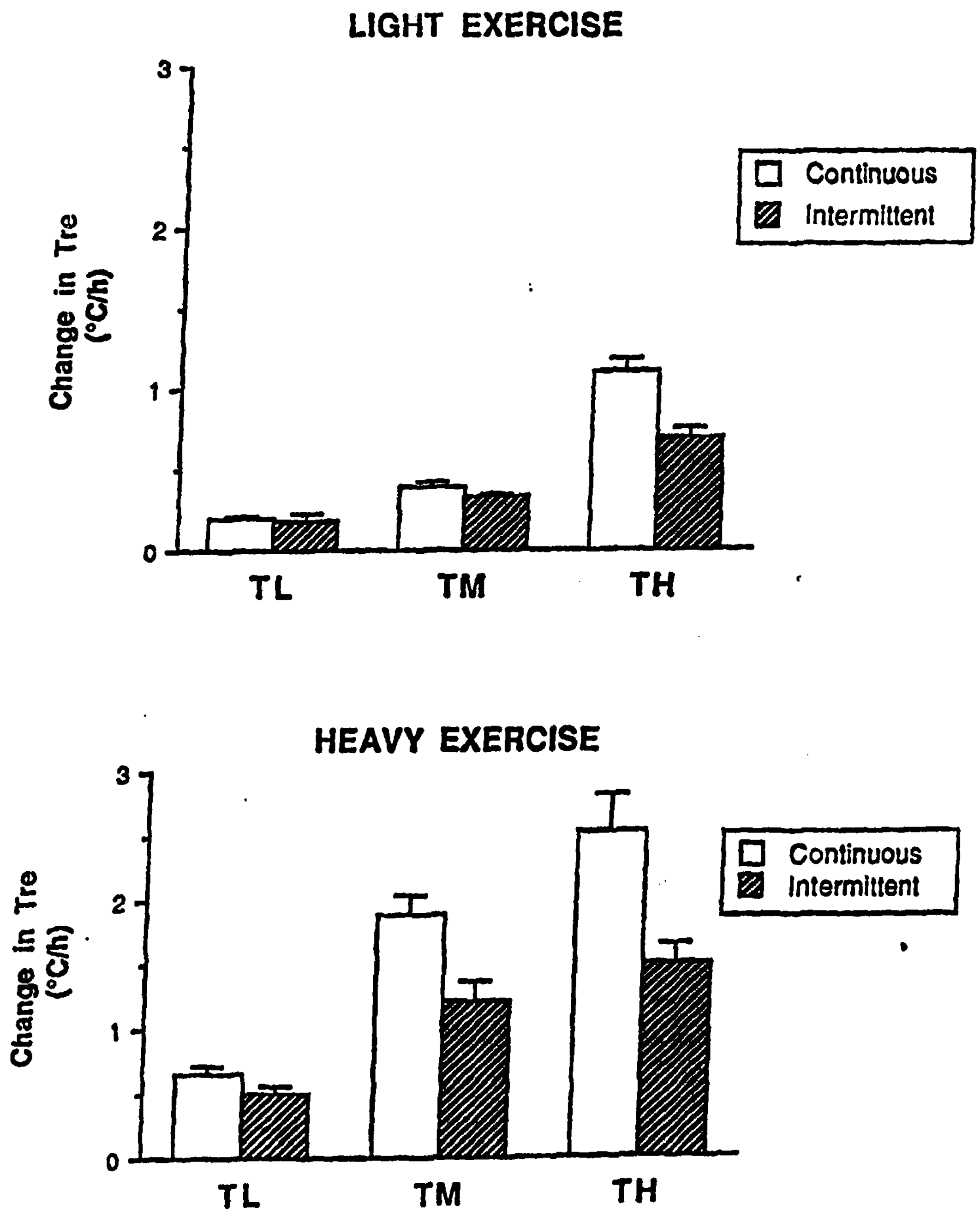
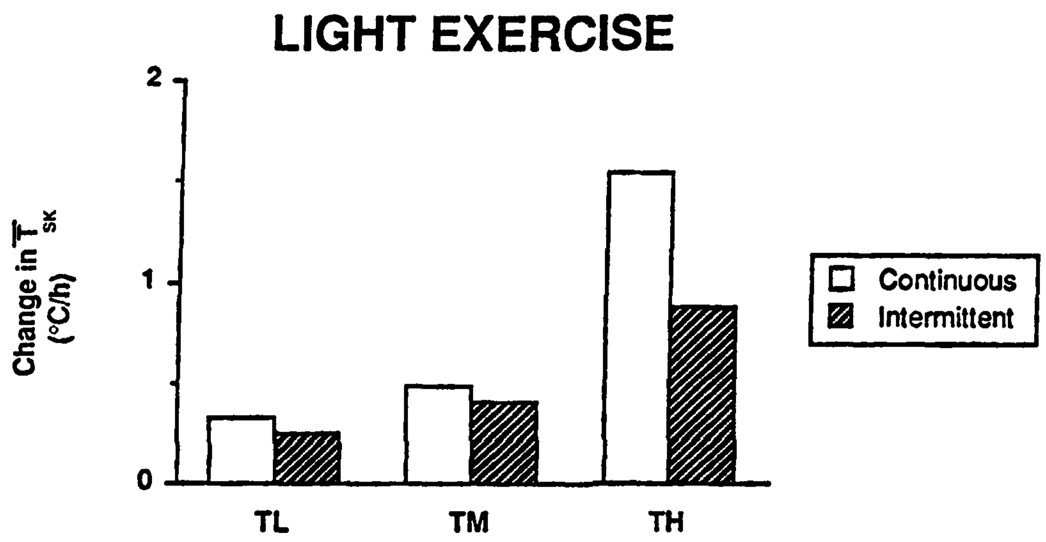
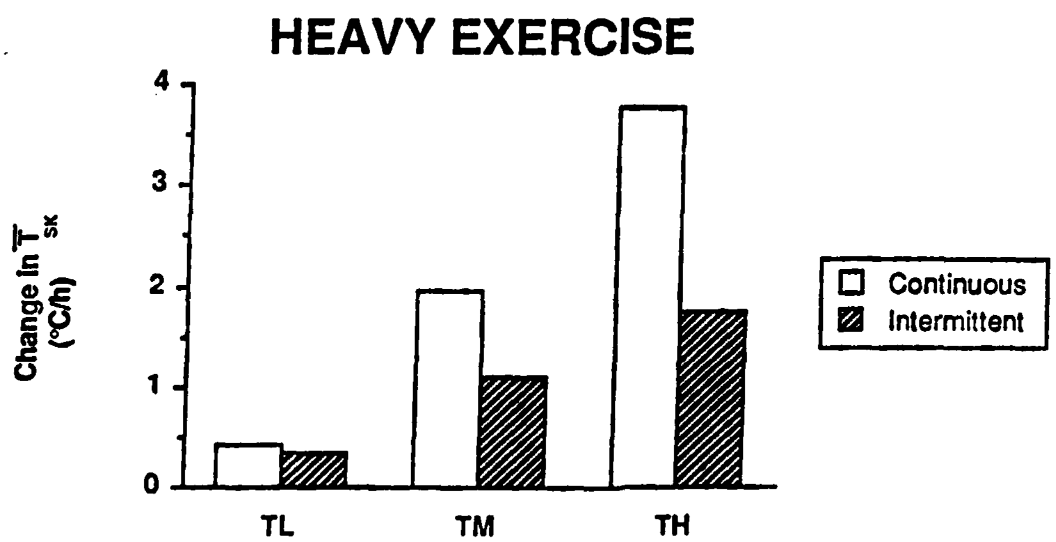


Figure 22. Comparison of rate of mean skin temperature change during exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.





intermittent and continuous work protocols were compared, the rate of change in $\overline{T}_{SK}$ was significantly slower in the intermittent protocol for the light intensity group only while wearing TH; similarly, for the high intensity group the $\overline{T}_{SK}$ rate of change during the intermittent work was less than half that of the continuous work protocol in TH.

4.2.4 Gas Exchange.

For the light exercise trials the intermittent work schedule for the TL and TM levels of protection (25 min work/5 min rest) and the TH condition (20 min work/10min rest) did not influence $\dot{V}O_2$ or $\dot{V}_E$ (Table 14). Similarly, for the heavy exercise trials the intermittent work schedule for the TL (25 min work/5 min rest), TM (20 min work/10 min rest) and TH (15 min work/15 min rest) levels of protection did not influence $\dot{V}O_2$ or $\dot{V}_E$ (Table 15).

4.2.5 Heart Rate.

The intermittent work schedule for the TL and TM levels of protection had no effect on the HR response during the 5 h of light exercise (Figure 23). In contrast, a lower HR was observed for the TH level of protection during the first treadmill walk and lifting task with the intermittent exercise schedule (Figure 23). During the heavy exercise trials the intermittent schedules for the different levels of protective clothing had no influence on the HR response (Figure 24). The intermittent schedule for the TM level of protection (20 min work/10 min rest) was associated with a lower HR response ($p < 0.06$) compared with the continuous exercise protocol.

Table 14. Gas exchange measurements ($\dot{V}O_2$ and $\dot{V}_E$) during the three treadmill walks of the light exercise and hot (30°C) continuous (C) or intermittent (I) chamber trials while wearing the Low, Medium or High level of protective clothing.

Light Exercise 30°C		TREADMILL WALK 1		2		3	
Time (min)		15	45	15	45	15	45
		N = 4		N = 4		N = 4	
$\dot{V}O_2$ ($L \cdot min^{-1}$) (STPD)	Low C	0.96 (0.05)	0.91 (0.04)	0.95 (0.04)	0.93 (0.05)	0.95 (0.07)	1.05 (0.08)
	Low I	0.94 (0.06)	0.96 (0.06)	0.95 (0.04)	0.92 (0.04)	1.01 (0.05)	0.91 (0.10)
	Medium C	0.94 (0.06)	0.90 (0.06)	0.98 (0.06)	0.99 (0.07)		
	Medium I	1.01 (0.07)	0.98 (0.02)	1.00 (0.05)	1.04 (0.06)		
	High C	1.11 (0.02)	1.11 (0.04)				
	High I	1.05 (0.02)	0.99 (0.02)				
$\dot{V}_E$ ($L \cdot min^{-1}$) (STPD)	Low C	21.6 (1.4)	20.7 (1.7)	21.5 (1.3)	20.5 (1.6)	21.8 (2.6)	23.4 (4.0)
	Low I	20.1 (1.4)	22.1 (2.2)	22.2 (2.4)	20.6 (1.8)	24.9 (3.9)	25.0 (4.7)
	Medium C	22.2 (1.4)	20.9 (2.1)	22.3 (2.0)	23.5 (3.0)		
	Medium I	21.4 (1.3)	22.3 (1.1)	22.6 (1.3)	25.6 (2.3)		
	High C	24.1 (0.6)	26.6 (2.0)				
	High I	22.7 (0.8)	22.5 (0.8)				

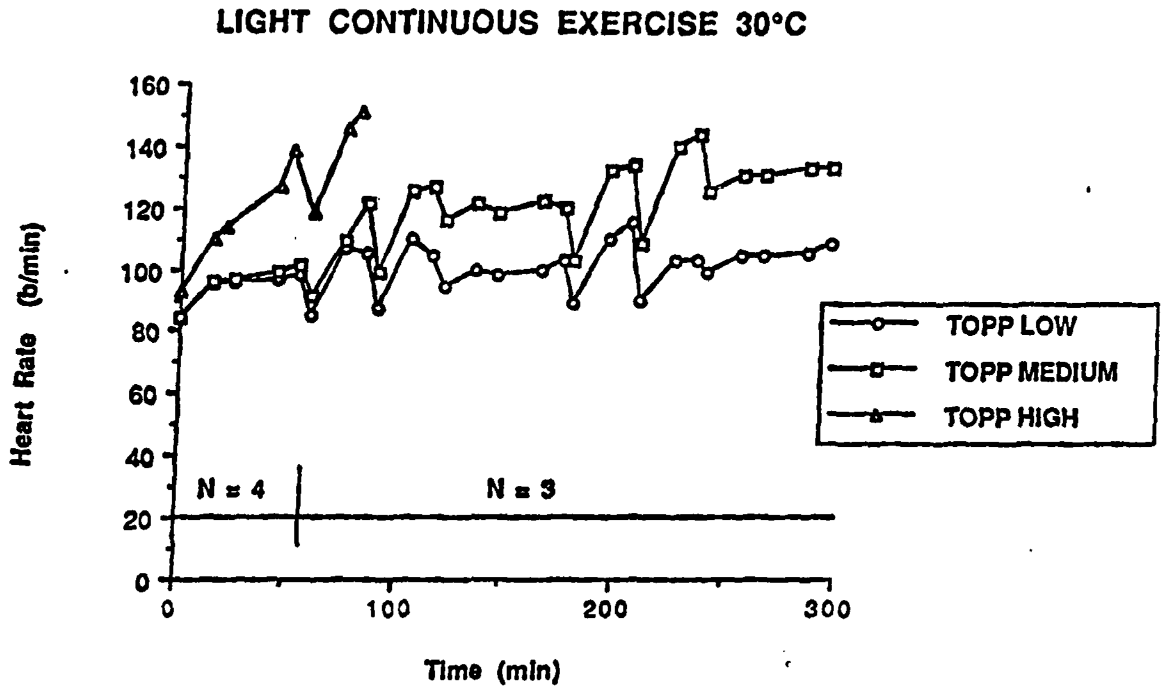
Values are means (SEM)

Table 15. Gas exchange measurements ($\dot{V}O_2$ and $\dot{V}_E$) during the three treadmill walks of the heavy exercise and hot (30°C) continuous (C) or intermittent (I) chamber trials while wearing the Low, Medium or High level of protective clothing.

Heavy Exercise 30°C		TREADMILL WALK 1		2		3	
Time (min)		15	45	15	45	15	45
		N = 4		N = 4			
$\dot{V}O_2$ ($L \cdot min^{-1}$) (STPD)	Low C	1.68 (0.04)	1.69 (0.04)	1.81 (0.03)	1.90 (0.03)		
	Low I	1.65 (0.07)	1.68 (0.05)	1.78 (0.04)	1.78 (0.03)		
	Medium C	1.74 (0.05)	1.76 (0.06)				
	Medium I	1.81 (0.06)	1.79 (0.06)				
	High C	1.91 (0.08)					
	High I	1.88 (0.05)					
$\dot{V}_E$ ($L \cdot min^{-1}$) (STPD)	Low C	35.8 (2.3)	37.9 (2.6)	38.8 (2.5)	49.5 (5.9)		
	Low I	34.9 (0.8)	36.6 (2.0)	38.4 (2.6)	38.8 (1.6)		
	Medium C	37.0 (2.2)	39.7 (2.4)				
	Medium I	38.2 (2.4)	39.0 (2.6)				
	High C	40.0 (0.9)					
	High I	39.1 (1.5)					

Values are means (SEM)

Figure 23. Heart rate responses during the light continuous and intermittent exercise trials at 30°C.



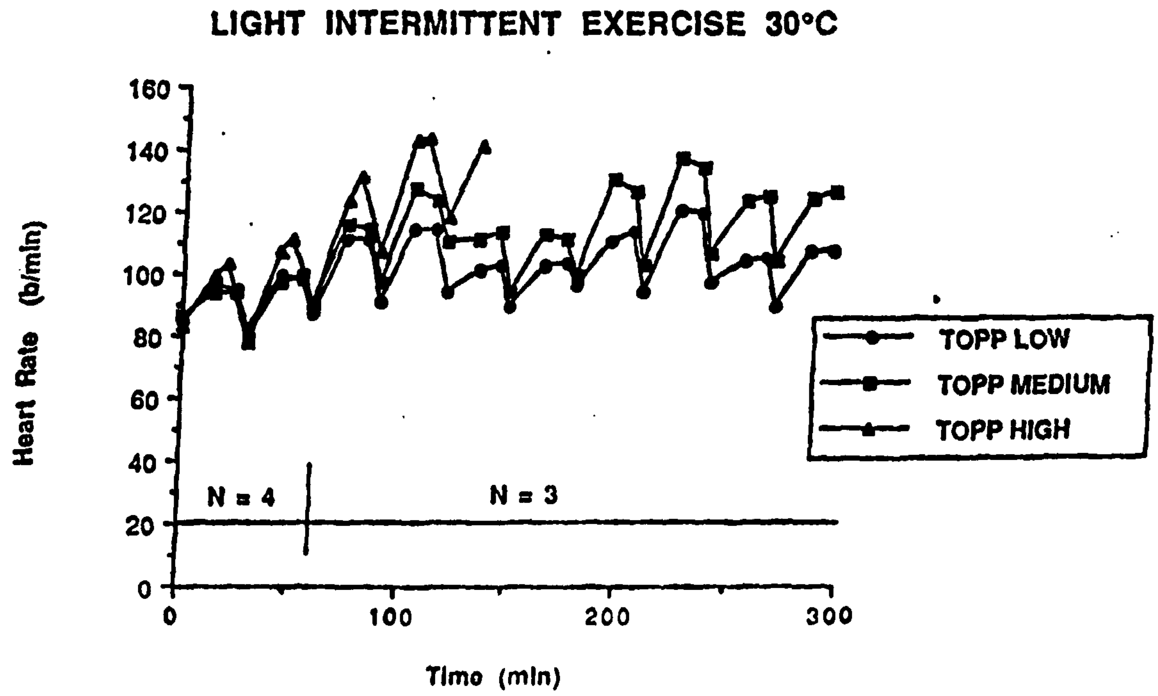
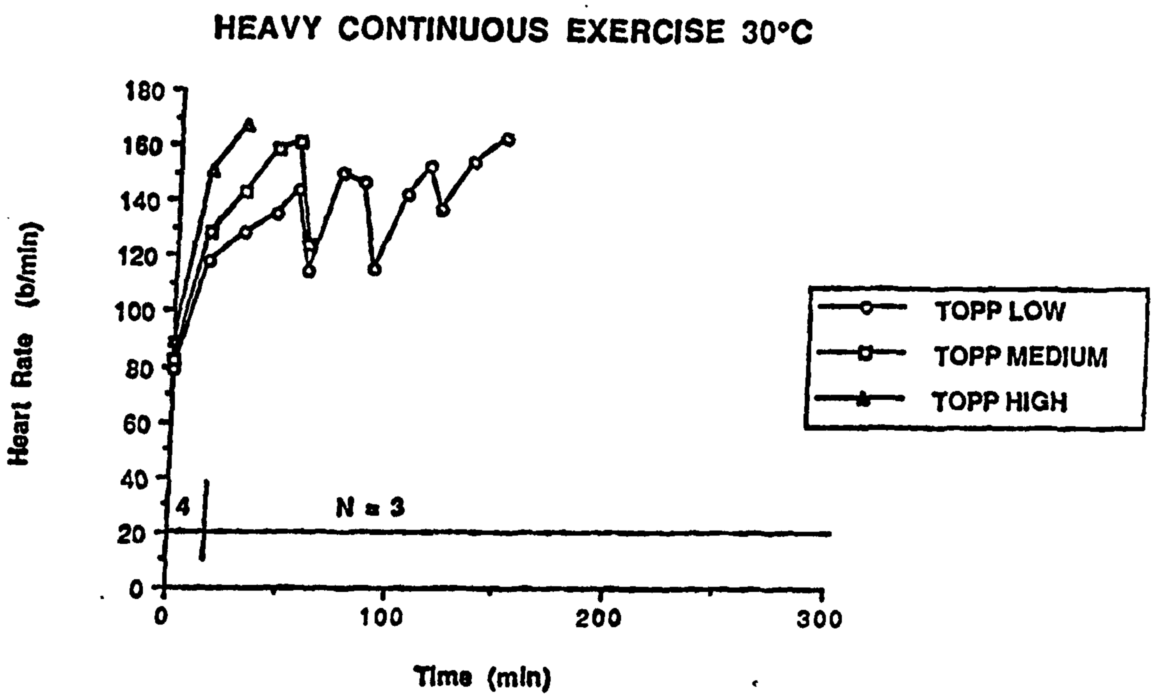
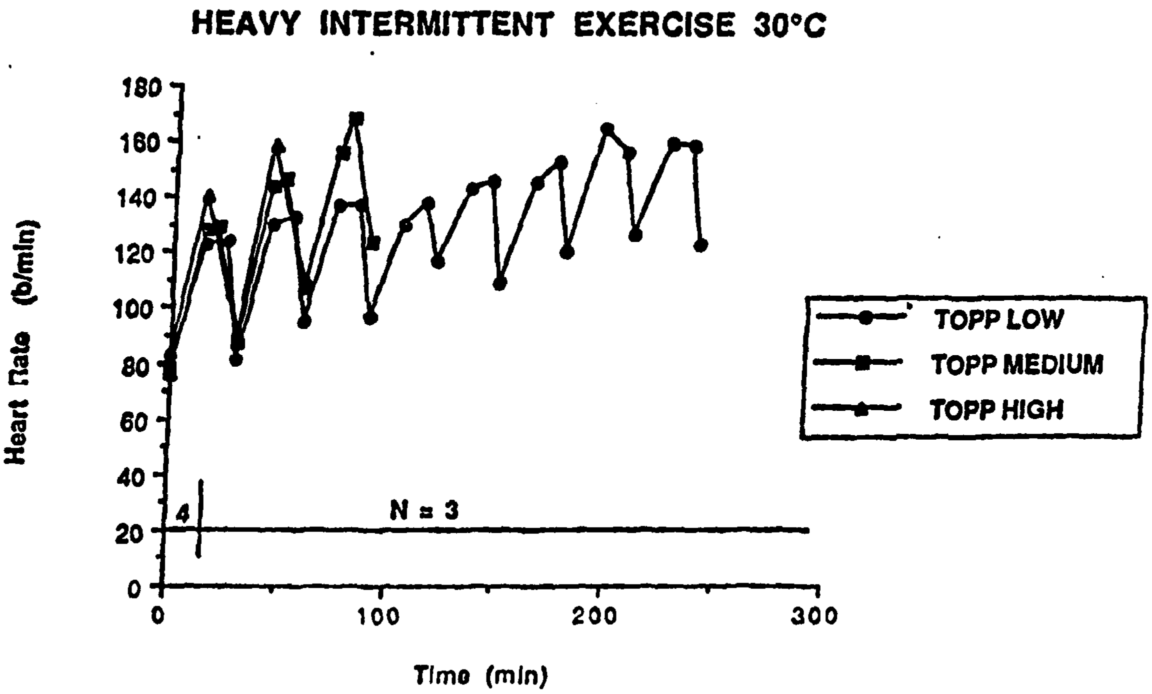


Figure 24. Heart rate responses during the heavy continuous and intermittent exercise trials at 30°C.





4.2.6 Acid-Base Balance.

The intermittent work schedule had no influence on the acid-base measurements for any level of protection, neither for the light nor heavy intensity groups (Tables 16 and 17).

4.2.7 FFA.

The intermittent work/rest protocol was only of significance for the low intensity exercise group while in TM; the increase in FFA was lower during the intermittent than the continuous trial. The level of protection did not affect the degree of change in either the low or high intensity groups (Figures 25 and 26).

4.2.8 Glycerol.

Similar to the FFA results, the increase in glycerol was lower during the intermittent than the continuous trial in the light intensity group; a similar effect occurred in the higher intensity group but only for the TL trial. The level of protection did not affect the change in glycerol (Figures 27 and 28).

4.2.9 Glucose.

Glucose changed similarly in the intermittent and continuous trials at both intensities (Figures 29 and 30). The extent of the change was similar when comparing levels of protection.

4.2.10 Lactate.

The intermittent and continuous protocols caused similar changes in lactate at both intensities of work for all three levels of protection (Figures 31 and 32).

Table 16. Acid-base measurements (pH and pCO_2) during the three treadmill walks of the light exercise and hot (30°C) continuous (C) or intermittent (I) chamber trials while wearing the Low, Medium or High level of protective clothing.

Light Exercise 30°C		TREADMILL WALK 1			2			3		
Time (min)		0	15	45	0	15	45	0	15	45
			N = 4			N = 4			N = 4	
pH	Low C	7.39 (0.02)	7.40 (0.01)	7.41 (0.01)	7.41 (0.02)	7.41 (0.01)	7.42 (0.01)	7.41 (0.02)	7.42 (0.01)	7.43 (0.01)
	Low I	7.38 (0.01)	7.40 (0.01)	7.41 (0.01)	7.41 (0.01)	7.41 (0.01)	7.42 (0.01)	7.42 (0.01)	7.43 (0.01)	7.43 (0.02)
	Medium C	7.37 (0.01)	7.38 (0.01)	7.40 (0.01)	7.42 (0.01)	7.41 (0.01)	7.41 (0.01)			
	Medium I	7.37 (0.01)	7.40 (0.01)	7.40 (0.01)	7.41 (0.01)	7.40 (0.01)	7.41 (0.01)			
	High C	7.37 (0.02)	7.39 (0.01)	7.42 (0.01)						
	High I	7.35 (0.02)	7.39 (0.01)	7.41 (0.01)						
pCO_2 (mmHg)	Low C	42.1 (3.2)	40.9 (1.1)	39.4 (1.5)	39.0 (3.1)	36.8 (1.9)	37.3 (2.5)	39.1 (3.7)	37.0 (3.0)	35.8 (4.1)
	Low I	42.5 (2.6)	39.4 (1.9)	39.2 (1.5)	39.4 (2.1)	39.9 (2.0)	37.3 (1.7)	38.2 (2.0)	36.0 (1.8)	37.3 (2.6)
	Medium C	46.8 (1.3)	44.6 (2.0)	41.2 (1.8)	38.0 (2.2)	38.3 (2.3)	37.5 (2.4)			
	Medium I	42.8 (1.2)	40.5 (1.6)	39.2 (1.2)	37.2 (0.8)	37.8 (1.6)	37.6 (1.9)			
	High C	45.7 (2.7)	39.8 (0.4)	38.1 (0.5)						
	High I	50.0 (4.1)	42.9 (1.9)	39.1 (0.4)						

Values are means (SEM)

Table 17. Acid base measurements (pH and pCO_2) during the three treadmill walks of the heavy exercise and hot (30°C) continuous (C) or intermittent (I) chamber trials while wearing the Low, Medium or High level of protective clothing.

Heavy Exercise		TREADMILL WALK								
30°C		1			2			3		
Time (min)		0	15	45	0	15	45	0	15	45
			N = 3			N = 3				
pH	Low C	7.32	7.36	7.38	7.39	7.38	7.41			
		(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)			
	Low I	7.37	7.38	7.40	7.39	7.39	7.40			
		(0.03)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)			
	Medium C	7.33	7.38	7.40						
		(0.02)	(0.01)	(0.01)						
	Medium I	7.33	7.37	7.39						
		(0.03)	(0.01)	(0.01)						
	High C	7.34	7.37							
		(0.02)	(0.01)							
	High I	7.32	7.36	7.37						
		(0.02)	(0.01)	(0.01)						
pCO_2	Low C	48.1	40.8	38.8	35.8	36.9	33.0			
(mmHg)		(1.2)	(1.2)	(1.9)	(1.7)	(0.9)	(1.3)			
	Low I	44.4	40.5	39.8	38.8	40.2	38.8			
		(3.9)	(1.7)	(1.3)	(1.4)	(0.8)	(0.9)			
	Medium C	50.7	43.0	38.5						
		(1.4)	(1.7)	(1.6)						
	Medium I	55.4	46.5	44.4						
		(4.5)	(2.5)	(0.5)						
	High C	51.0	42.9							
		(3.7)	(0.5)							
	High I	49.8	44.1	42.8						
		(3.9)	(2.1)	(1.6)						

Values are means (SEM)

Figure 25. Comparison of FFA concentrations during light exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.

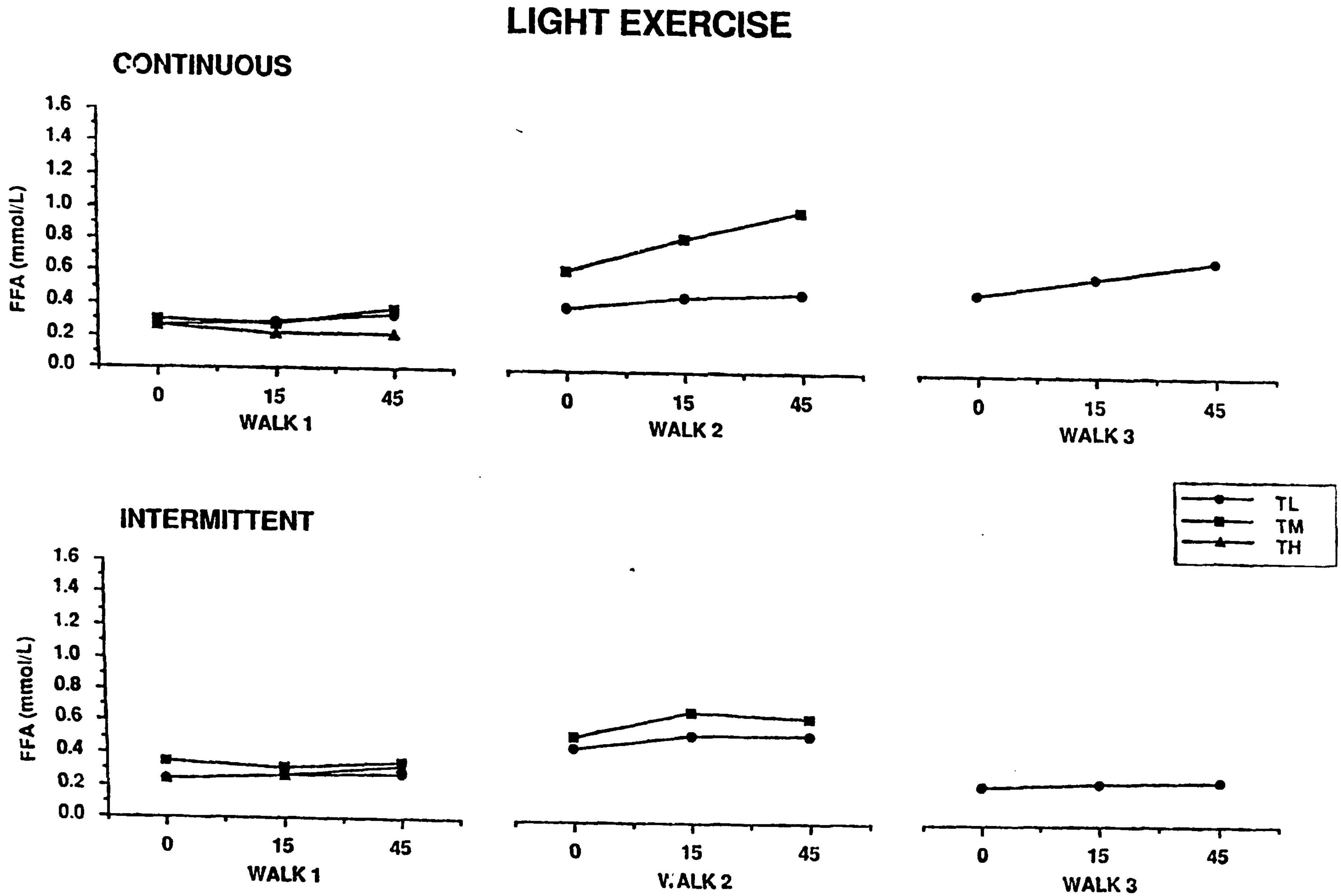


Figure 26. Comparison of FFA concentrations during heavy exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.

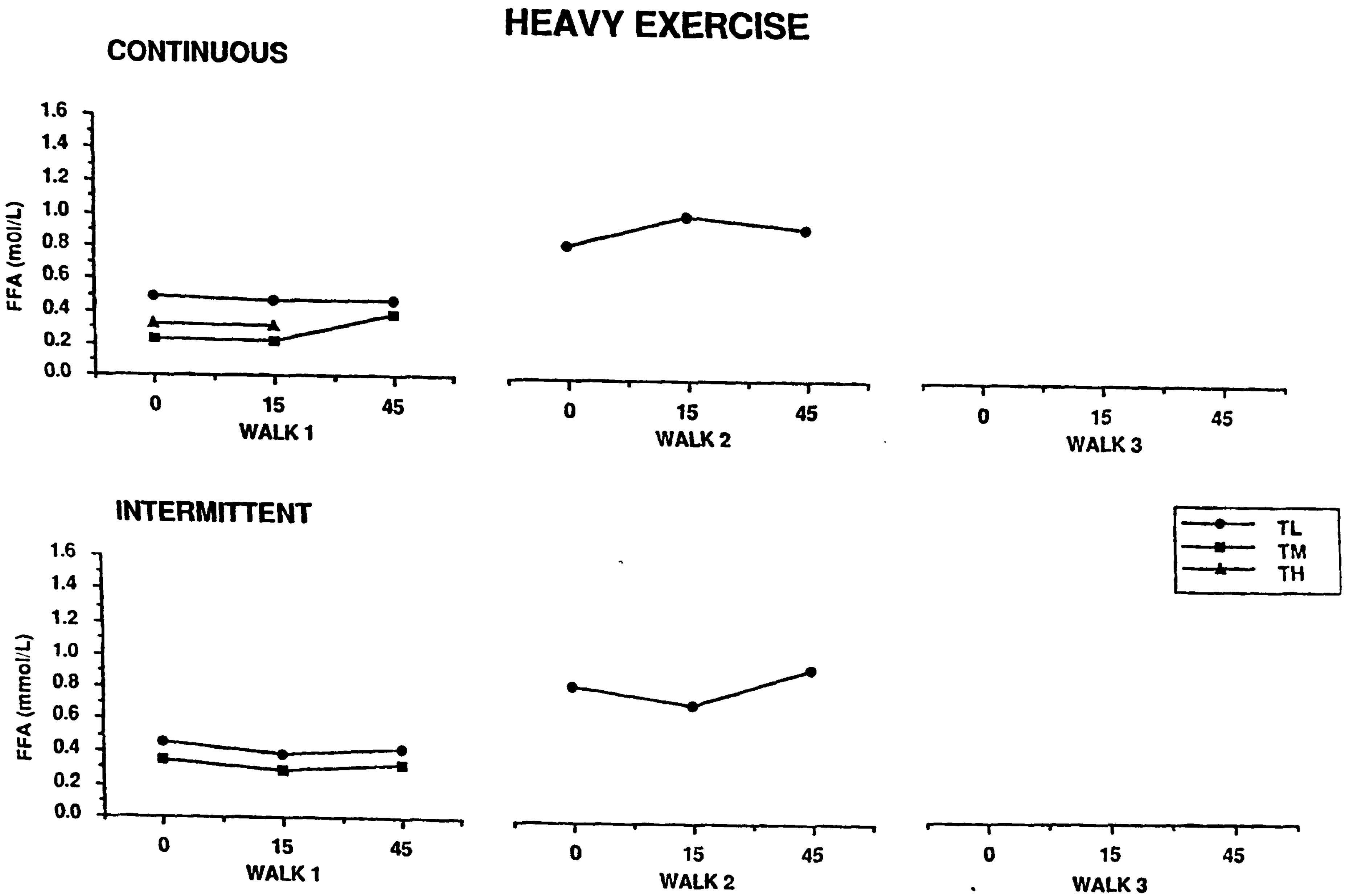


Figure 27. Comparison of glycerol concentrations during light exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.

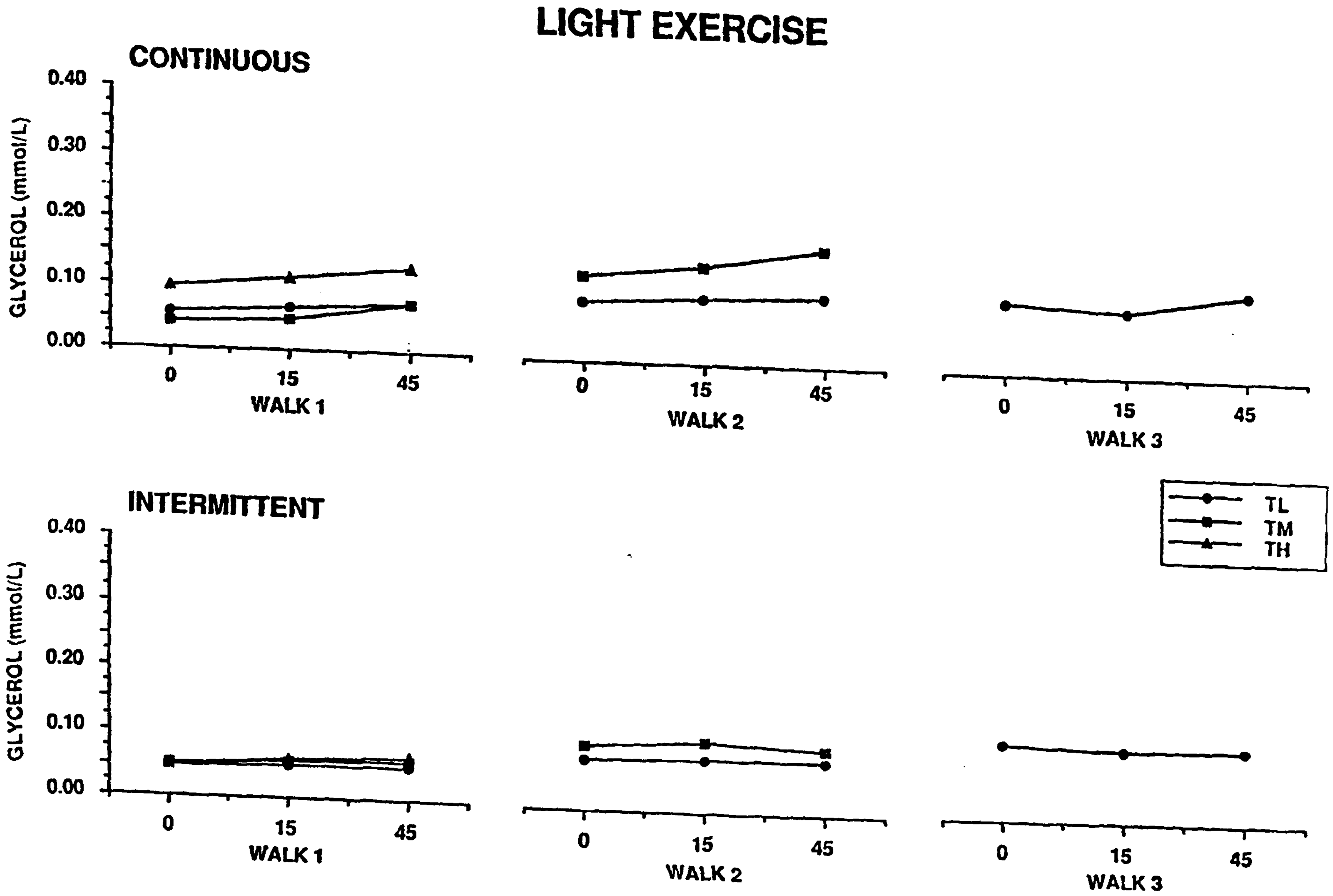


Figure 28. Comparison of glycerol concentrations during heavy exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.

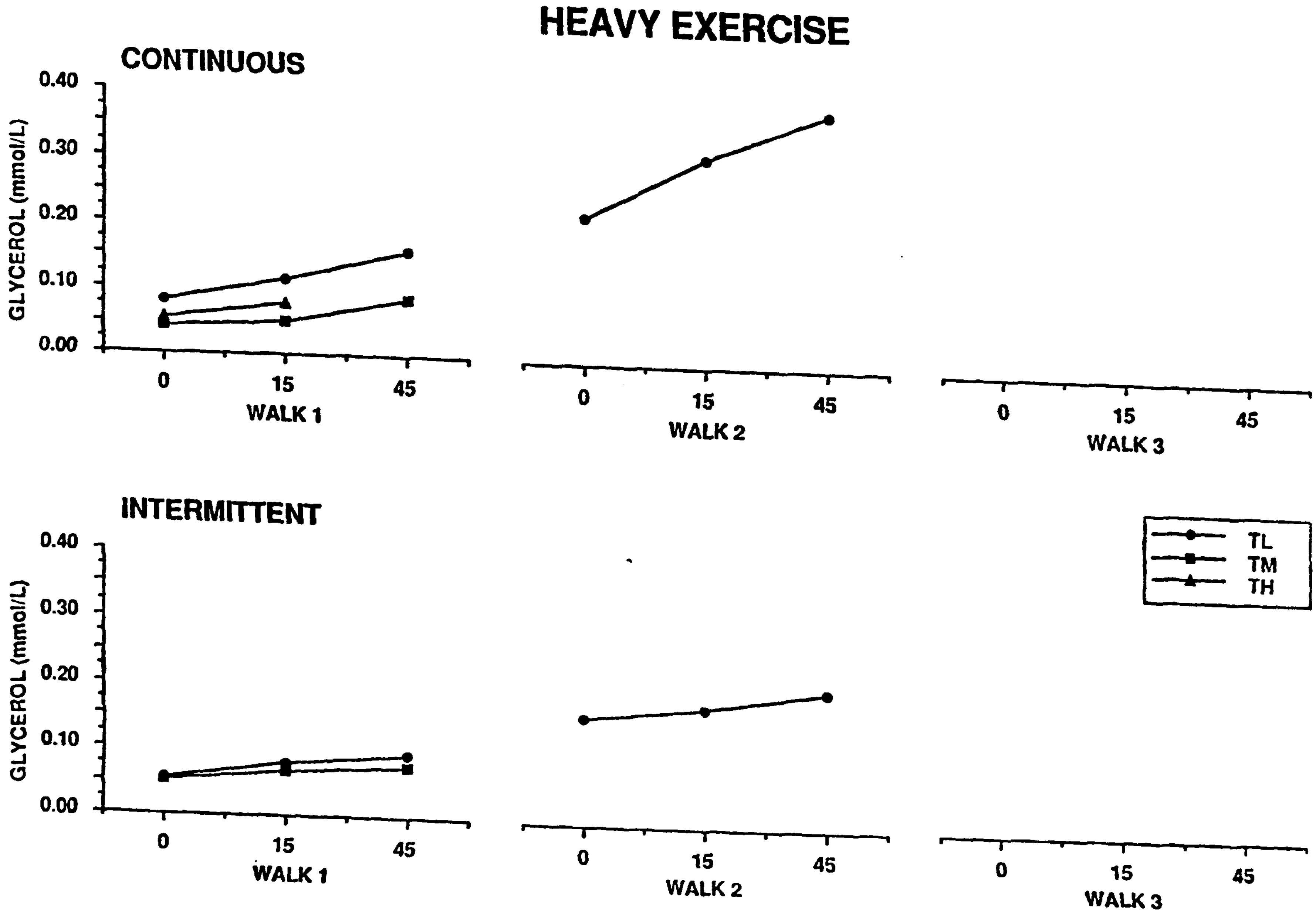


Figure 29. Comparison of glucose concentrations during light exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.

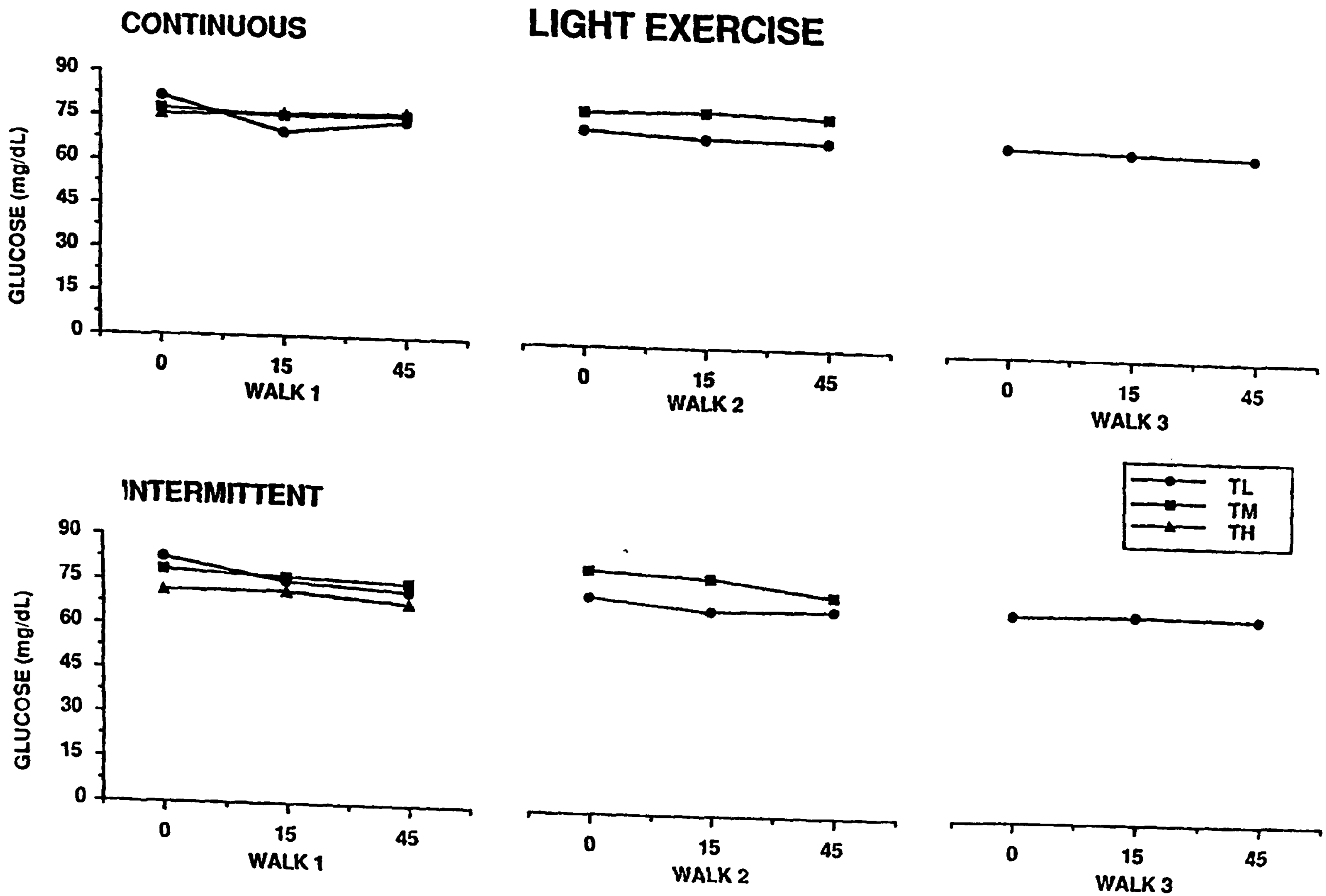


Figure 30. Comparison of glucose concentrations during heavy exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.

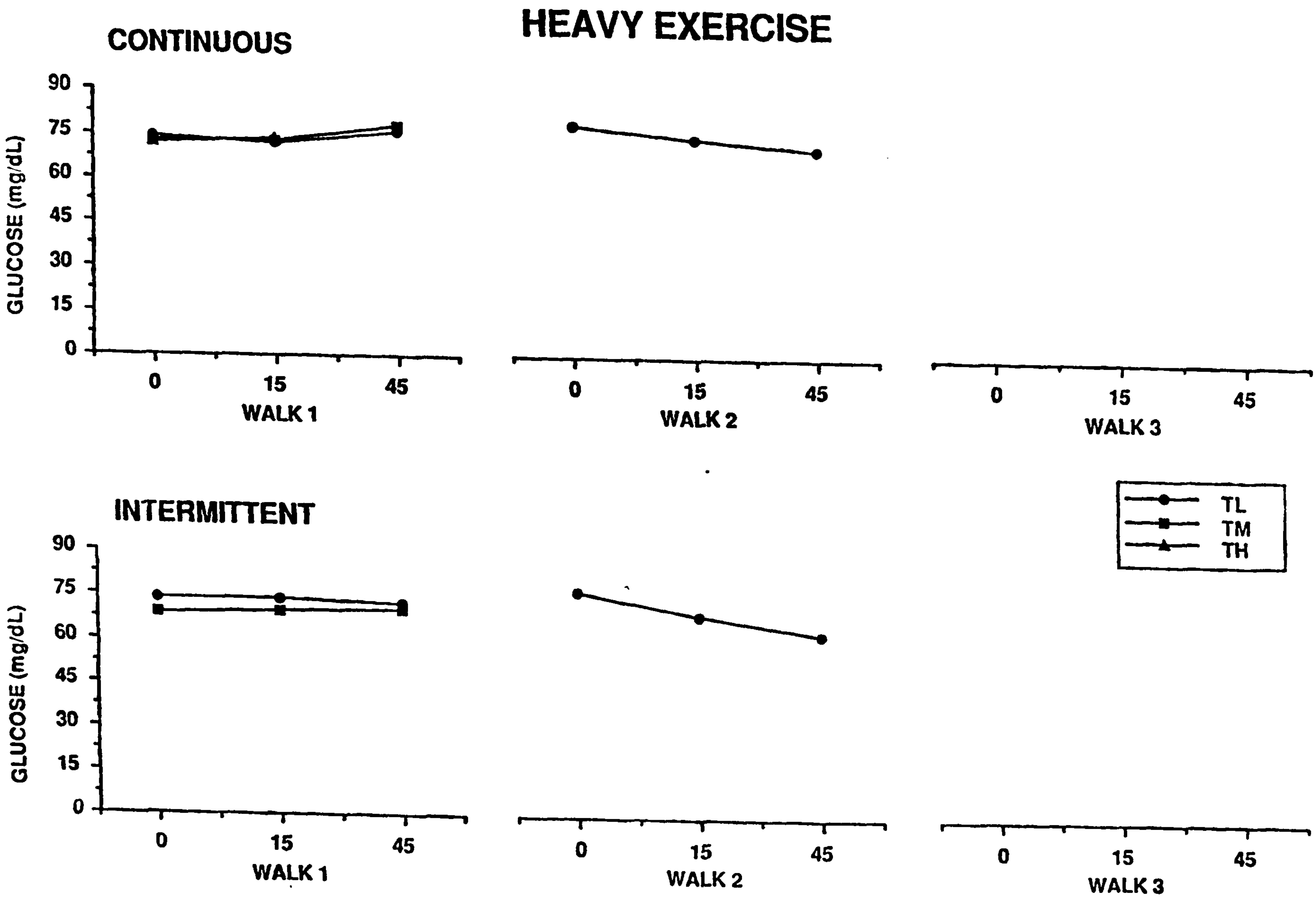


Figure 31. Comparison of lactate concentrations during light exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.

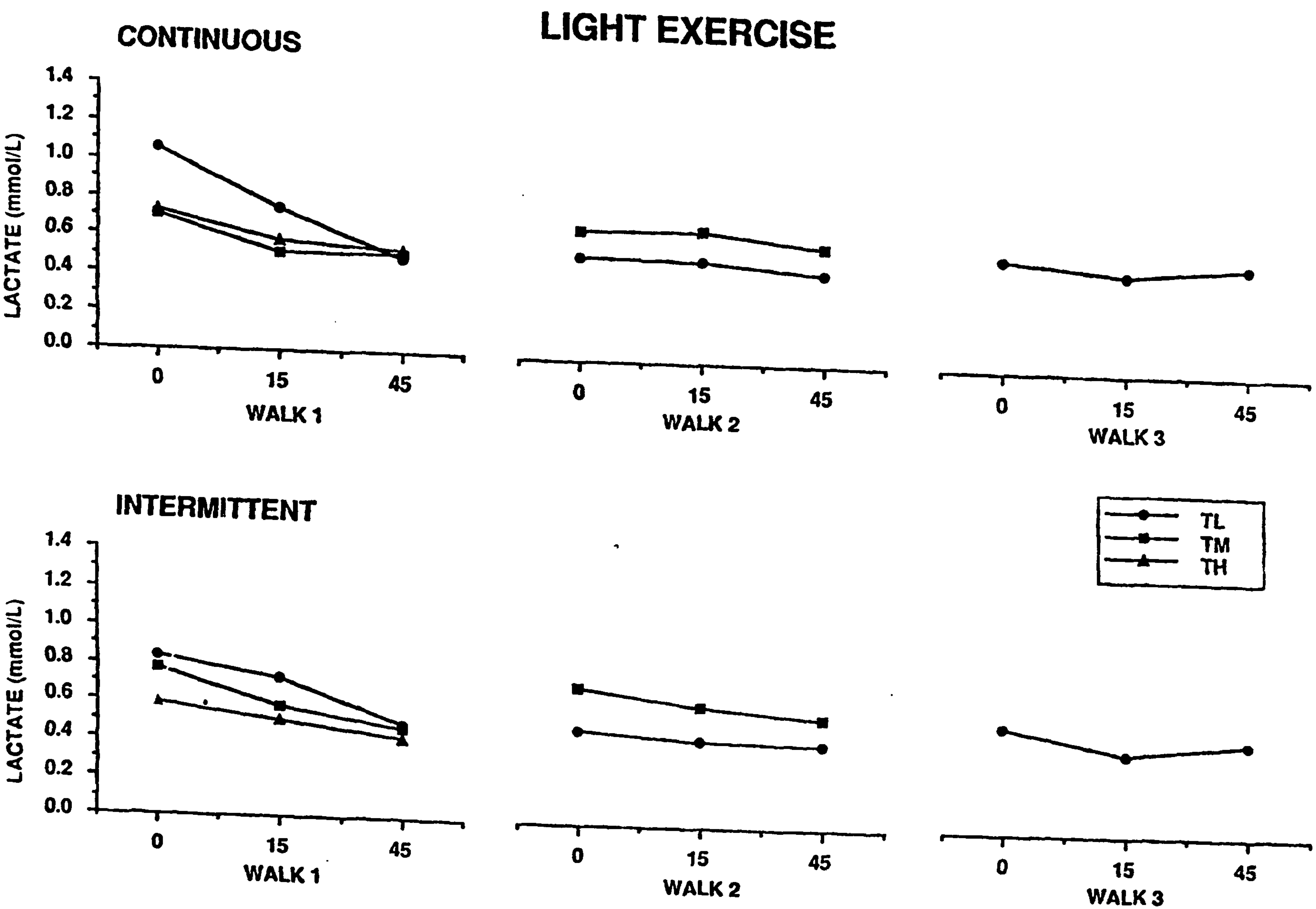
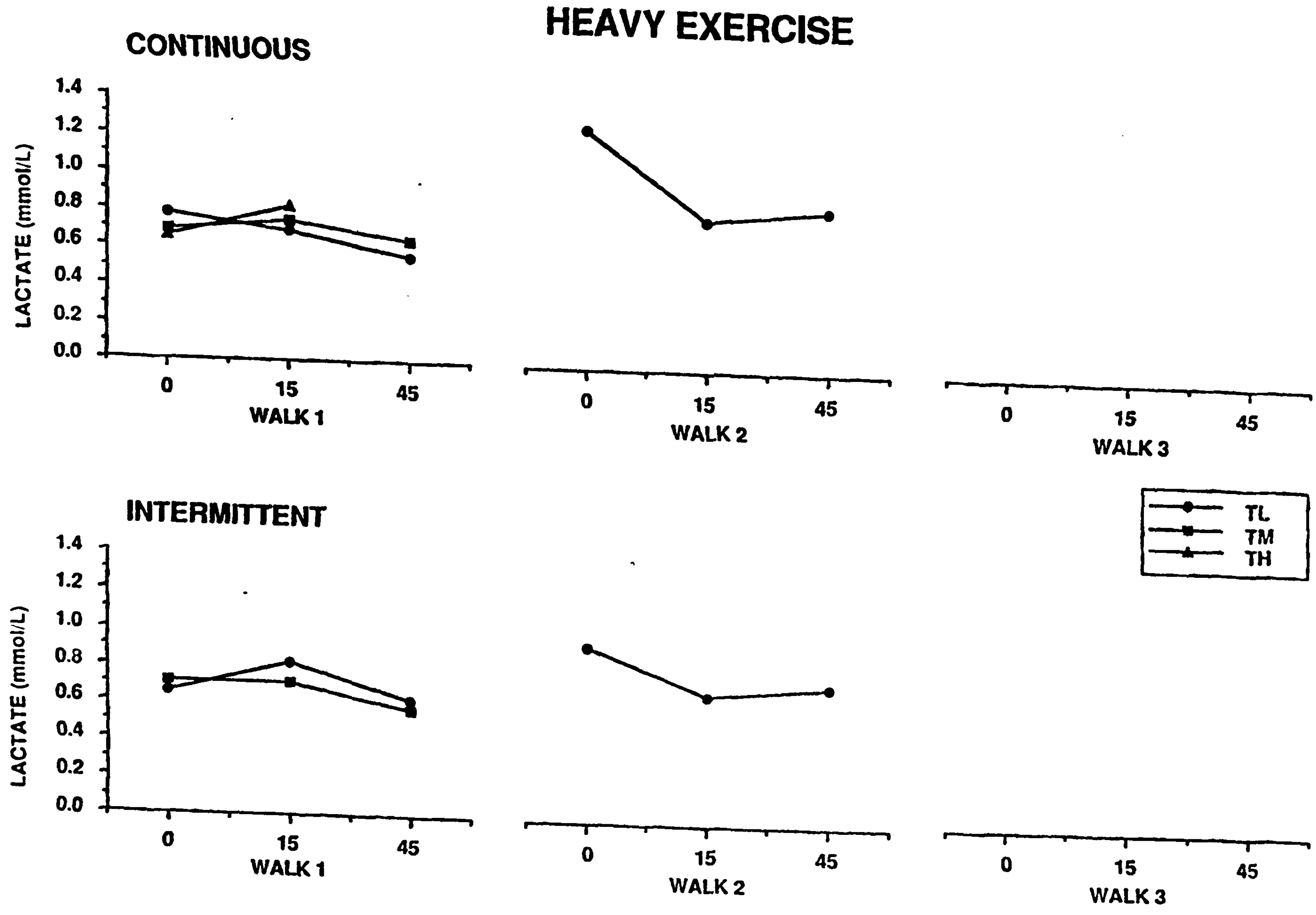


Figure 32. Comparison of lactate concentrations during heavy exercise performed either continuously or intermittently while wearing TL, TM, and TH levels of protective clothing at 30°C.



4.2.11 Rate of Fluid Loss and Evaporative Efficiency.

During the light exercise trials the rate of fluid loss was not affected by the intermittent work schedule (Figure 33). The TH level of protection was associated with an increased rate of fluid loss compared with the TM or TL conditions. During the heavy exercise the intermittent schedules for the TL and TM levels of protection did not influence the rate of fluid loss. For the TH level of protection the intermittent schedule (15 min work/15 min rest) showed a significantly lower rate of fluid loss than the continuous protocol; this difference reflected the greater fluid intake during the rest period of the intermittent protocol. For both the light and heavy exercise conditions the intermittent work schedules did not influence the evaporative efficiency for the different levels of protective clothing (Figure 34).

5.0 DISCUSSION

This study quantifies and documents the problems of body temperature regulation and the associated impairment of physical work tolerance times while wearing CF standard issue infantry IPE. The effects of wearing IPE were evaluated at two (somewhat arbitrarily chosen) ambient temperatures and for two work intensities. The work intensities were chosen to represent the metabolic rates that would be elicited during routine infantry activities of a light or moderately heavy nature. At the more moderate temperature, i.e., 18°C, all subjects were able to complete 5 continuous hours of work in TL, be it of a light or moderatively heavy nature. While wearing TH and doing heavy work at 18°C, the inability to dissipate body heat dramatically reduced this work time to an average tolerance time of less than one hour.

Figure 33. Rate of fluid loss during the light or heavy continuous and intermittent exercise trials at 30°C while wearing TL, TM or TH levels of protective clothing.

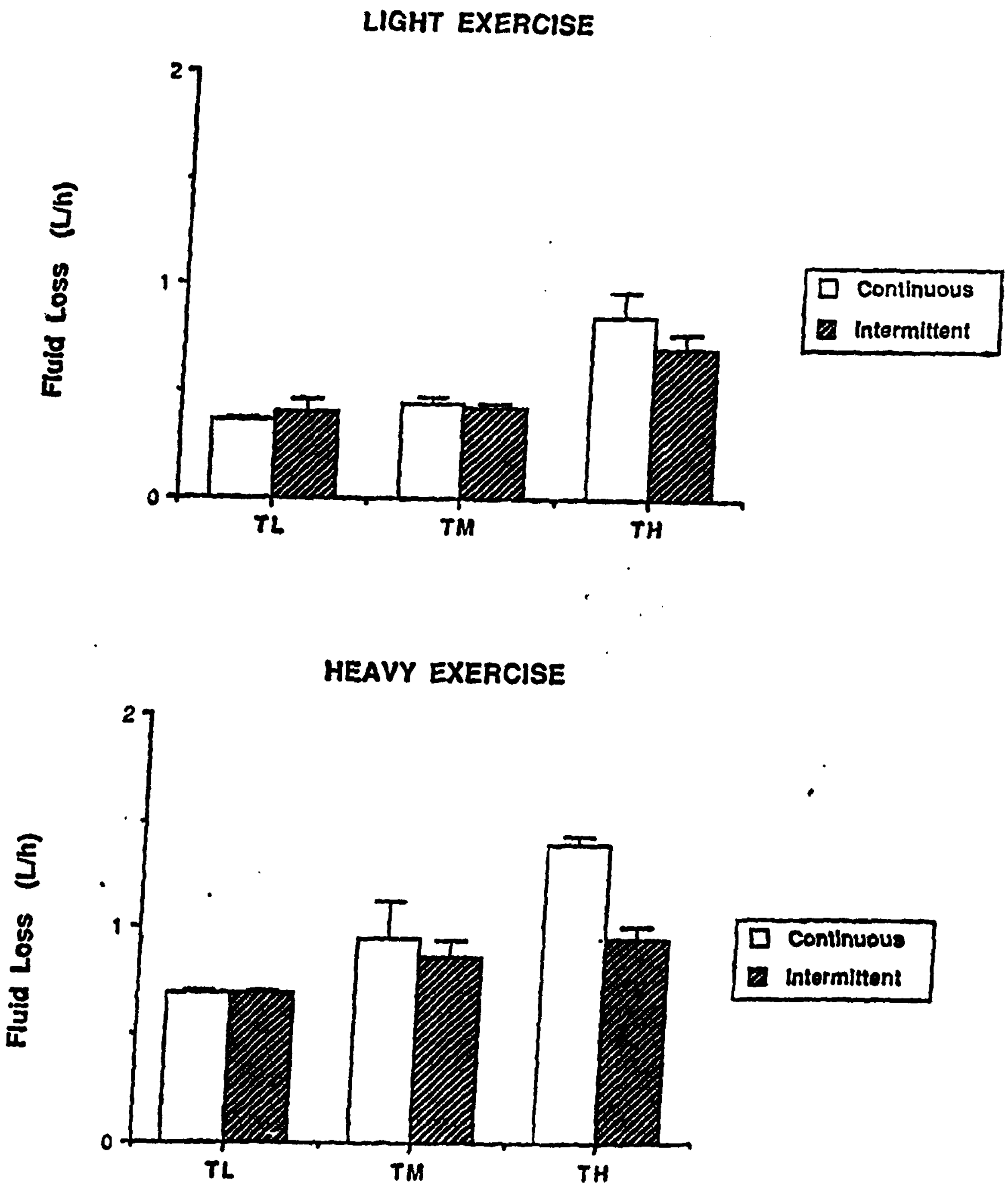
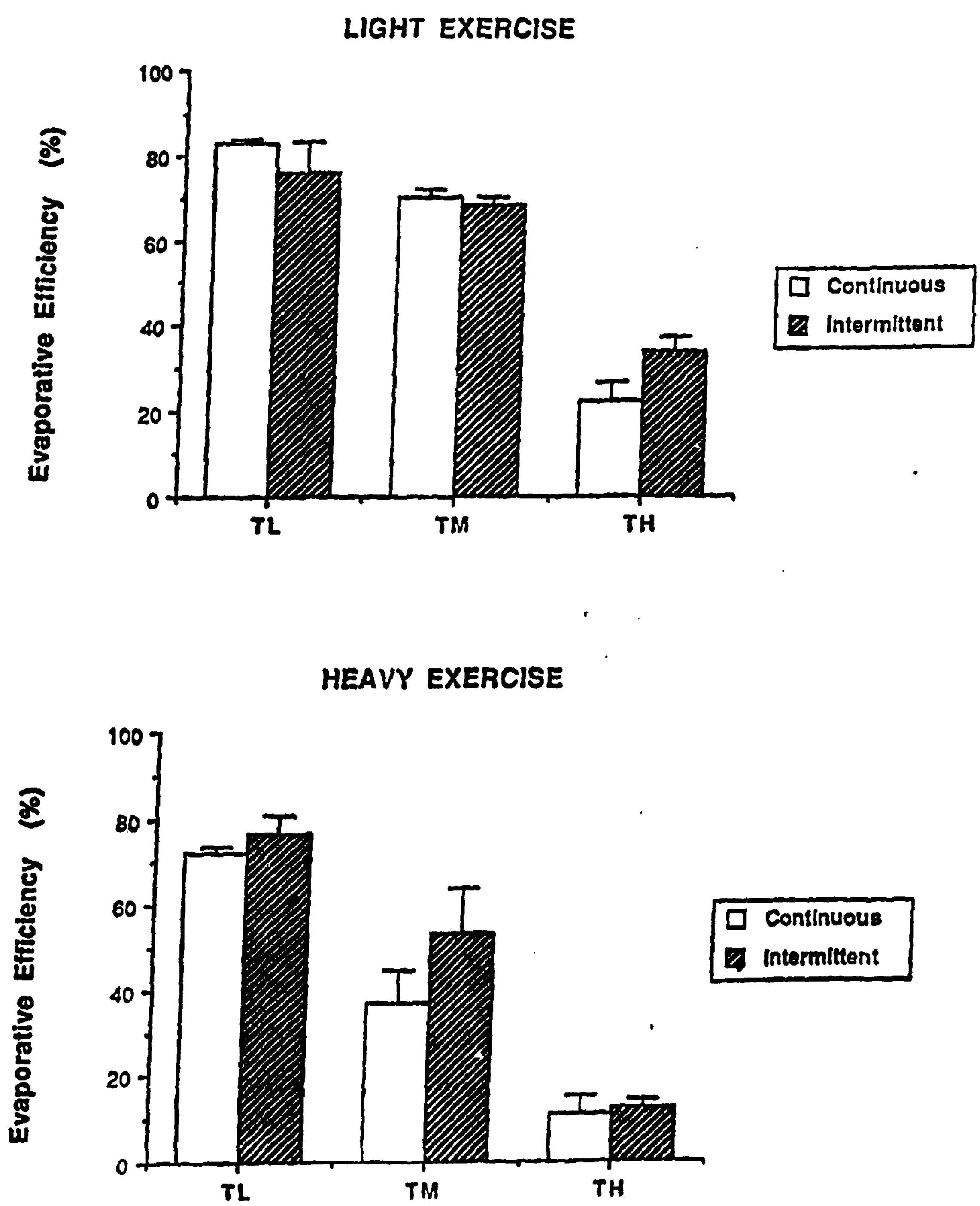


Figure 34. Evaporative efficiency during the light or heavy continuous and intermittent exercise trials at 30°C while wearing TL, TM or TH levels of protective clothing.



The effect of changing the ambient temperature to 30°C simply compounded the severity of the problem. The heavy work that could be performed for 5 hours in normal combat fatigues at 18°C could only be performed for less than 3 hours at 30°C. While wearing TH in these conditions tolerance time was further reduced to 34 minutes.

The question can be asked as to whether our criteria for determining work tolerance times were too conservative, and therefore not representative of what the actual tolerance of the subjects would be in a "real" scenario. It should be remembered that for several of our subjects WTT was a function of their physical inability to continue the experiment because of dizziness or nausea; thus their tolerance times were "real." The heart rate and rectal temperature criteria, although conservative in order to ensure the health and safety of the subjects, were extremely close to the well documented levels at which either physical exhaustion or heat injury occur (15,28-30) In particular the rapid rate at which T_{re} was increasing while wearing IPE indicates that heat-related incapacitation was imminent within a few minutes of the times at which we halted the experiments. We are thus confident in relating our experimental work tolerance times to work tolerance times in the field; if our estimated work tolerance times are on the conservative side, this will only serve to decrease the rate of heat-related injuries that may be incurred if our recommendations are followed.

In the present study the intensity of exercise was classified as light or heavy in accordance with the U.S. Army guidelines proposed by Rakaczky (3). These classifications were based on metabolic heat production and correspond to approximately 225 and 450 watts (200 and 400 kcal·h^{-1}) for the light and heavy exercise loads, respectively. For both the "light" and "heavy" loads in this investigation, however, the relative exercise intensity was less than 50% $\dot{V}O_2max$. Under normal environmental and/or clothing conditions (e.g., TL at 18°C) these loads could be maintained for several hours. The fact that blood lactate and glucose decreased slightly from resting values, that pH and PCO_2 did not change, and that plasma FFA and glycerol levels increased over time support the statement that these exercise loads, per se, represented a light metabolic stress. In contrast, the rate of core temperature change (see Figure 4) and fluid loss (see Figure 16) demonstrate the magnitude of the thermal stress imposed by the IPE. The rate of fluid loss (i.e., ~ 1.5 $L \cdot h^{-1}$) observed during the TH "heavy" exercise trial in the 30°C environment is comparable with values reported for well-trained endurance athletes exercising at much higher relative exercise intensities in comfortable climatic conditions. Similar rates of fluid loss were reported for subjects in IPE of other countries (5, 19, 31-33). In spite of the high rate of fluid loss for 30HC, the short duration of the TH trials meant that the absolute magnitude of fluid loss did not result in a significant degree of dehydration. Thus the dramatic reductions in WTT in TH are more a function of the rapid increase in T_{re} than dehydration.

Recently, Jetté et al. (34) reported that $\dot{V}_E$ and plasma lactate values were reduced when subjects wore the CB respirator (with canister) during a progressive treadmill exercise test to exhaustion. The lower values for $\dot{V}_E$ and lactate were observed during exercise above 65% $\dot{V}O_2max$. Mean ventilations were approximately 70 $L \cdot min^{-1}$ (BTPS) when the relative hypoventilation was recorded. The lower plasma lactate levels most likely reflected the influence of a resultant respiratory acidosis (due to the hypoventilation) on lactate release (35). In the present study, and in agreement with the findings of Jetté et al. (34) at lower relative exercise intensities, there was no evidence of a respiratory acidosis during the TOPP High trials when $\dot{V}_E$ approached 50 $L \cdot min^{-1}$ (BTPS) (see Tables 7 and 8).

The semi-permeable nature of the IPE overgarment allows the eventual transfer and evaporation of water vapour from the skin surface. During the TOPP High trials in the hot environment (30°C) and/or heavy exercise conditions, WTT was less than 90 minutes, sweat rates ranged from 0.8 to 1.3 $L \cdot h^{-1}$ and the evaporative efficiency was calculated at approximately 20% (see Figures 2, 16 and 17). For these trials, therefore, approximately 0.2 L of sweat had passed through the IPE overgarment by the end of the experiment. In comparison, despite the reduced sweat rate of 0.5 $L \cdot h^{-1}$ for the TH trial in the cool environment and light exercise, evaporative efficiency increased to almost 50% as WTT increased to approximately 4 hours. As exposure time increases more sweat will pass through the IPE overgarment. In this latter case, almost 1.0 L of sweat had moved through the protective clothing. The relative impairment that this passage of fluid would have on the protective charcoal layer of the clothing is not known. However, it is likely that with prolonged exposure in a NBC-contaminated environment the effectiveness of the overgarment would decrease.

Estimated continuous work tolerance times for different military tasks are presented in Table 18 for TM and TH in a hot environment. These estimated work times were derived from the equations presented in Figures 19 and 20. It should be realized tha., on average, the soldier will be completely exhausted and unable to perform any additional work after WTT is attained. For example, it is estimated that

Table 18. Estimated continuous work tolerance times for different tasks in TOPP Medium or TOPP High at 30°C.

Task	Work Classification	Metabolic Rate ($\dot{V}O_2$) ($mL \cdot kg^{-1} \cdot min^{-1}$)	Work Tolerance Time (min)	
			TOPP Medium	TOPP High
Guard Duty	Light	5	indefinite	645
Labour Detail	Light	6	indefinite	310
Driving a Truck	Light	7	indefinite	205
Marching, 2.3 mph	Moderate	10	500	100
Labour Detail	Moderate	12	218	75
Littering 80 kg man, Marching 3.4 mph	Moderate	13	170	67
Marching 110-120 paces/min, Road March full pack 3.2 mph Decontamination of vehicles, Loading of equipment on vehicles,	Heavy	14	140	60
Scouting Patrol, Crawling Full Equipment, Foxhole Digging, Trench Digging	Heavy	15	118	55
Field Rushes, Fire Fight, Minelaying, Cratering	Heavy	16	103	50
Forced March with 30-lb pack and 9-lb rifle	Very Heavy	17	90	45
Lifting 22kg, 8 lifts/min to waist height, Tank Crew Firing Drill	Very Heavy	20	67	38
Lifting 45kg, 6 lifts/min to waist height	Very Heavy	24	50	30

Metabolic rates are from Bergh and Danielsson (8), Consolazio et al. (36), and Legg and Pateman (37).

soldiers could march in TH at 2.3 mph for 100 minutes, thereby covering a distance of 3.8 miles. If the destination is 3.5 miles (~ 5.5 km) away the soldier could march continuously at the above pace and safely reach the target. However, any additional tasks that must be performed once the destination is reached may not be completed successfully without an intervening rest period.

It must be emphasized that, when wearing TH, our results show that the amount of work accomplished or distance covered is dictated primarily by the metabolic rate or intensity of the work task. Introducing work/rest schedules that use a metabolic rate during the work period that is the same as for a continuous work schedule will not alter the total amount of work accomplished, but simply spreads that work out over a longer period of time. Work tolerance time will be prolonged since the average metabolic rate has decreased (due to the rest periods) but the actual work done will be the same as if the task had been performed without a rest schedule. Again, using the above example a total distance of 3.8 miles would be covered in 100 minutes walking at 2.3 mph in TH. If a work/rest schedule of 20 min/10 min were implemented the average metabolic rate would decrease from 10 to 8 $mL \cdot kg^{-1} \cdot min^{-1}$ (using a resting $\dot{V}O_2$ of 4 $mL \cdot kg^{-1} \cdot min^{-1}$) and WTT would increase from 100 to 152 minutes. However, of this total only two-thirds (20/30 minutes) or 100 minutes of actual work would be accomplished. Similarly, if the work/rest schedule were 10 min/20 min the average metabolic rate would decrease to 6 $mL \cdot kg^{-1} \cdot min^{-1}$ and WTT would increase to 310 minutes but, again ~ 100 minutes (1/3 of 310) of work time would be involved.

If the main objective for implementing work/rest schedules is to increase the amount of work performed before exhaustion occurs while wearing IPE, then the metabolic rate of the work period must be reduced compared with a continuous work schedule. This strategy benefits from the increasing curvilinear nature of the WTT and metabolic rate relationship (see Figure 18). In other words, a given decrease in metabolic rate produces a disproportionate increase in WTT and a subsequent increase in the total amount of work performed. As an extreme example, a double-time march (slow jog) represents a metabolic rate of ~ 25 $mL \cdot kg^{-1} \cdot min^{-1}$. This work intensity would be associated with a WTT of 29 minutes in TH at 30°C and a total distance covered of ~2.5 miles (4.0 km). If the work intensity were reduced to a slow walk (2.3 mph) WTT would increase to 100 minutes and the total distance covered would increase to 3.8 miles (6.1 km). This represents slightly more than a 50% improvement in the total work done. Clearly, this example represents almost the largest improvement in work accomplished that one could expect from the relationship shown in Figure 18. The fact remains, however, that for work/rest schedules to be of any benefit for increasing total work done then the intensity (or metabolic rate) of the work period must be reduced compared with the intensity that would be chosen for a continuous work schedule.

In contrast, if the purpose of selecting work/rest schedules is to allow some operations to continue at their usual intensity, in spite of having to wear IPE in a hot environment, then schedules such as those presented in Table 19 could be used with a fair degree of certainty of the calculated WTT.

There are important additional physiological considerations if WTT is increased by employing work/rest schedules. As discussed above, dehydration was not a main contributing factor to limiting WTT in TH in the present trials because of the short

Table 19. Work and rest schedules for work tolerance times of 2, 3, 4, 6 or 8 hours for different tasks performed in TOPP High and 30°C.

Task	Work Classification	Work to Rest Schedule — Work Tolerance Time (hours): 2	3	4	6	8
Labour Detail, light	Light	-	-	-	25/5 (5:1)	20/10 (2:1)
Marching 2.3 mph	moderate	25/5 (5:1)	18/12 (1.5:1)	12/18 (1:1.5)	10/20 (1:2)	15/45 (1:3)
Marching 3.4 mph	Moderate	18/12 (1.5:1)	12/18 (1:1.5)	10/20 (1:2)	12/48 (1:4)	10/50 (1:5)
Trench Digging	Heavy	15/15 (1:1)	10/20 (1:2)	15/45 (1:3)	10/50 (1:5)	10/80 (1:8)
Forced March	Very Heavy	12/18 (1:1.5)	15/45 (1:3)	12/48 (1:4)	10/60 (1:6)	10/90 (1:9)

duration of the trials. The rate of sweating, while wearing TH, however, is very high. Thus extending WTT will result in a greater absolute fluid loss causing levels of dehydration associated with significant performance impairments. A discussion of fluid requirements with a military perspective can be found in other reports (33, 38).

The responses of our subjects to working in CF standard issue infantry IPE were very similar to the results of studies performed by others. Our results fit, for the most part, the predictive models developed by the U.S. Army to predict body temperature responses to working in IPE at various temperatures (30). We employed the U.S. model to calculate what the T_{re} of our subjects should be at their respective work tolerance times for the TH trials; these values were then compared with the observed T_{re}. For 18LC the model predicted the final TH T_{re} to be 38.2°C compared with the observed mean value of 38.2°C; for 30LC the predicted value was 38.4 vs an observed value of 38.9°C; for 18HC the predicted value was 38.5 vs an observed value of 38.5°C; for 30HC the predicted value was 38.4 vs an observed value of 38.3°C. With the exception of the 30LC group the model was quite accurate. Thus, U.S. Army guidelines for maximum allowable work times with minimum heat casualties (contained in U.S. Army FM 21-40), based on the Pandolf et al. (30) model, can be considered to be applicable to our CF infantry IPE. Tables 18 and 19 in this report are consistent with those guidelines. The extrapolation of our findings to environmental temperatures above 30°C should be viewed with caution. However, it should be apparent that work times will be reduced for any given task (i.e., for any given metabolic rate) as the environmental temperature increases. It is conceivable that the estimated work times presented in Table 18 for TOPP High at 30°C may be reduced by 50% if environmental temperature approaches 40-45°C.

6.0 CONCLUSIONS

Based upon the results obtained from the present study, the following conclusions are evident;

1. the various levels of protective clothing exert a minimal, if any, impairment on work times if the metabolic rate of the task is light and the environmental temperature is cool (less than 20°C),

2. as the metabolic rate and/or the environmental temperature is increased work times are progressively reduced while wearing the different levels of protective clothing,

3. the reduction in work time is most severe while wearing the full level of NBC protective clothing (i.e., TOPP High), and

4. a strong relationship is observed between the inverse of work time and the metabolic rate for both the Medium and High levels of protection in a hot environment (i.e., 30°C).

7.0 RECOMMENDATIONS FOR FURTHER STUDY

If additional tasking from DNBCC is recommended based on the findings of the present investigation, then future research should focus on the following;

1. increase the number of subjects tested in the 30°C environment at various metabolic rates to increase the accuracy of the equations that were established for the relationship between work time and metabolic rate.

2. examine the relationship between work time and metabolic rate at higher environmental temperatures (i.e., 35, 40 and 45°C) for the different levels of protective clothing, and

3. create a database for female CF personnel.

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This study examined the effects of environmental temperature and metabolic rate on soldiers' work tolerance time (WTT) while wearing various levels of nuclear, biological and chemical defence (NBCD) protective clothing. Twenty-three unacclimatized males (23 ± 3y, 76 ± 8kg, 177 ± 8cm) were assigned to exercise at either a light (walking 1.11 $m \cdot s^{-1}$ 0% grade, alternating with lifting 10kg) or heavy metabolic rate (walking 1.33 $m \cdot s^{-1}$ 7.5% grade, alternating with lifting 20 kg) in an environmental chamber at either 18°C, 50% R.H. (cool) or 30°C, 50% R.H. (hot). Subjects were tested wearing three levels of clothing protection: combat fatigues (Low); fatigues and a semi-permeable NBCD overgarment (Med); fatigues and NBCD overgarment, gloves, boots and respirator (High). WTT was the time until rectal temperature (T_{re}) reached 39.3°C, heart rate reached 95% maximum, dizziness or nausea precluded further exercise, or 5 h had elapsed. During the hot trial, 8 subjects (light (N=4) and heavy exercise (N=4)) performed an additional three clothing trials using an intermittent rather than a continuous work schedule. During the light and cool trials (N=5), the levels of protective clothing did not impair WTT (277 ± 47 min). For the light and hot experiments (N=6), WTT was significantly impaired with the High level of protection (82.7 ± 10.6 min) and T_{re} increased 1.3 ± 0.3 °C/h. With the heavy and cool condition (N=6), WTT was reduced with the Med (240.5 ± 73.8 min, T_{re} increased 0.5 ± 0.2°C/h) and High (56.7 ± 17.9 min, T_{re} increased 1.8 ± 0.5°C/h) levels of protection. Finally, during the heavy and hot trials (N=6), WTT was progressively impaired for the Low (172.5 ± 52.8 min, T_{re} increased 0.8 ± 0.3 °C/h), Med (65.8 ± 18.2 min, T_{re} increased 2.0 ± 0.5°C/h) and High (34.0 ± 9.7 min, T_{re} increased 2.6 ± 0.5°C/h) levels of protection. In the hot environment, the average metabolic rate (VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)) was directly proportional to the inverse of WTT for both the Med ($WTT^{-1} = 0.00129VO_2 - 0.0109$, r = 0.9) and High ($WTT^{-1} = 0.00167VO_2 - 0.0068$, r = 0.9) levels of protection. If the metabolic rate of a task is known, these relationships can be used to calculate work to rest schedules that may prolong work time in the Med or High levels of NBCD protective clothing.

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Exercise, heat stress, protective clothing.

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