EVALUATION OF INHALATION REWARMING AS A THERAPY FOR HYPOTHERMIA

by

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ABSTRACT

To resolve the controversy regarding the effectiveness of inhalation rewarming as a therapy for hypothermia two separate studies were conducted.

The initial study was designed to investigate the effect an increase in respiratory heat input would have on core temperature gains during rewarming from hypothermia. Ten subjects were immersed in sea water (mean temperature 12°C) until a 2°C drop in rectal temperature occurred. The subjects were then rewarmed by breathing hot saturated air at 44°C for 30 minutes. Each subject was rewarmed once with spontaneous ventilation breathing air and once rebreathing a controlled fraction of expired air adjusted to produce a hyperventilation of 50 l/min. At the end of the rewarming period, mean rectal temperature had increased 0.39°C when breathing spontaneously compared with 0.77°C when hyperventilating ($P < 0.01$). Corresponding gains in tympanic temperatures were 1.1°C and 1.5°C, respectively. Calculations indicate that the additional respiratory heat input from hyperventilation yielded a core (rectal) temperature gain of 5.1×10^{-4} °C/litre. Thus, it is concluded that each additional 10 l/min of hyperventilation of

44°C saturated air will increase the rate of core rewarming from hypothermia by approximately 0.3°C/hr.

The second study was designed to evaluate the contributions made by respiratory heat input and metabolic heat production to core temperature gain during rewarming from hypothermia. Ten subjects were immersed in water (mean temperature 11.3°C) until rectal temperature fell to 35°C. The subjects were then rewarmed with three different levels of respiratory heat input (RH), for 60 minutes. Each subject was rewarmed once by shivering (mean RH= -10 kcal/hr), once by normal inhalation rewarming breathing air (mean RH= 20 kcal/hr), and once by hyperventilation inhalation rewarming (mean RH= 40 kcal/hr) using the same rebreathing technique as in the previous study. As respiratory heat input increased core temperature gains increased ($P < 0.05$). However, metabolic heat production and the total heat available for rewarming decreased as respiratory heat input increased ($P < 0.05$). The percentage of total heat supplied to the core (measured as 46% of body weight at rectal temperature) increased as respiratory heat input increased, from 11% in shivering to 15% in normal inhalation rewarming and to 22% in hyperventilation inhalation rewarming. Theoretical considerations suggest that respiratory heat may be 4 to 6 times as effective as metabolic heat in elevating core temperature.

It was concluded that inhalation rewarming is an effective rewarming therapy and that inhalation rewarming provides a significant improvement over shivering thermogenesis alone in the treatment of hypothermia.

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A. INTRODUCTION

Accidental hypothermia is a common hazard in both recreational and industrial activities as a result of both climatic conditions and low water temperatures. In many accidents where drowning is given as the cause of death, the drowning most probably results from loss of consciousness due to hypothermia (Keatinge, 1968). Hypothermia caused by cold water immersion and mountain accidents requires correct diagnosis and therapy if high mortality rates are to be avoided (Coopwood and Kennedy, 1971). The type of therapy administered is a controversial issue due to the danger of sudden changes in physiological function in response to the treatment.

A major problem associated with treatment of accidental hypothermia is the requirement for rapid transport of victims to hospital. Incidents commonly occur in remote areas. Climatic conditions may delay or prevent removal of the patient. There is at present an urgent requirement by rescue teams for a suitable method of resuscitating severely hypothermic patients, or even a "holding" method to preventing further core cooling during transit. In most rescue situations, local conditions preclude the more sophisticated rewarming techniques usually administered in hospitals.

Inhalation rewarming is an attractive tecnique for application under field conditions. It supplies heat directly to the central core, equipment for its implementation can be made portable and it is ncn-invasive.

Presently there is controversy regarding the usefulness of this technique (Hudson and Robinson, 1973; Marcus, 1978; Hayward and Steinman, 1975; Lloyd, 1973; Marcus, 1979; Auld, Light and Norman, 1979). Disagreement exists both over the quantity and the distribution of the heat delivered. Animal and human studies are equivocal. This could be due to differing experimental conditions and/or small subject samples. Although theoretical and practical considerations argue in favour of the effectiveness of inhalation rewarming, experimental studies have been far from conclusive.

To resolve the controversy regarding the effectiveness of inhalation rewarming as a therapy for hypothermia two separate studies were conducted. The initial study was designed to establish whether an increase in the ventilation of warm saturated air would produce an increase in core rewarming and to quantify any such increase by evaluating the thermal increment provided by any increased ventilation. The initial study was carried out under field conditions as part of a much larger field study to test the effectiveness of various cold water

survival suits. While the field study did provide postive results the lack of control over environmental conditions, the lack of subject uniformity and the lack of data regarding changes in important variables (i.e. respiratory heat gain, metabolic heat production and body heat losses) prompted a second study.

The second study, conducted under laboratory conditions, was designed to evaluate the relative contributions of metabolic heat production and respiratory heat input to core temperature gain during rewarming from mild hypothermia.

B. LITERATURE REVIEW

Accidental hypothermia is a serious problem in cold air and water environments. It commonly occurs in hikers and mountaineers lost or stranded in cold weather (Freeman, Griffith and Pugh, 1969; Pugh, 1966), in fishermen and yachtsmen following cold water immersion (Andrew and Orkin, 1964; Golden, 1973) and in military personal operating in cold environments. The rapid rate of cooling which occurs in cold water immersion (Hayward, Eckerson and Collis, 1975) and in mountain accidents (Freeman, Griffith and Pugh, 1969) can readily progress to a medical emergency. Keatinge (1968) estimated that approximately 1,000 persons per year died from immersion in British coastal and inland waters. Although these deaths were usually attributed to drowning, Keatinge believed that hypothermia was the primary cause of death. After a study of the Lakonia and Titanic disasters (Keatinge,1968) he concluded that most of the deaths were caused by hypothermia.

There are many techniques described in the literature for rewarming of hypothemic patients. These can be grouped in three categories: passive rewarming (shivering thermogenesis), active peripheral rewarming, and active core rewarming. Passive rewarming usually takes in excess of 24 hours to attain normal

body temperatures and has produced poor survival results, with mortality rates of 45 to 100 per cent when core temperatures were initially below 32°C (Tolman and Cohen, 1970). A review by Fernandez, O'Rourke and Ewy (1970) concluded that more patients survived accidental hypothermia if normal body temperatures were reached in less than 12 hours, and suggested that this would be more likely if active rewarming was attempted. Many authorities (Keatinge, 1977; Davies, 1975; Golden and Rivers, 1975; Jessen and Haqelsten, 1972) have recommended peripheral rewarming be used particularly for acute hypothermia, usually by immersion in a hot bath, by thermal mattress (Fernandez, O'Rourke and Ewy, 1970), by heated blankets (Phillipson and Herbert, 1967), or by plumbed hot water garments (Webb, 1973; Marcus, 1978).

Gregory and Doolittle (1973) in a review of 201 clinical cases occuring between 1951 and 1972 (Table 1) concluded:

1. In mild hypothermia, the method of rewarming was not as important for survival as in moderate or severe hypothermia.
2. The lower the initial body core temperature when passive or active external rewarming was started the higher the mortality rate.
3. The mortality rate for passive rewarming was lower than with active external rewarming for all degrees of hypothermia.
4. All patients receiving core rewarming survived.

TABLE 1

ANALYSIS OF SURVIVAL FROM HYPOTHERMIA
BY METHOD OF REWARMING AND DEGREE OF HYPOTHERMIA

	PASSIVE		ACTIVE EXTERNAL		CORE	
	Died	Survived	Died	Survived	Died	Survived
Mild (94-90°F)	4	15	4	8	0	1
Moderate (89-80°F)	38	43	25	16	0	1
Severe (< 79°F)	12	9	15	5	0	5
TOTALS:	54	67	44	29	0	7

Thus, while active peripheral rewarming may be effective in the treatment of rapid-onset hypothermia of mild severity, physiological problems may arise with active peripheral rewarming of the slow-onset, unconscious or severely hypothermic victim.

The major disadvantage of active peripheral rewarming is that the peripheral tissues are rewarmed in advance of the still cool "core" and may make metabolic and circulatory demands that the cardiovascular system is unable to meet (Truscott, Firor and Clein, 1973). Tansey (1973) cautioned that the rate of restoration of core temperature must be carefully balanced between the risk of anoxic damage from too brisk an increase in tissue oxygen requirement before circulation is improved and the risk of vascular collapse from the critical afterdrop in core temperture associated with the restoration of peripheral blood flow through cold deeper layers of subcutaneous tissue. Active peripheral rewarming relieves the intense peripheral vasoconstriction associated with hypothermia. This causes a redistribution of circulating blood to the periphery, impairs venous return to the heart and further reduces cardiac output. Also, active peripheral rewarming may cause tissue liberation of acid end products of metabolism and the resulting metabolic acidosis may lead to ventricular fibrillation and death (Mills, 1976).

In chronic hypothermia intravascular volume is decreased secondary to fluid shifts, and rapid peripheral rewarming may precipitate hypovolemic shock (Burton and Edholm, 1955; Keatinge, 1969). However, according to Golden (1973), it is unlikely to have fatal consequences in immersion victims, as the duration of exposure is usually insufficient to permit the occurence of major physiological adjustments in circulatory fluid volume.

Active peripheral rewarming inhibits shivering thermogenesis. Recent studies by Hayward, Eckerson and Collis (1977) demonstrated that thermoregulatory heat production in man depends on an interaction of signals from peripheral and central receptors. An abrupt cessation of shivering was found in mildly hypothermic subjects immersed in warm water baths when the skin temperatures reached aproximately 33°C. This occured at a time when core temperatures were at their lowest levels.

Core rewarming has the distinct advantage of rewarming the heart in advance of the increasing metabolic requirements at the periphery. Theoretically, core rewarming avoids all the physiological hazards mentioned above through delivery of heat directly to the central circulation and tissues, leaving the limbs and peripheral tissues to warm more slowly.

Sophisticated techniques of core rewarming have been practised with success and are recommended particularly for severly hypothermic patients. Methods of core rewarming include peritoneal dialysis (Lash, Berdette and Ozdil, 1967), extracorporeal circulation (Davies, Millar and Miller, 1967; Kugelberg, Schiller, Berg and Kallum, 1967; Truscott, Firor and Clein, 1973), endotracheal administration of warm, moist air (Shanks and Sara, 1972) and administration of heated intravenous fluids. In some cases, a combination of the above methods have been employed (Ledingham and Mone, 1972; Shanks, 1975).

One of the greatest problems in the treatment of acute accidental hypothermia is transport of the patient to a medical centre. Adverse weather conditions may delay or prevent removal of the patient. In situations where therapy must be applied by rescue teams, local conditions preclude most rewarming methods used in hospitals. Inhaltion rewarming has recently received much attention (Lloyd, 1973; Hayward and Steinman, 1975; Guild, 1976). The necessary equipment for instituting treatment can be condensed to a size which is readily portable (Lloyd, Conliffe, Orgel and Walker, 1972) and, as the method is non-invasive, it can be used by suitably trained non-medical personnel. Inhalation rewarming is now being practised by a small number of rescue services (Collis, Steinman and Chaney, 1977), in addition to being used as a treatment in hospitals.

Various opinions have been expressed regarding the effectiveness of inhalation rewarming. The heat gain is recognized to be small in comparison to normal metabolic heat production and it has been suggested that the benefit to core temperature is negligible (Hudson and Robinson, 1973). Lloyd, Mitchell and Williams (1976a) concluded that the main benefit of inhalation rewarming is derived from the elimination of respiratory heat loss rather than from additional heat supplied to the core. Protagonists of inhalation rewarming present equally strong arguments. As heat is distributed preferentially to the central core, a much smaller input may achieve significant rewarming results. Successful treatment of chronically hypothermic patients by inhalation rewarming alone have been reported by Lloyd (1973) and Lloyd, Conliffe, Orgel and Walker (1972).

Previous studies have shown that a close parallel exists between esophageal temperature and the temperature of the heart and great vessels during hypothermia in anaesthesized humans (Cooper and Kenyon, 1957). This has recently been confirmed in hypothermic humans under conscious experimental conditions (Hayward, 1979). Hayward and Steinman (1975) demonstrated that esophageal temperature showed no afterdrop but rather a rapid increase once inhalation rewarming began. A rapid delivery of heat to the heart might therefore be expected. Direct warming of

the endocardium via pulmonary venous return, coronary arterial warming of the myocardium, and mediastinal warming of the pericardium would minimize the possibility of ventricular fibrillation and would potentiate increased cardiac output (Rose, McDurmott, Lilienfield, Porfido and Kelly, 1957; Sabiston, Thielen and Gregg, 1955).

It has been claimed that inhalation rewarming as a therapy for hypothermia offers the following advantages:

1. Peripheral vasodilation is avoided, and hence, the hazards of rewarming shock and induction of ventricular fibrillation by cold, acidotic venous return are minimized (Hayward and Steinman, 1975; Collis, Steinman and Chaney, 1977).
2. Direct warming of the brain by conduction from the nasopharynx and circulation of warmed vertebral and carotid arterial blood occurs. Rewarming of the brain reverses cold-induced depression of the respiratory centres and stimulates consciousness in severe hypothermia (Hayward and Steinman, 1975; Collis, Steinman and Chaney, 1977).
3. Cold-induced depression of ciliary activity is reversed by direct thermal stimulation and hence any pulmonary congestion is cleared. Also, humidification liquifies congestion and mobilizes it for transport (Harnett, Sias and Pruitt, 1979).

4. Airway rewarming has a beneficial effect on cardiovascular status and cardiac rhythm out of proportion to the actual rise in core temperature. Clinical observations suggest a similar improvement in cerebral function (Lloyd, Mitchell and Williams, 1976b; Lloyd and Mitchell, 1974).

In a comparitive study, Collis, Steinman and Chaney (1977) showed that core temperature afterdrop was significantly reduced when inhalation rewaming was administered compared to shivering thermoqenesis alone. Experimental studies comparing the effectiveness of hot bath and inhalation rewarming found that hot bath rewarming produced a greater rise in rectal temperature than inhalation rewarming but the gain in tympanic temperature was slightly less (Hayward and Steinman, 1975). In contrast, Marcus (1978) showed that the effectiveness of inhalation rewarming in raising typmanic temperature was not significantly different from shivering alone and was significantly less than hot bath rewarming. A study comparing hot bath, inhalation and passive rewarming using anaesthetized, intubated sheep showed hot bath rewaming to be the best method for elevating core temperature (Lloyd, Mitchell and Williams, 1976a). Inhalation rewarming, however, showed considerable advantage over passive rewarming alone and the core/shell temperature gradients were more normal in inhalation rewarming than in hot bath rewarming. Auld, Light and Norman (1979) using lightly anaesthetized,

intubated dogs showed no difference in rewarming rates between shivering and inhalation rewarming.

The animal studies by Lloyd, Mitchell and Williams (1976a) and Auld, Light and Norman (1979) were carried out under anaesthesia. This not only decreases heat production by affecting the hypothalamic heat center, by inhibiting shivering, and by depressing metabolism to basal levels, but also increases heat loss by dilating the peripheral vasculature directly and by overcoming the vasoconstrictor response to cold (Burton and Edholm, 1955; Keatinge, 1969; Lloyd, Mitchell and Williams, 1976a). Anaesthesia would therefore slow the rewarming rate in shivering thermogenesis and inhalation rewarming; methods which rely on intrinsic metabolic activity as a major heat source (Burton and Edholm, 1955; Lloyd, Conliffe, Orgel and Walker, 1972). It would however, have a minimal effect on hot bath rewarming which is dependent on the physical transfer of heat from the water to the body.

A second problem with these studies was the animals were intubated. Normally, in airway rewarming, much of the heat gain which occurs takes place across the nasopharnyx (Keatinge from Marcus, 1979). Intubation would therefore reduce the effectiveness of inhalation rewarming.

Lloyd, Mitchell and Williams (1976a) observed that inhalation rewarming provided no additional benefit when the ventilatory rate is increased. This result is challenged by Pavlin, Hornbein and Chaney (1976) who showed that increasing ventilation increases the rate of temperature elevation in aneasthetized dogs (Table 2).

Suprisingly, there have been few serious attempts to calculate the effectiveness of inhalation rewarming as a heat source. This may be attributed to the difficulty of estimating the actual heat surrendered by the inhalate and its distribution through the airways. Hudson and Robinson (1973) estimated that the gain in body temperature from inhalation rewarming would be 0.03°C/hr based on a heat input of 13 Kcal/hr. They assumed however, that inhalation rewarming would have to provide 70 Kcal to produce a 1°C rise in core temperature. Lloyd, Conliffe, Orgel and Walker (1972) calculated a similar figure for respiratory heat input during rewarming of a profoundly hypothermic patient (core temperature 30°C) but pointed out that the elimination of respiratory heat loss amounted to a further 15 Kcal/hr heat gain if the air temperature was 0°C. In their calculation, Lloyd, Conliffe, Orgel and Walker (1973) ignored the potential benefits of the latent heat of condensation. Wessel, James and Paul (1966) examined blood temperatures in the aorta and pulmonary artery of the dog and found inhalation of

TABLE 2

EFFECT OF TWO DIFFERENT LEVELS OF VENTILATION ON CARDIOVASCULAR TEMPERATURE CHANGES OF ANAESTHIZED DOGS IN RESPONSE TO INHALATION REWARMING

	V_E = 6 litres/min Δ T (°C/hr)	V_E = 12 litres/min Δ T (°C/hr)
I. Vena Cava	0.6	2.5
S. Vena Cava	1.7	3.5
Pulmonary Artery	1.4	2.3
Left Ventricle	1.4	2.3

heated humidified gas warmed the blood as it passed through the pulmonary circulation. However it was also demonstrated that inhalation of heated dry gas cooled the blood as it passed through the pulmonary circulation. Shanks and Marsh (1973) calculated that if saturated air were inhaled, then the respiratory heat gain would be 9.2 Kcal/hr (core temperature 30°C; inhalate 40°C). Allowing that the profoundly hypothermic patient will have a low metabolic rate of approximately 54 Kcal/hr (Lloyd, Conliffe, Orgel and Walker, 1972), then the estimated difference in respiratory heat of 24 Kcal/hr offered by inhalation rewarming may become significant, particularly if it is applied directly tc the core.

The equivocal nature of the arguements presented regarding inhalation rewarming justifies further study to quantitatively determine the effect inhalation rewarming has on core temperature changes during rewarming from hypothermia. This controversy continues because there is a lack of accurate and adequately detailed scientific data to resolve arguements based largely on theoretical prediction. A thorough and detailed evaluation of inhalation rewarming is therefore needed.

C. FIELD STUDY

I. Introduction

A preliminary theoretical investigation was made to estimate the quantity of heat delivered by inhalation rewarming and to determine whether any modifications could be made to the inhalation rewarming technique which would increase delivery of heat to the patient.

When a completely water-saturated gas is used to rewarm a hypothermic subject there are two components in the saturated rewarming gas that contribute to the ability of the gas to rewarm the hypothermic victim. The first component is the convective heating ability of the gas. This heat is released when a warm gas inspired at an initial temperature (T_i) cools to a final temperature (T_e). The second component, condensatory heat gain, is due to condensation of water vapor when the saturated gas is cooled.

Strictly, convective heat gain (CONV) from a rewarming gas depends on the volume of gas ventilated ($\dot{V}$), the density of the gas (p), the specific heat of the gas at constant pressure (Cp) and the change in temperature of the gas ($T_i - T_e$). Thus:

$$CONV = (\dot{V} \times T \times p \times Cp)_i - (\dot{V} \times T \times p \times Cp)_e \quad (1)$$

where i and e denote inspired gas and expired gas respectively.

If inspired and expired ventilations are assumed to be equal and independent of gas mixture, the change in temperature is considered independent of gas mixture, and the inspired and expired density-specific heat products are assumed to be equal, then convective heat gain, assuming a constant ventilation and temperature drop, can be represented by the following modified equation.

$$CONV = \text{constant} \times (p \times Cp) \quad (2)$$

To maximize the convective heating ability of a rewarming gas, for a given ventilation and temperature drop, the density-specific heat product should be maximized. The results of this investigation, to determine the optimal gas mixture for convective heat delivery, is detailed in Table 3.

It may be seen that to ensure maximum convective heat gain, oxygen should be used; however, the convective heating ability of air is only fractionally smaller. Thus the only remaining avenue of increasing the convective heat gain is by increasing the ventilation or increasing the temperature drop of the gas. If it is assumed that the expired gas temperature is closely

TABLE 3

PHYSICAL CHARACTERISTICS OF GASES

Gas	p g/l	Cp cal/g	p·Cp cal/l
He	0.1785	1.242	0.2217
Ar	1.784	0.124	0.2212
H_2	0.0899	3.41	0.3066
Kr	3.736	0.059	0.2204
Ne	0.900	0.246	0.2214
N_2	1.2506	0.249	0.3114
O_2	1.429	0.219	0.3130
Xe	5.887	0.038	0.2237
Air	1.288	0.243	0.3127

related to core temperature then to increase the temperature drop, for a given core temperature, inspired temperature must be elevated.

Condensatory heat gain (COND) depends only on the mass of the water vapor that condenses and amount of heat that is released per unit weight of water vapor that condenses (latent heat of condensation). The mass of water vapor that condenses is:

$$\text{Mass of Water} = (\dot{V} \times p \times FH_2O)_i - (\dot{V} \times p \times FH_2O)_e \quad (3)$$

Where p= density of water vapor at STP = 0.8162 grams/liter

FH_2O = fraction of the gas mixture that is water vapor

The latent heat of condensation of water vapor, corrected for temperatures others than 20°C, is given by the following equation (Hoke, Jackson, Alexander and Flynn, 1976).

$$\text{Latent Heat} = \{590 - 0.55(T - 20)\} \text{ cal/gram} \quad (4)$$

Combining equations 3 and 4 produces the equation used to calculate condensatory heat gain.

$$COND = (\dot{V} \times 0.8162 \times \{590 - 0.55(T-20)\} \times FH_2O)_i - (\dot{V} \times 0.8162 \times \{590 - 0.55(T-20)\} \times FH_2O)_e \quad (5)$$

Condensatory heat gain depends on ventilation, %saturation or relative humidity of the respired gas and the inspired and expired gas temperatures. If the rewarming gas is 100% saturated then the only means of increasing condensatory heat gain are by increasing ventilation or increasing the temperature drop.

It has been suggested that the inhalation of warm moist air can be tolerated to temperatures as high as 50 to 60°C (Lloyd, Conliffe, Orgel and Walker, 1972; Moritz, Henriques and McLean, 1945). Several authors state however, that inspired temperatures over 45°C are not readily tolerated by hypothermic subjects (Hayward and Steinman, 1975; Lloyd, 1974; Collis, Steinman and Chaney, 1977; Shanks and Marsh, 1973; Guild, 1976). Tests have shown that inhalation of warm moist air above 47°C was 'unpleasantly hot' and above 50°C produced burning sensations (Guild, 1976). Lloyd (1973) refers to some laryngeal edema and tracheal scalding in an elderly patient following maximal humidifier treatment for acute hypothermia. Thus, increasing the subject's ventilation represents the only suitable means of increasing both the convective and condensatory heat delivered by a saturated rewarming gas.

The method chosen to increase the subject's ventilation was that of rebreathing expired gas. Hyperventilation could be controlled by adjusting the carbon dioxide fraction of the inspired gas mixture.

A second investigation was made to determine the relative contribution of convective and condensatory heat to the total respiratory heat gain (RH).

If the rewarming gas is air, inspired temperature is 45°C, expired temperature is 32°C, and inspired and expired ventilation are 20 l/min, then combining equations 1 and 5:

$$RH = CONV + COND \quad (6)$$

$$RH = 0.081 \text{ Kcal/min} + 0.513 \text{ Kcal/min}$$

$$RH = 13.6\% \text{ convective} + 86.4\% \text{ condensatory}$$

From this result, it is seen that most of the heat provided by inhalation rewarming is from the condensation of water vapor. Therefore for inhalation rewarming to be effective the rewarming gas must be 100% saturated.

The purpose of following experiment was to demonstrate that increasing respiratory heat input to mildly hypothermic subjects (by increased ventilation) produces increased core temperature gain. An attempt to quantify this increase in terms of core temperature rise per liter of increased ventilation was made.

II. Methods

Experiments were carried out under field conditions on the Pacific Coast of British Columbia. This particular study formed an integral part of a larger field study to test the effectiveness of different survival suits designed for cold water immersion (Hayward, Lisson, Collis and Eckerson, 1978). The experiments were conducted on a diving float, off which the subjects were immersed each day in the ocean. During the study, average water temperature was 11.8°C and average air temperature was 12.4°C.

Twenty volunteer, male subjects were selected as subjects. Selection was on the basis of minimizing inter-individual variation in body size and fatness which affect cooling rate (Timbal, Loncle, and Boutelier, 1976). Table 4 presents a summary of subject physical characteristics. All subjects were athletically active, passed cardiovascular-respiratory fitness tests, and met the requirements for informed consent, according to procedures outlined previously (Hayward, Eckerson, and Collis, 1975). Of the 20 subjects who participated in the survival suit study, 14 were chosen to participate in the inhalation rewarming study.

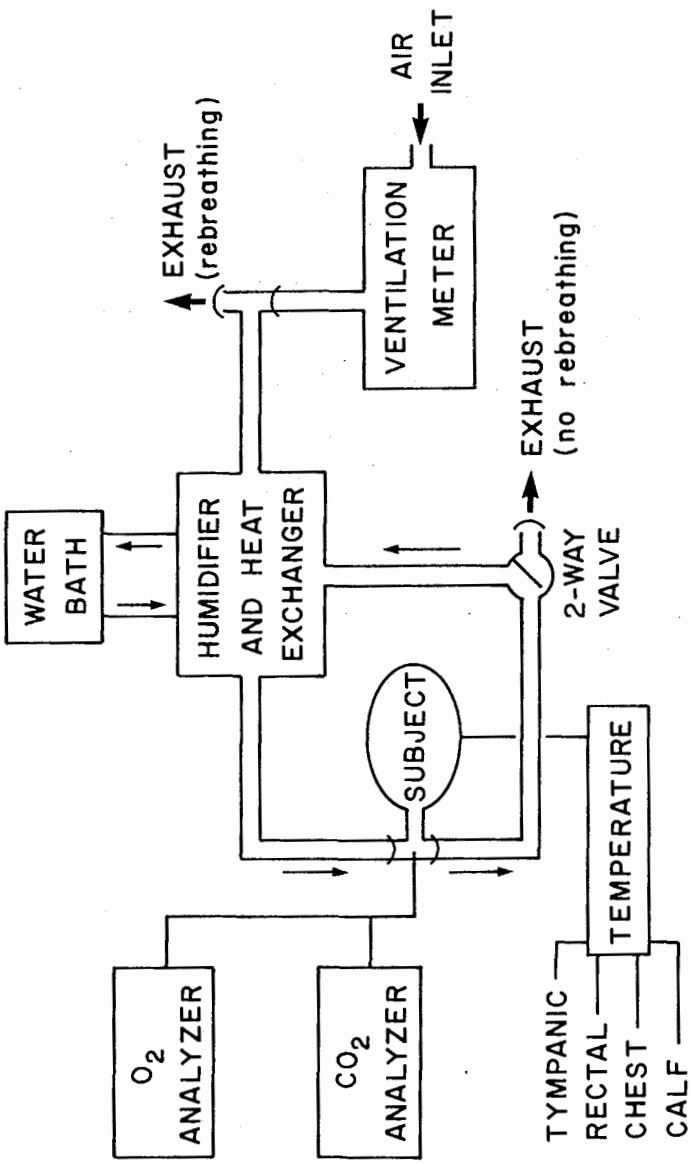
TABLE 4

PHYSICAL CHARACTERISTICS OF SUBJECTS IN FIELD STUDY (n=10)

Age (yrs)	22.0 ± 2.0
Weight (kg)	73.8 ± 1.3
Height (cm)	179.8 ± 1.6
Body Fat (%)	9.28 ± 0.44

A respiratory rewarming apparatus (Figure 1) was designed to supply hot moist gas at a controlled temperature. A feedback loop was incorporated into the apparatus to control the ventilatory response of the subject by rebreathing expired gas. Inspired air was heated and saturated by passing through a heat exchanger and humidifier unit. Warm water entered the top of the unit in the form of a spray and was removed at the bottom. The water was recycled to the unit through a thermostatically controlled water bath heated by an electric coil (HETO, T443). The subject inspired through a mouth-piece connected to the heat exchanger. Inspired gas temperature was measured by a thermistor (YSI type 401) placed immediately before the inlet valve of the mouth-piece. Gas temperature could be controlled to $\pm 1^{\circ}C$ by altering the thermostat setting of the water bath. Expired gas was either exhausted directly to the atmosphere or, by adjusting the two-way valve, was recirculated to the heat exchanger where it mixed with incoming air before exhausting to the atmosphere. The inspired carbon dioxide fraction could be controlled to the desired level by adjusting the proportion of expired gas recirculated. The ventilation of the subject was measured by passing incoming air through a dry gas-meter (Parkinson-Cowan) connected to the inlet of the heat exchanger.

Figure 1. Schematic diagram of the respiratory rewarming appartus and instrumentation used in the field study.


EXHAUST
(rebreathing)
AIR
INLET
VENTILATION
METER
EXHAUST
(no rebreathing)
WATER
BATH
HUMIDIFIER
AND HEAT
EXCHANGER
2-WAY
VALVE
SUBJECT
TEMPERATURE
O_2
ANALYZER
CO_2
ANALYZER
TYMPANIC
RECTAL
CHEST
CALF

Respiratory gases were measured by continuous sampling directly at the mouthpiece. Inspired and expired alveolar carbon dioxide fractions were analyzed by a rapid response infrared carbon dioxide analyser (Godart Statham). Corresponding oxygen fractions were analysed by a rapid response zirconium oxide oxygen analyser (Applied Electrochemistry S-3A).

Oxygen uptake ($\dot{V}O_2$) was calculated from inspired and expired alveolar gas fractions.

$$\dot{V}O_2 = \dot{V}_A \times \{F_i O_2 - (F_i N_2 / F_e N_2) \times F_e O_2\} \quad (7)$$

Where $\dot{V}_A = (1 - \dot{V}_D) \times \dot{V}_i$ (l/min STPD)

Respiratory deadspace ($\dot{V}_D$) was estimated from the data of Morrison, Butt, Florio and Mayo (1976) which relates minute ventilation and tidal volume and the data of Asmussen and Nielson (1956) which relates tidal volume and respiratory dead space.

Each day, one or two subjects underwent respiratory rewarming, the remainder being rewarmed using conventional hot bath rewarming. The subjects selected for respiratory rewarming were dressed either in shirt, jeans and life preserver or wore a

survival suit offering inadequate thermal protection. Rectal temperatures were measured by a thermistor (YSI type 401) inserted 15 centimeters beyond the anus. Temperatures were recorded at ten-minute intervals and the subjects were removed from the cold water when a 2°C drop in rectal temperature was registered.

On removal from the water, the subject entered a cabin on the dive float where he was stripped of clothing, dried lightly, and laid on a bunk. Skin thermistors (YSI type 409) were attached to the right chest in the region of pectoralis major and to the lateral aspect of the right calf. The subject was then covered with a blanket. A copper constantan thermocouple was inserted in the left auditory canal near the tympanum and sealed in position with soft wax. The rectal, skin and inspired gas temperature probes were connected to a temperature meter having a zero offset selector switch and expanded scale measuring 11°C fullscale deflection, read to $\pm$0.05°C.

The subject began breathing hot moist air from the respiratory rewarming apparatus six minutes after leaving the water. Inspired air temperature was controlled at 44°C. Minute ventilation, inspired and alveolar oxygen and carbon dioxide gas fractions, inspired gas temperature and rectal, tympanic, chest and calf temperatures were recorded at three minute intervals.

The experiment was terminated 36 minutes after exit from the water and the subject was then transferred to a hot bath for additional warming if necessary.

Each subject underwent respiratory rewarming on two occasions. During one protocol, the subject was rewarmed breathing air containing no carbon dioxide. Therefore, the level of ventilation varied according to metabolic rate. In the second protocol, the expired gas was recirculated through the heat exchanger and ventilatory response varied as a function of both metabolic rate and inspired carbon dioxide. The inspired carbon dioxide fraction was adjusted throughout the experiment in order to maintain a relatively constant ventilation of 45 to 50 l/min (BTPS).

As the experiments were carried out in the field and the primary objective was to establish the rate of cooling when wearing different types of protection, there was some variation in core and skin temperatures at the start of rewarming (Tzero). Analysis of the data of the 14 subjects showed a significant difference between the mean rectal temperatures at Tzero for the two methods of rewarming. These data showed a tendancy for the rate of rewarming to be influenced by core temperature at time Tzero presumably due to its effect on shivering metabolism. In order to eliminate this factor from the analysis, ten subjects

were selected such that the mean rectal temperatures at time Tzero, for the two rewarming methods, were balanced to $\pm 0.1^{\circ}C$.

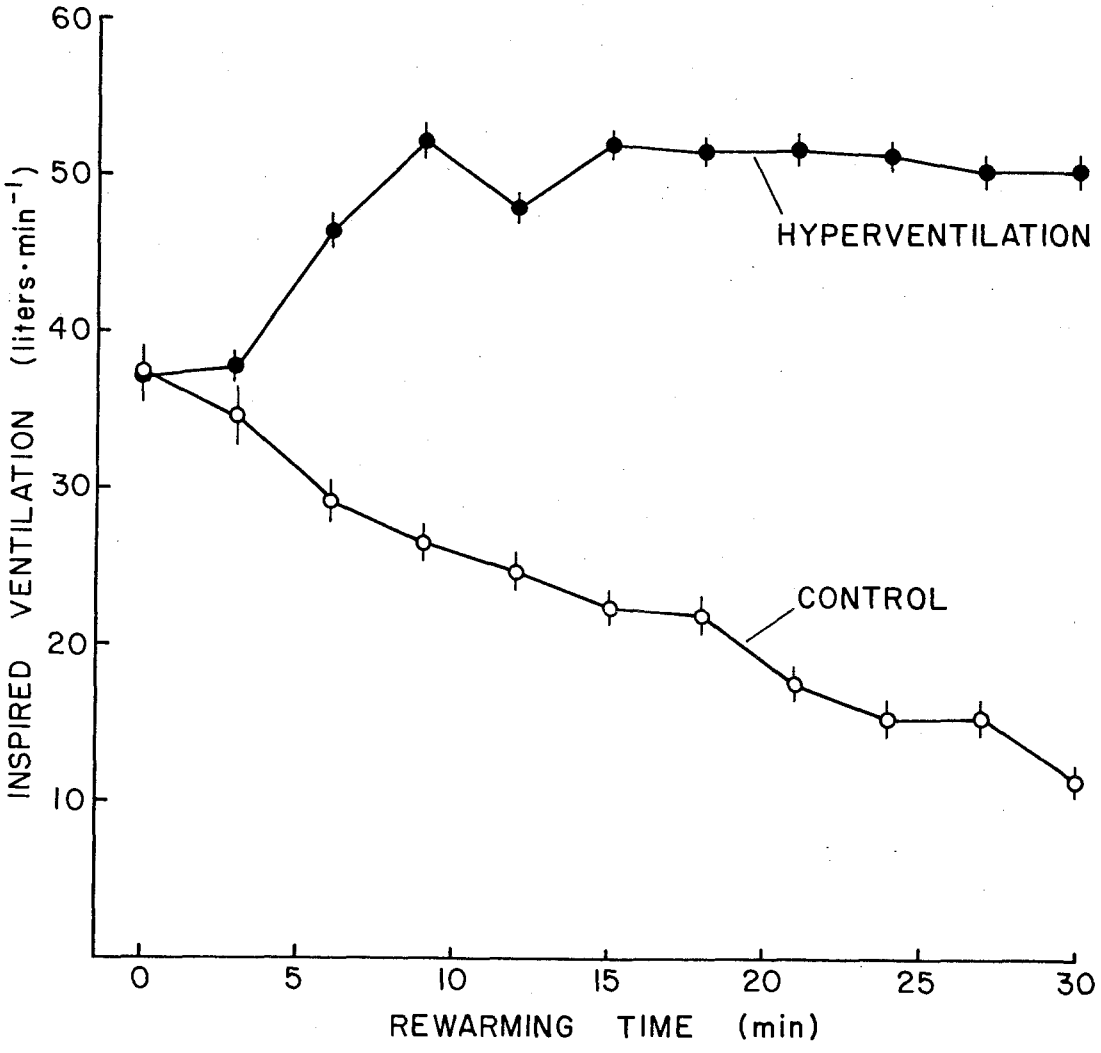
All data were quoted as the mean plus or minus the standard error of the mean. Differences in response between the two rewarming methods were analysed for significance by comparing the data sets (n=10) in a paired T-test.

III. Results

Ventilation

When breathing air, minute ventilation (BTPS) decreased rapidly with the decline of shivering from an initial value of 37.2 ± 1.4 l/min to 11.4 ± 0.7 l/min after 30 minutes of rewarming (Figure 2). In contrast, when rebreathing expired air, minute ventilation was increased from an initial value of 37.0 ± 1.6 l/min (no rebreathing in first 5 minutes) to 50 ± 2 l/min by ten minutes. This level of ventilation was maintained for the duration of the experiment.

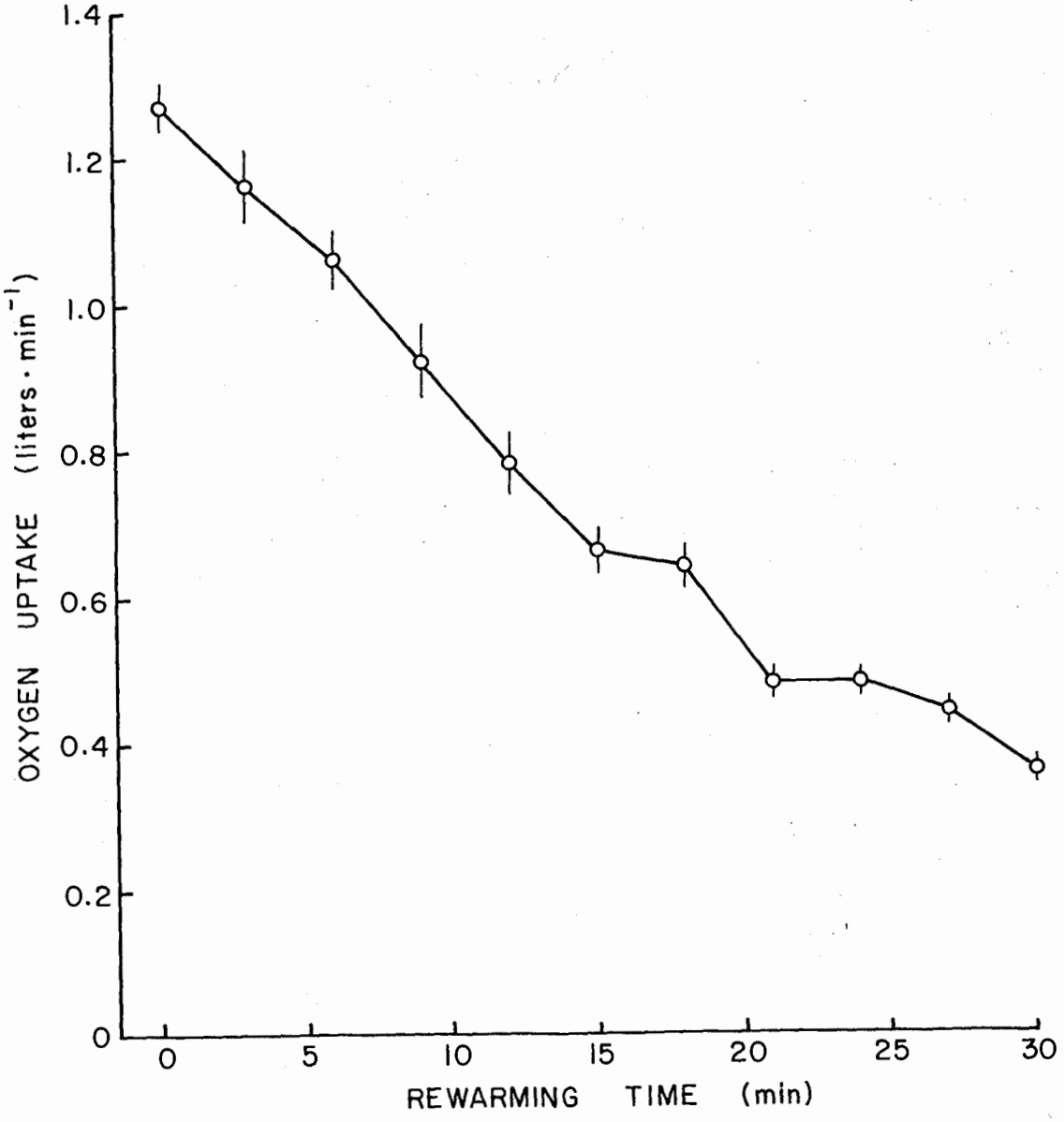
Figure 2. Comparison of inspired ventilation (l/min BTPS) during rewarming with normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Hyperventilation was controlled at approximately 50 l/min by rebreathing a fraction of expired air. During control ventilation varied in response to shivering thermogenesis. Mean data of 10 subjects. Vertical lines denote standard errors of means.


60
50
40
30
20
10
INSPIRED VENTILATION (liters·min⁻¹)
HYPERVENTILATION
CONTROL
0
5
10
15
20
25
30
REWARMING TIME (min)

Oxygen Uptake

Oxygen uptake was calculated only when breathing air (control rewarming). During controlled hyperventilation, the differences between inspired and alveolar oxygen and carbon dioxide values were insufficient to allow accurate measurement of oxygen uptake. Oxygen uptake varied greatly among the subjects, being dependent on the extent of shivering thermogenesis. Oxygen uptake was 1.27 $\pm$ 0.03 l/min in the first minute of rewarming and decreased rapidly at first and then more slowly to a value of 0.36 $\pm$ 0.01 l/min after 30 minutes of rewarming (Figure 3).

Figure 3. Oxygen uptake (l/min STPD) during rewarming with normal inhalation rewarming (control). Other conditions as in Figure 2.

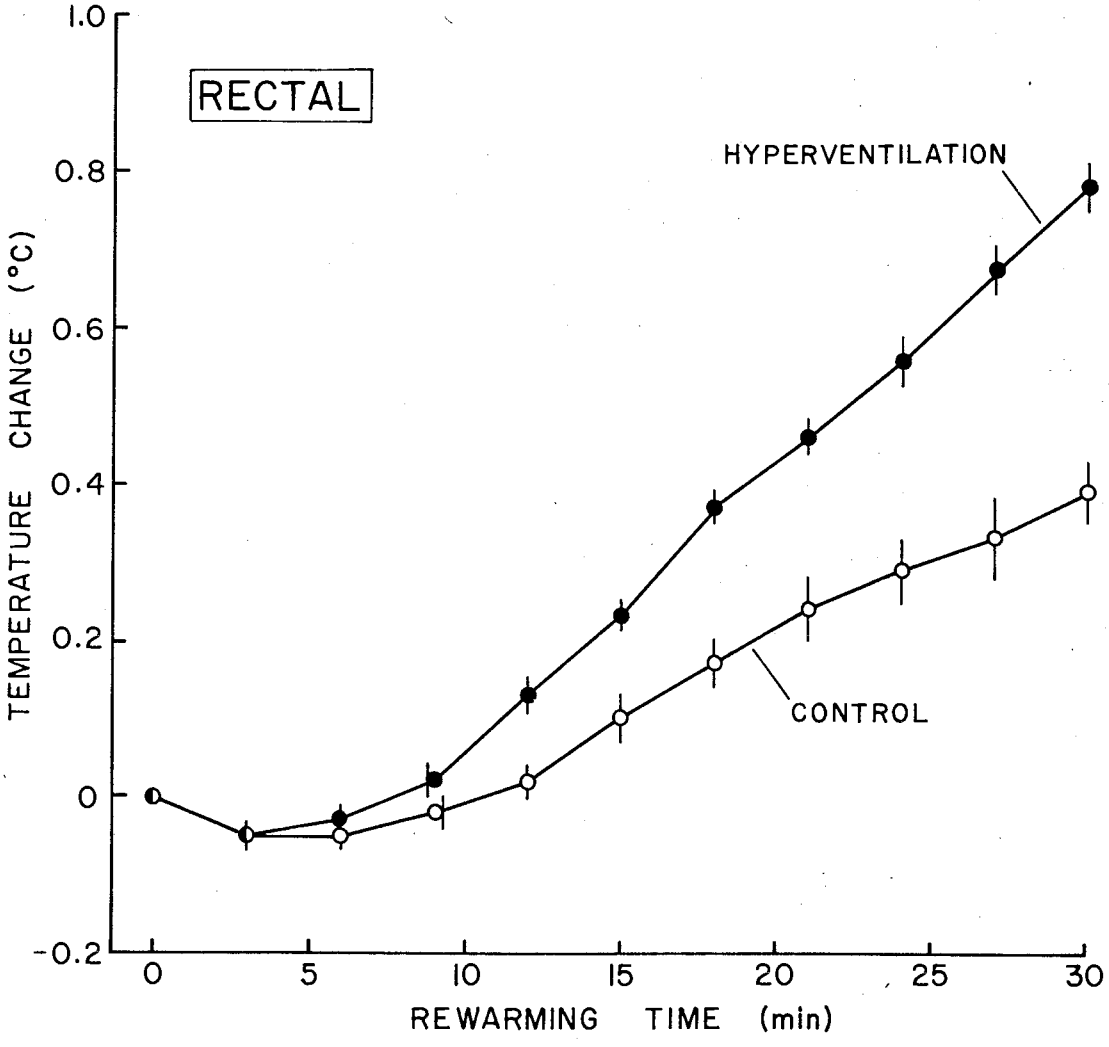

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
OXYGEN UPTAKE (liters · min⁻¹)
0
5
10
15
20
25
30
REWARMING TIME (min)

Core and Skin Temperatures

The rectal, tympanic and skin temperatures of each subject were normalized by subtracting the initial temperature (Tzero) from the temperature at any future time. The mean temperature changes of the 10 subjects were then calculated at time intervals of 3 minutes.

With both rewarming methods, rectal temperature (Figure 4) recorded a minimum value (Tad) within the first six minutes of rewarming. The mean gain in temperature at minute 30 was 0.39°C when breathing air, compared with 0.77°C when hyperventilating ($P < 0.01$). Using the mean data, a least squares regression line was fitted to the part of the curve in which the temperature was rising steadily (minutes 9 - 30). The regression equation gave a mean rise in rectal temperature of 1.21°C/hr when breathing air compared with 2.15°C/hr when hyperventilating. The means of the slopes of the individual regression lines, calculated for each subject, were significantly greater ($P < 0.1$) with controlled hyperventilation than with normal inhalation rewarming.

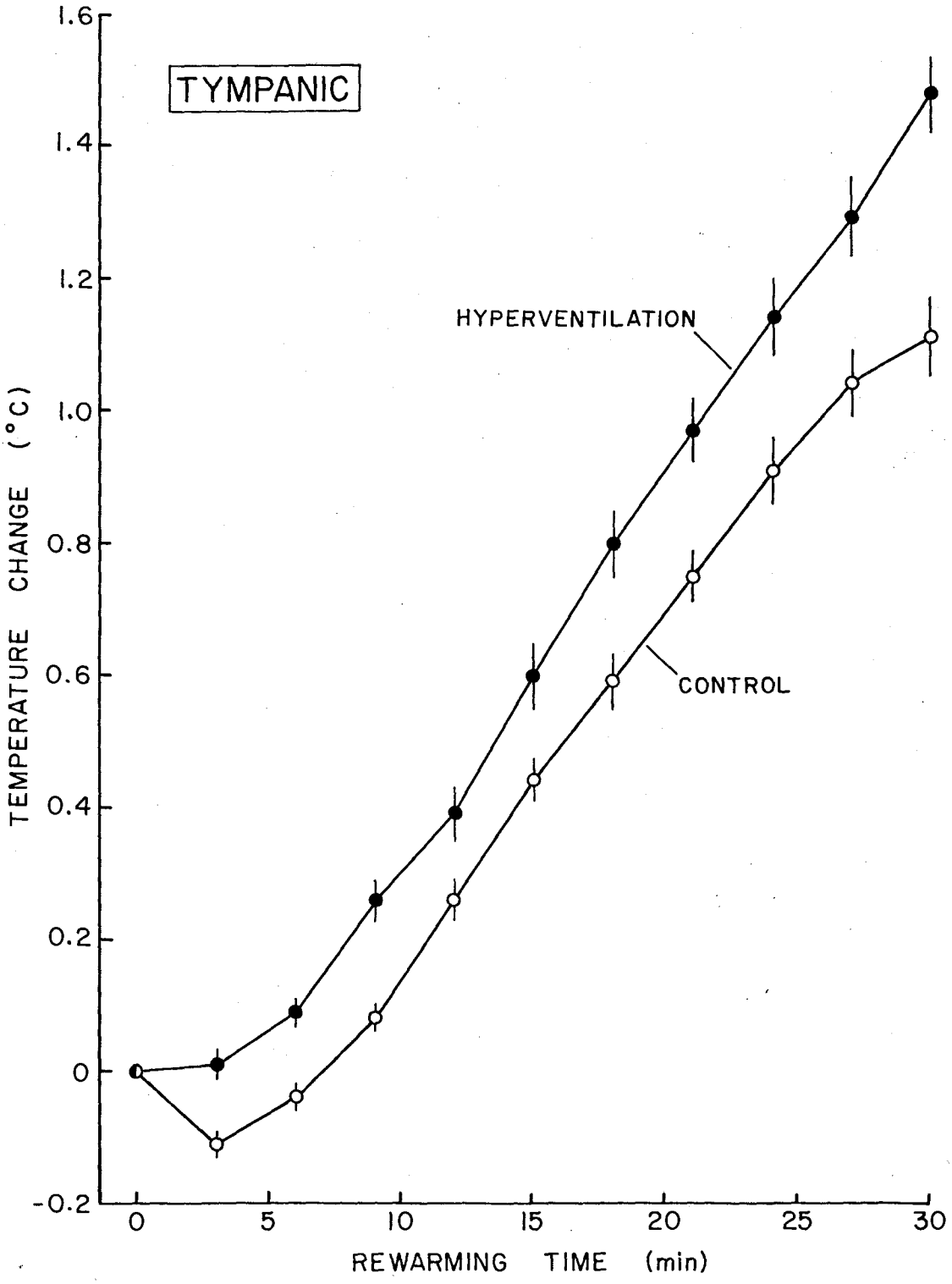
Figure 4. Comparison of rectal temperatre changes (°C) during rewarming with normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 2.


RECTAL
HYPERVENTILATION
CONTROL
TEMPERATURE CHANGE (°C)
1.0
0.8
0.6
0.4
0.2
0
-0.2
0
5
10
15
20
25
30
REWARMING TIME (min)

There was no difference in the magnitude of rectal temperature afterdrop (Tad = 0.5°C), but when breathing air, afterdrop duration was longer ($P < 0.1$). Two subjects failed to increase their rectal temperature above the initial value during the 30 minutes of rewarming when breathing air. In these subjects, rectal temperature tended to stabilise, the lowest temperature change at minute 30 being -0.35°C. In contrast, during controlled hyperventilation all ten subjects registered an increased rectal temperature.

Tympanic temperature gains (Figure 5) were considerably greater than corresponding rectal temperature gains ($P < 0.01$). The minimum value of mean tympanic temperature was recorded after 3 minutes of rewarming by breathing air. With hyperventilation, the mean data showed no afterdrop in tympanic temperature. The mean gain in tympanic temperature was 1.1°C when breathing air and 1.5°C when hyperventilating. The rate of gain in tympanic temperature from minute 6 to 30 was calculated using a least squares regression as described for the rectal temperatures. The regression equations gave a mean temperature gain of 3.0°C/hr when breathing air compared with 3.5°C/hr when hyperventilating.

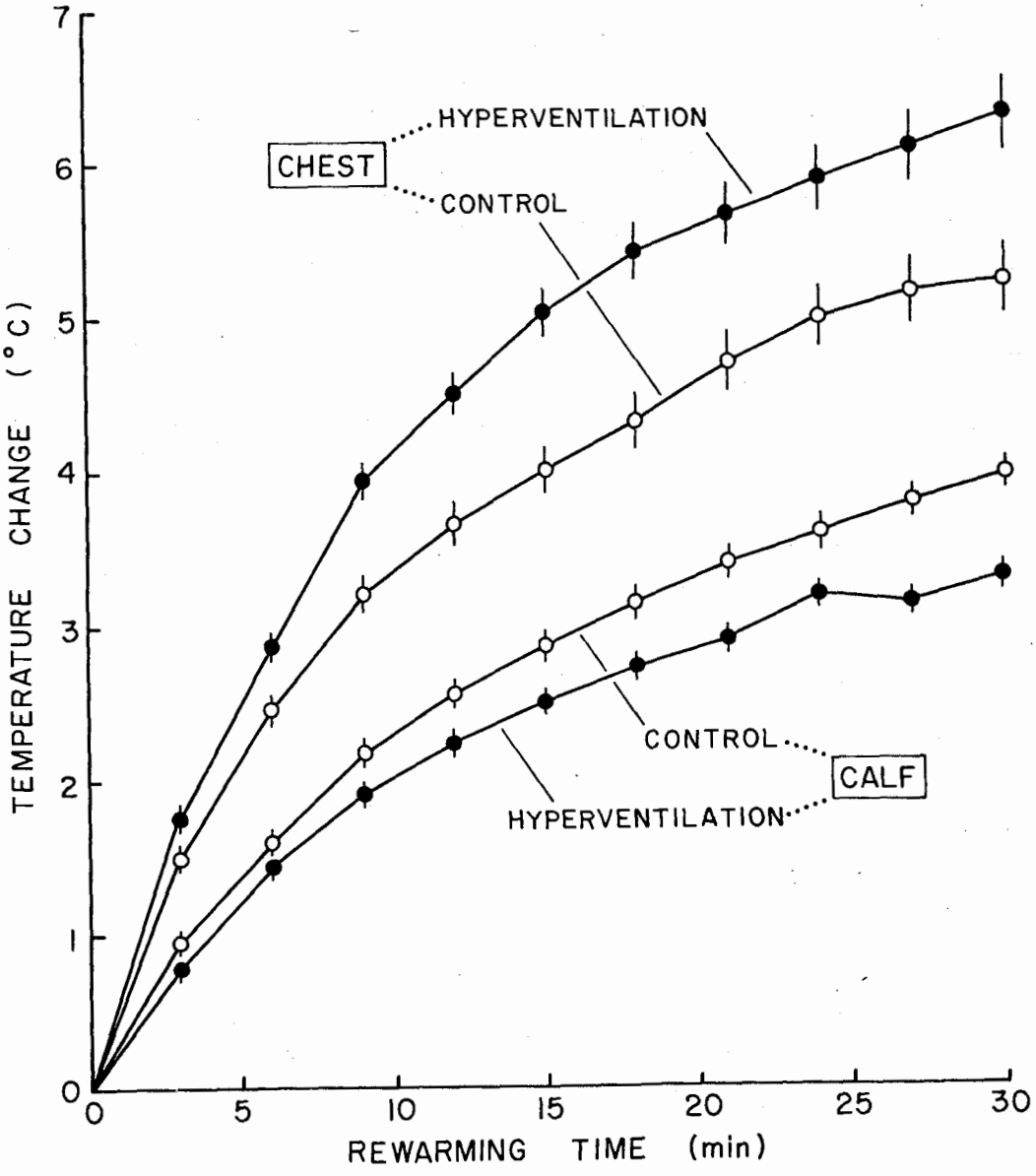
Figure 5. Comparison of tympanic temperatre changes (°C) during rewarming with normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 2.


TYMPANIC
HYPERVENTILATION
CONTROL
TEMPERATURE CHANGE (°C)
REWARMING TIME (min)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
0
5
10
15
20
25
30

The minimum tympanic temperatures recorded were lower and temperatures took longer ($P < 0.1$) to rise above their initial value when breathing air. For all subjects, respiratory rewarming achieved an increase in tympanic temperature above the initial value of Tzero during the 30 minute period.

The mean changes of chest and calf skin temperatures during the rewarming period are shown in Figure 6. Mean chest skin temperature rose 5.2°C when breathing air compared with 6.3°C when hyperventilating ($P < 0.1$) to reach an absolute value of 33.6°C in both cases. Calf skin temperatures rose 4.0°C during air breathing and 3.3°C during hyperventilation ($P < 0.1$) to reach a common absolute value of 24.7°C.

Figure 6. Comparison of chest and calf temperature changes (°C) during rewarming with normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 2.


HYPERVENTILATION
CHEST
CONTROL
CONTROL
CALF
HYPERVENTILATION
TEMPERATURE CHANGE (°C)
REWARMING TIME (min)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30

IV. Discussion

The only treatment differences between the two rewarming methods was the respiratory stimulus. Thus, the difference in rewarming rate (°C/hr) resulted from the difference in ventilatory rate. The rewarming data of Figures 2 and 4 show that after 30 minutes of inhalation rewarming an additional 741 litres of ventilation resulted in a rectal temperature gain of 0.38°C (hyperventilation - control). This yields an increase of core (rectal) temperature of 5.1×10^{-4} °C/litre of additional ventilation. If this value is taken to represent the effectiveness of hyperventilation, then each additional 10 l/min of inhalation rewarming will increase core (rectal) rewarming rate by 0.3°C/hr.

As core temperature gain was greater when hyperventilating, shivering thermogenesis may have been less when breathing air. This effect on metabolic rate would be somewhat offset, however, by the increased work of breathing. The "inhalation rewarming factor" (°C/litre) calculated above, therefore, encompasses both increased respiratory heat gain and changes in metabolic rate caused by the treatment. In order to obtain a more accurate measure of respiratory heat gain per se, a laboratory study was

required in which metabolic rates, respiratory heat exchange, and body heat losses could be monitored.

Tympanic temperatures increased considerably faster than rectal temperatures (Figures 4 and 5). This could have been caused by an artifact such as air passing through the eustachian tube during a valsalva manoeuvre. An erratic recording would have been expected however, whereas a smooth, continuous gain was recorded. A more likely explanation is that perfusion of the head is proportionately greater than that of the abdomen, and applying heat at the nasopharynx prevents heat loss from the head to colder areas of the body.

Hyperventilation had a greater effect on the rate of change in rectal temperature than in tympanic temperature, although the absolute effects were of a similar magnitude. One possible explanation is that tympanic temperature is more sensitive to heat conduction across the upper airways and nasopharynx and thus more dependent on inspired gas temperature rather than ventilatory rate. When inhalation rewarming is applied, tympanic temperature may be a better indicator of CNS temperature change than of general core temperature changes.

Results shown in Figures 4 and 5 agree with the findings of Pavlin, Hornbein and Chaney (1976) who noted that when the ventilation of anaesthetized dogs was increased from 6 l/min to 12 l/min, the rate of core temperature elevation was greatly enhanced. In contrast, Lloyd, Mitchell, and Williams (1976) found that assisted ventilation had no significant effect on the rate of rewarming of sheep. This discrepancy may result from a difference in the relative humidity of inspired air. The potential respiratory heat gain from inhalation rewarming is derived largely (80 to 90%) from the latent heat of condensation. Thus, inhalation of unsaturated gas (eg. 70% relative humidity) will have little effect other than eliminating respiratory heat loss.

Marcus (1978) found that inhalation of hot moist air had no significant effect on the rate of tympanic rewarming. The rewarming rates quoted by Marcus must be treated with caution however, as they are based on tympanic temperatures of only four subjects and it is doubtful whether all the subjects were truly hypothermic (mean rectal temperature 36.4 $\pm$ 0.6°C). Rectal temperatures shown in Figure 4 contradict the claim of Marcus that rectal core temperature is not a suitable measure for comparing rewarming techniques in acute hypothermic conditions.

A factor to be considered in evaluating the effectiveness of induced hyperventilation for rewarming is that the relative benefit is in proportion to ventilation decrement. Because spontaneous ventilation is initially high (Figure 2) due to shivering thermogenesis, the potential for improved heat transfer by further ventilation increase is limited. Therefore, during the important early phase of rewarming, where treatment is oriented towards minimizing afterdrop, hyperventilation is of less value. Its benefits become greater during the temperature increment phase of rewarming when spontaneous ventilation and shivering thermogenesis are decreasing. The foregoing is important in appreciating the different situation that applies between mild or moderate hypothermia and severe hypothermia. In the first case, increased spontaneous ventilation will facilitate inhalation rewarming, whereas in severe hypothermia, metabolism would be depressed to approximately 60% of its normal resting value (Lloyd, Conliffe, Orgel, and Walker, 1972) and the ability to administer heat via the respiratory tract would be limited. Theoretical considerations indicate that if ventilation were depressed to 5 l/min, the net change in (rectal) temperature derived from respiratory heat gain would be approximately 0.15°C/hr. If inhalation rewarming is to be attempted in such cases, a degree of hyperventilation may be necessary in order to convert core temperature change from a negative to a positive rate. While hypercapnia can be tolerated

in mild hypothermia, in severe cases it should be avoided. Hyperventilation could only be applied provided acid-base balance was maintained.

In conclusion, hyperventilation of 44°C saturated gas offers an improvement in the rate of core rewarming from mild hypothermia. This study was designed to quantify the relationship between core rewarming rate and ventilatory rate and an inhalation rewarming factor of 5.1×10^{-4} °C/litre was obtained for rectal core temperature gain. As heat gain is dependent on ventilatory rate, controlled hyperventilation should be beneficial particularly where metabolism is depressed.

D. LABORATORY STUDY

I. Introduction

Inhalation rewarming has been promoted as a safe rewarming process which can be easily administered to cases of hypothermia in remote environments (Lloyd, Conliffe, Orgel and Walker, 1972; Hayward and Steinman, 1975; Collis, Steinman and Chaney, 1977). The effectiveness of inhalation rewarming as a heat source has been questioned however, (Hudson and Robinson, 1973; Marcus, 1978) and the results of experimental studies are contradictory (Hayward and Steinman, 1975; Collis, Steinman and Chaney, 1977; Marcus, 1978). The rate of rewarming will vary not only with the heat supplied by the rewarming technique, but also with the metabolic heat production and heat losses from the core during rewarming. Metabolic heat production will be largely dependent on core and skin temperatures (Hayward, Eckerson and Collis, 1977), while heat losses will be largely dependent on temperature gradients within the body and the environmental conditions.

Studies which have shown no significant differences between inhalation rewarming and shivering thermogenesis have implied that metabolic heat production is not altered by respiratory heating (Auld, Light and Norman, 1979; Marcus, 1978). However,

in a study comparing various rewarming methods (Collis, Steinman and Chaney, 1977) subjects reported subjectively that shivering was greatest when no additional means of rewarming was administered. This implies that the ability of the mildly hypothermic subject to rewarm himself through shivering thermogenesis was reduced by active rewarming. If the magnitude of heat delivered during treatment with an active rewarming technique approximated the magnitude of heat production lost through inhibition of shivering thermogenesis, then no significant difference in the efficacy of the therapies might be expected.

If it may be shown that respiratory heat is at least as effective as metabolically produced heat in rewarming the core from depressed states, then inhalation rewarming must be considered a viable therapy in the treatment of hypothermia.

The purpose of the present experiment was to quantify the contributions made by metabolic heat production and respiratory heat input to the elevation of core temperature during rewarming from mild hypothermia.

II. Methods

Hypothermia was induced on three occasions in each of ten subjects. Each subject was then rewarmed, on one occasion by normal inhalation rewarming (control), on another by hyperventilation inhalation rewarming (hyperventilation), and on another by shivering thermogenesis (shivering). To minimize habituation and circadian effects on the resultant rewarming rates the experiments were started at the same time each day and sequence of the three treatments were varied.

Cold immersions took place in the laboratory in order to minimize variations in water and air conditions. The immersion posture was standardized so that the head remained clear of the water, while the neck and remainder of the body were completely immersed. Subjects made a minimum of voluntary movements and maintained their position by sitting on an aluminum bench insulated with a 1 cm neoprene covering. The temperature of the water was maintained at 11.3 $\pm$ 0.1°C. The average air temperature during the study was 21 $\pm$ 2°C.

Ten healthy, male, volunteer subjects, all athletically active, were selected for the study. Table 5 provides a summary

of subject physical characteristics. After having satisfied the rigid medical and safety criteria stipulated by the university ethics committee and detailed below, subjects were allowed to participate in this study.

1. Subjects were given an informed consent which described subject involvement in the study and a Standard Kinesiology Medical Form and were required to have a physician examine them. If the physician was satisfied that the subject was in good health and could safely participate in the test, he provided the subject with written authorization to that purpose.
2. After written authorization was obtained, the subject underwent a modified Sjostrand work capacity test (PWC 170). The test consisted of pedalling a bicycle ergometer for four work periods of five minutes each at a pedalling frequency of 80 revolutions per minute. The first work period was a warm-up, conducted with no brake load. The remaining three work periods were conducted at increasing brake loads and designed to elicit heart rates of 120, 140 and 160 beats per minute respectively. After each work period there was a 30 second rest period, during which the subject's blood pressure was taken. Electrocardiogram (ECG) activity was monitored continuously throughout the test.
3. The data from the test was used to determine the subject's

TABLE 5

PHYSICAL CHARACTERISTICS OF SUBJECTS IN LABORATORY STUDY (n=10)

Age (yrs)	25.4 ± 1.5
Weight (kg)	72.9 ± 2.7
Height (cm)	181.6 ± 1.9
Body Fat (%)	8.4 ± 0.5
PWC 170 (Kpm/Kg)	20.4 ± 1.0
Fitness (Percentile)	93.4 ± 2.1

percentile fitness using the C.A.H.P.E.R. norms (Metivier and Orban, 1968). No subject who rated less than at the 80th percentile was used in this study. The high level of fitness was demanded for two reasons, the most important of which was subject safety. The secondary reason was that fitness level may affect physiological responses to cold (Leblanc, Cote, Dulac and Turcot, 1977). In addition, all ECG and blood pressure data were analysed for abnormalities by an independent physiologist experienced in interpretation of cardiac data. Only those subjects who satisfied every phase of the above procedure were used in our experiments. Rejection rate was approximately 50% of the volunteers who expressed interest and 25% of those who underwent preliminary fitness testing.

Core temperatures were recorded at the tympanic membrane and rectum. Tympanic temperature was monitored by a copper constantan thermocouple inserted in the left auditory canal and sealed with soft wax. Rectal temperature was monitored by a thermistor (YSI type 701) inserted 15 cms beyond the anus. Copper constantan thermocouples were attached to the skin surface to monitor skin temperature and mean skin temperature (MST) was calculated according to Ramanathan (1964).

$$MST = 0.3(arm + chest) + 0.2(thigh + calf) \quad (8)$$

To assure skin temperature was measured and not water temperature the thermocouples were taped to the skin, covered with a gauze pad and then covered with a 0.5 inch diameter plastic cup.

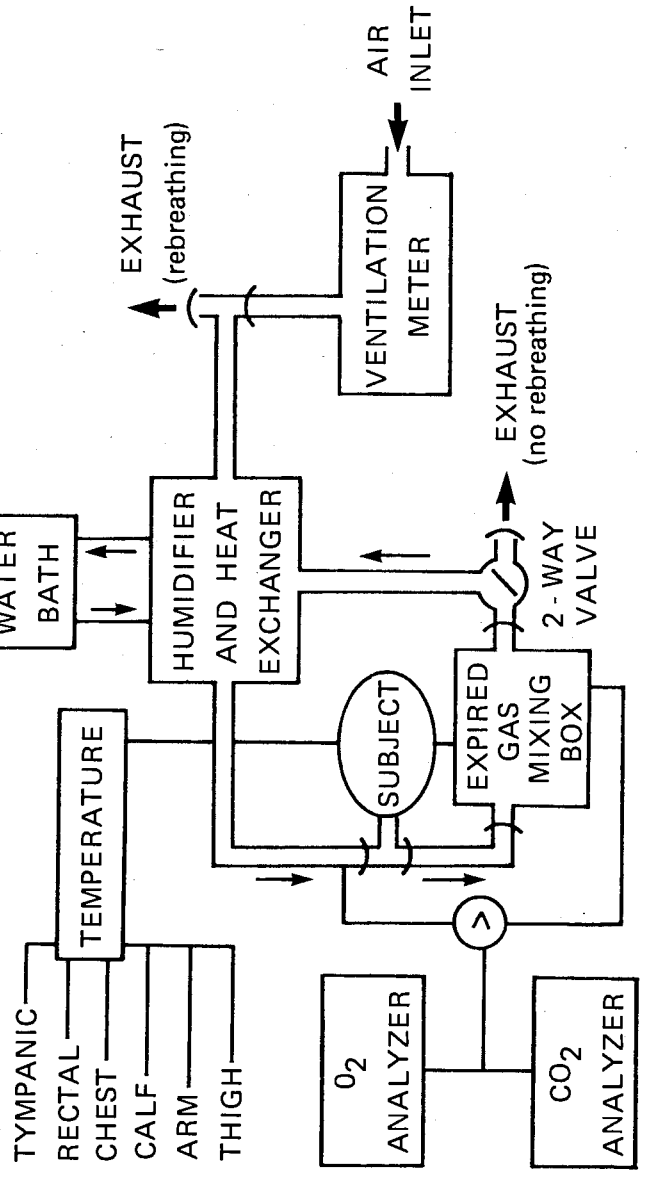
During immersions, the subject was under the constant surveillance of the experimenters. ECG activity was monitored during both cooling and rewarming phases of the experiment. Immersion was terminated when the subject's rectal temperature reached 35.0°C. The subject was helped from the water on the completion of immersion and lightly dried with towels. The subject was then placed supine on an adjacent mattress and enclosed within a sleeping bag. The purpose of the bag was to insulate the subject from room air and keep skin temperature low (i.e. maintain developed vasoconstriction). This tactic maintained maximum shivering thermogenesis and the skin temperatures reflected peripheral temperature changes rather than room air temperature. The time interval from leaving the water to initiation of rewarming was six minutes. After each immersion, the subject was rewarmed by a different rewarming technique.

The respiratory rewarming apparatus described in the field study underwent minor modifications for use in the present study (Figure 7). The modifications were an expired gas mixing box

inserted between the subject and the two-way valve used to control rebreathing, and 2 cm neoprene insulation wrapped around the inlet and outlet breathing hoses. The mixing box allowed accurate measurement of subject's expired gas while the neoprene insulation prevented heat losses and afforded stable reading of inspired and expired gas temperatures.

Inspired respiratory gas was measured by sampling close to the mouthpiece, immediately before the inlet valve. Mixed expired gas was measured by sampling directly at the distal end of the expired gas mixing box. Inspired and mixed expired carbon dioxide fractions were analysed alternately by a rapid response infrared carbon dioxide analyser (Godard Statham). Corresponding oxygen fractions were analysed by a rapid response zirconium oxide oxygen analyser (Applied Electrochemistry S-3A). Instruments were calibrated with the use of 3 primary standard gas mixtures (accurate to 0.02%) at the beginning and end of each experiment. Oxygen uptake was calculated from inspired and mixed expired gas fractions during all rewarming trials. Metabolic heat production was calculated assuming a metabolic equivalent for oxygen of 4.8 Kcal/liter.

Figure 7. Schematic diagram of the respiratory rewarming apparatus and instrumentation used in the laboratory study.


AIR
INLET
EXHAUST
(rebreathing)
VENTILATION
METER
EXHAUST
(no rebreathing)
WATER
BATH
HUMIDIFIER
AND HEAT
EXCHANGER
2 - WAY
VALVE
SUBJECT
EXPIRED
GAS
MIXING
BOX
TEMPERATURE
TYMPANIC
RECTAL
CHEST
CALF
ARM
THIGH
O_2
ANALYZER
CO_2
ANALYZER

All temperature and respiratory gas data were recorded by a programmable data logger (Kaye Instruments) having 10 thermocouple inputs connecting to an internal ice point reference and 10 voltage inputs. The experiment was terminated after 60 minutes of rewarming and the subject was then transferred to a hot bath for additional warming.

Temperature and respiratory data were also collected during the cooling phase of each experiment. Four head temperatures (forehead, right and left cheek and chin) and four sleeping bag temperatures were monitored during rewarming. These additional data were collected for research projects that were not part of this thesis.

All data were expressed as mean $\pm$ SEM. Differences in response between the three rewarming methods were first analyzed for statistical significance by a repeated measures analysis of variance (BMDP2V; BMDP Manual, 1977). Significant differences between rewarming methods were then determined by a Tukey Post-Hoc test (Kirk, 1968).

III. Results

Ventilation

Mean inspired minute ventilation was calculated at minute 2, 4 and then at 4 minute intervals for the remainder of the rewarming period (Figure 8). A summary of inspired ventilation during rewarming is given in Table 6.

The initial ventilation reading was higher ($P < 0.05$) for shivering than for both control and hyperventilation. For shivering and control, minute ventilation decreased exponentially from the initial values, with reduction in metabolic rate, to approximately 9 l/min after 60 minutes of rewarming. The average inspired minute ventilation for the entire rewarming period was higher ($P < 0.05$) for shivering (21.7 l/min) than for control (17.2 l/min). The average inspired minute ventilation for hyperventilation was 39.6 l/min.

Figure 8. Comparison of inspired ventilation (l/min BTPS) during rewarming from hypothermia by shivering thermogenesis (shivering), normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). During shivering subjects spontaneously ventilated room air (21 ± 2°C), during control subjects spontaneously ventilated saturated air (47 ± 1°C) and during hyperventilation subjects ventilated saturated air (47 ± 1°C) at approximately 40 l/min. Mean data of 10 subjects. Vertical lines denote standard errors of means.

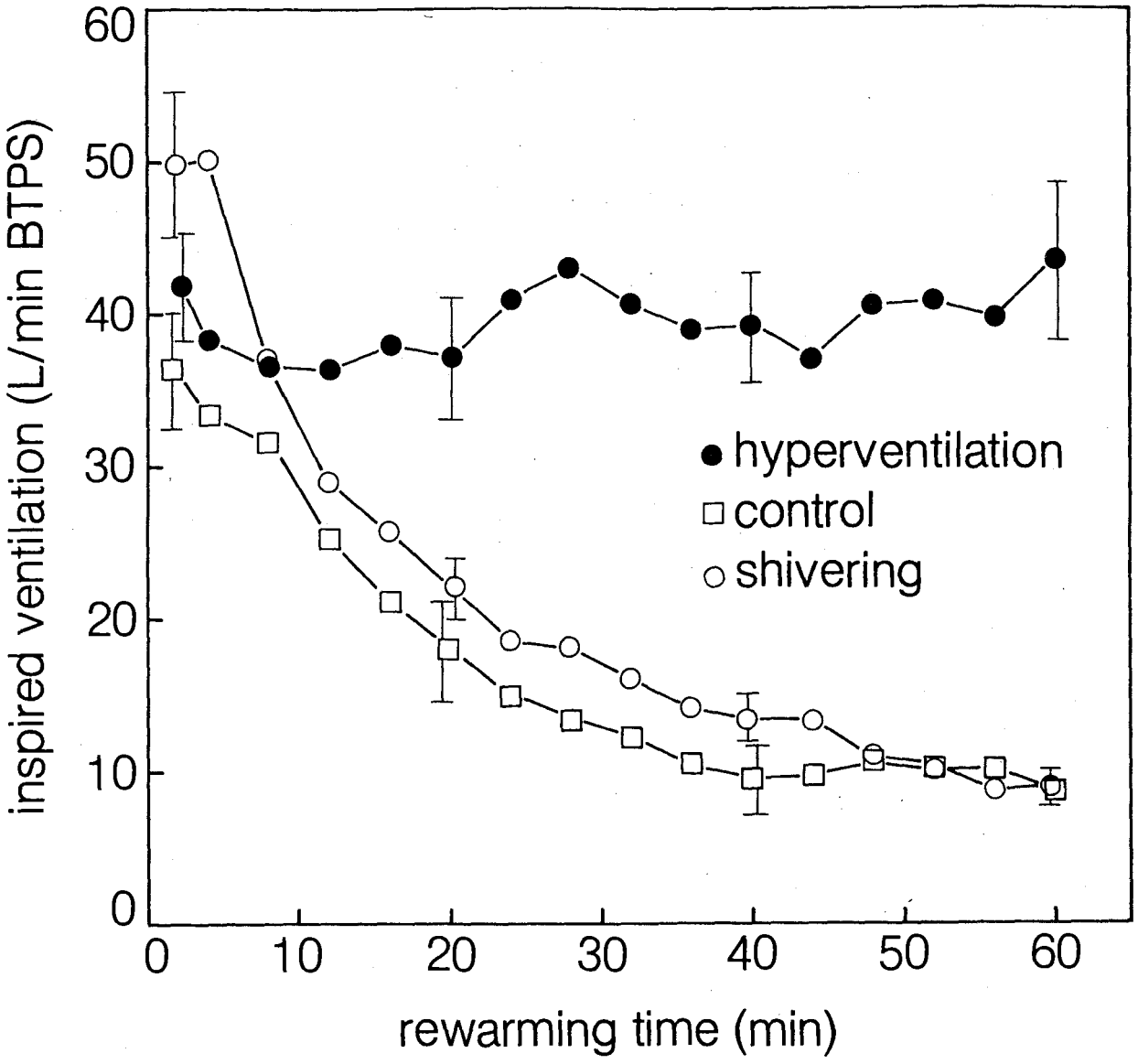

60
50
40
30
20
10
0
inspired ventilation (L/min BTPS)
0
10
20
30
40
50
60
rewarming time (min)
hyperventilation
control
shivering

TABLE 6

COMPARISON OF INSPIRED VENTILATION
DURING REWARMING FROM HYPOTHERMIA
(l/min - BTPS)

	Shivering	Control	Hyperventilation
Initial	49.8 ± 4.3	36.3 ± 8.8	42.0 ± 4.1
Final	9.0 ± 1.1	8.9 ± 1.1	43.5 ± 5.1
Average	21.7 ± 4.1	17.2 ± 3.0	39.6 ± 0.7

Oxygen Uptake

Oxygen uptake ($\dot{V}O_2$) was calculated at the same time intervals as inspired ventilation. Mean oxygen uptake versus time is shown in Figure 9. A summary of oxygen uptake during rewarming is provided in Table 7.

The initial $\dot{V}O_2$ reading was higher for shivering than the two inhalation methods ($P < 0.05$). During all rewarming procedures $\dot{V}O_2$ decreased exponentially towards basal metabolism. This decrease was most rapid in hyperventilation while shivering showed the slowest decrease in $\dot{V}O_2$. This is shown by total oxygen consumed and mean oxygen uptake during rewarming. Thus, mean oxygen uptake was greater ($P < 0.05$) for shivering (0.76 l/min) than mean oxygen uptake for either control (0.64 l/min) or hyperventilation (0.51 l/min). Also, mean oxygen uptake was greater for control than for hyperventilation ($P < 0.05$).

After the initial rapid decrease, $\dot{V}O_2$ decreased more slowly to a value of 0.33 ± 0.01 l/min after 60 minutes for all three rewarming methods.

Figure 9. Comparison of oxygen uptake (l/min STPD) during rewarming from hypothermia by shivering thermogenesis (shivering), normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 8.

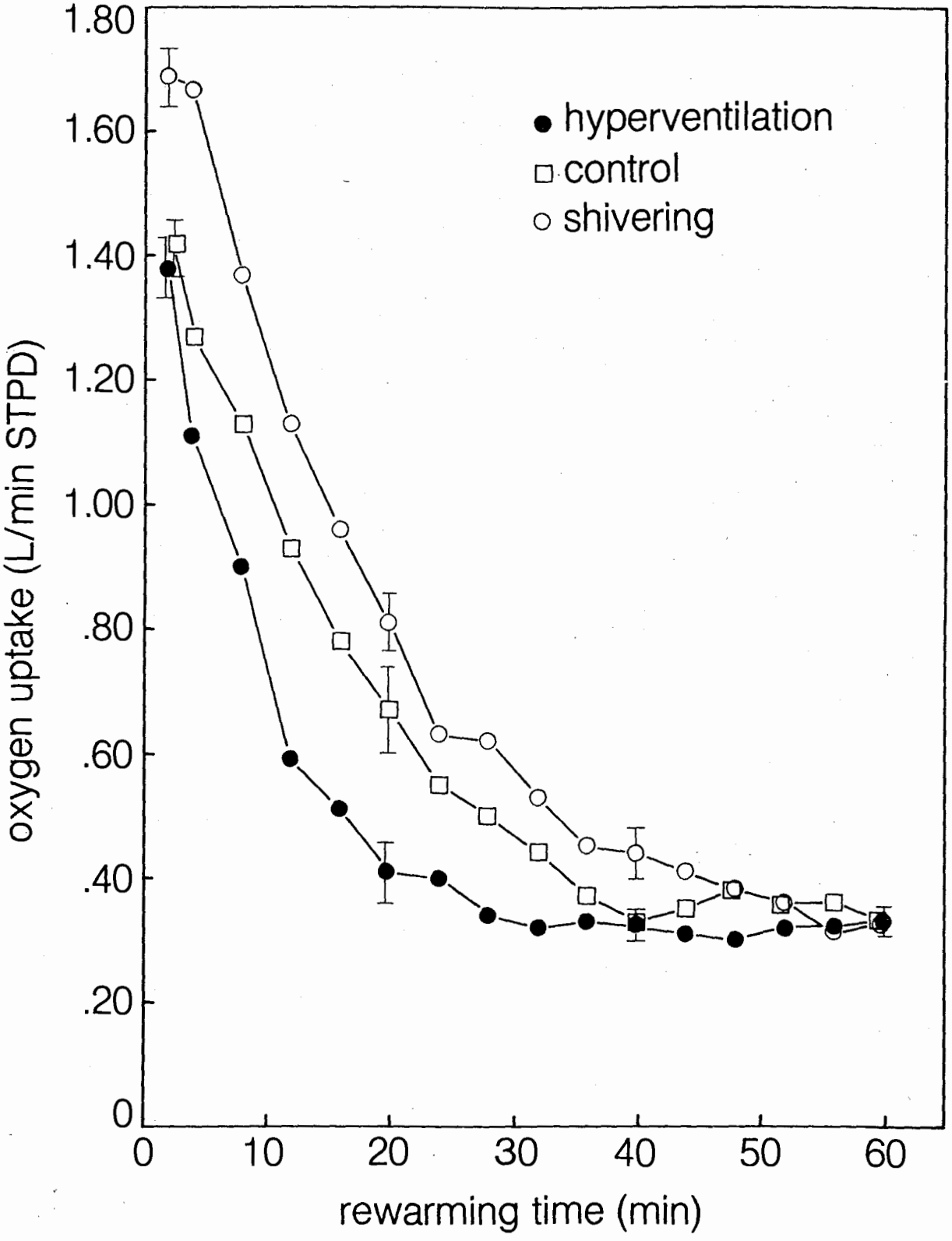

1.80
1.60
1.40
1.20
1.00
.80
.60
.40
.20
0
oxygen uptake (L/min STPD)
hyperventilation
control
shivering
0
10
20
30
40
50
60
rewarming time (min)

TABLE 7

COMPARISON OF OXYGEN UPTAKE
DURING REWARMING FROM HYPOTHERMIA

	Shivering	Control	Hyperventilation
Initial (l/min - STPD)	1.69 ± 0.13	1.42 ± 0.13	1.38 ± 0.16
Final (l/min - STPD)	0.33 ± 0.01	0.33 ± 0.01	0.33 ± 0.01
Average (l/min - STPD)	0.76 ± 0.15	0.64 ± 0.11	0.51 ± 0.10
Total (l/hr - STPD)	45.4 ± 1.3	38.1 ± 1.1	30.5 ± 1.0

Respiratory Heat Input

Respiratory heat input (RH) was calculated at the same time intervals as inspired ventilation. The mean RH data versus time for each of the 3 rewarming methods is shown in Figure 10. A summary of RH during rewarming is provided in Table 8.

Respiratory heat input under these experimental conditions depended on inspired temperature and ventilation. Thus, as expected, RH was greatest for hyperventilation and negative (ie a net heat loss) for shivering.

The initial values of RH (minute two) for shivering (-0.37 kcal/min) and control (0.74 kcal/min) decreased exponentially in reponse to the decrease in ventilation to -0.06 kcal/min and 0.19 kcal/min respectively. For hyperventilation RH was maintained at approximately 0.70 kcal/min during the entire period of rewarming.

Figure 10. Comparison of respiratory heat input (kcal/min) during rewarming from hypothermia by shivering thermogenesis (shivering), normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 8.

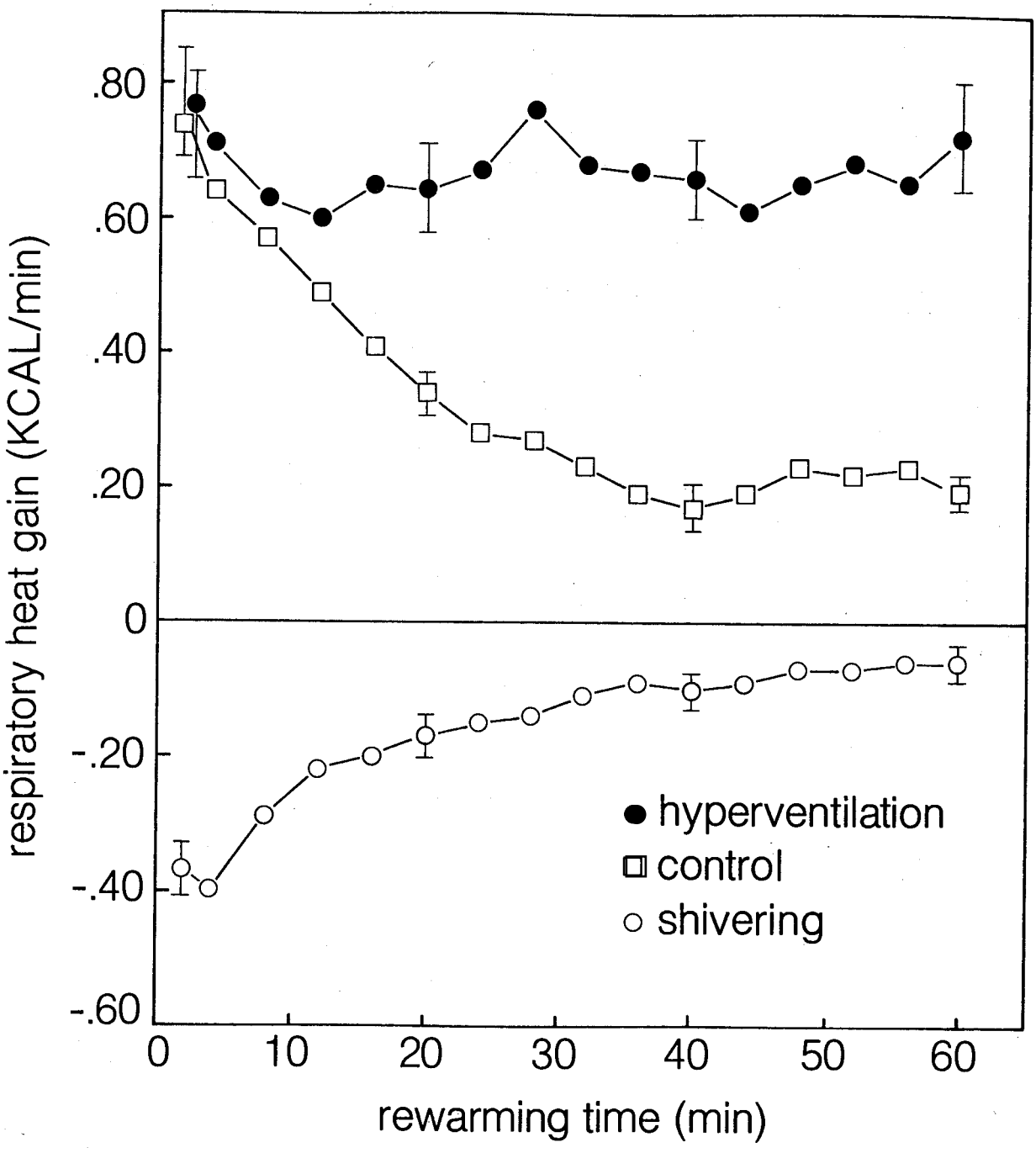

.80
.60
.40
.20
0
-.20
-.40
-.60
respiratory heat gain (KCAL/min)
0
10
20
30
40
50
60
rewarming time (min)
hyperventilation
control
shivering

TABLE 8

COMPARISON OF RESPIRATORY HEAT INPUT
DURING REWARMING FROM HYPOTHERMIA

	Shivering	Control	Hyperventilation
Initial (Kcal/min)	-0.37 ± 0.04	0.74 ± 0.08	0.77 ± 0.08
Final (Kcal/min)	-0.06 ± 0.01	0.19 ± 0.02	0.72 ± 0.08
Average (Kcal/min)	-0.16 ± 0.03	0.34 ± 0.06	0.67 ± 0.02
Total (Kcal/hr)	-9.7 ± 1.1	20.2 ± 1.9	40.4 ± 3.2

Skin Temperatures

Mean skin temperature was calculated from the skin temperatures measured at the arm, chest, thigh and calf according to the method of Ramanathan (1964). The mean skin temperature of each subject was normalized, as in the field study, relative to the temperature at the start of rewarming (Tzero). The mean skin temperature changes versus time for each of the rewarming methods is shown in Figure 11. While there were no significant differences between mean skin temperatures for the different methods of rewarming studied, mean skin temperature for shivering showed the greatest rise.

Table 9 shows the starting temperatures (Tzero) and temperatures gains (T60) for the 4 skin temperatures monitored in this experiment. No significant differences between methods could be demonstrated for initial or final temperature at any skin site. However, two general trends were apparent:

1. Initial temperatures, from highest to lowest were - chest, thigh, arm, calf.
2. Temperature gains, from largest to smallest were - thigh, chest, arm, calf.

Figure 11. Comparison of mean skin temperature changes (°C) during rewarming from hypothermia by shivering thermogenesis (shivering), normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 8.

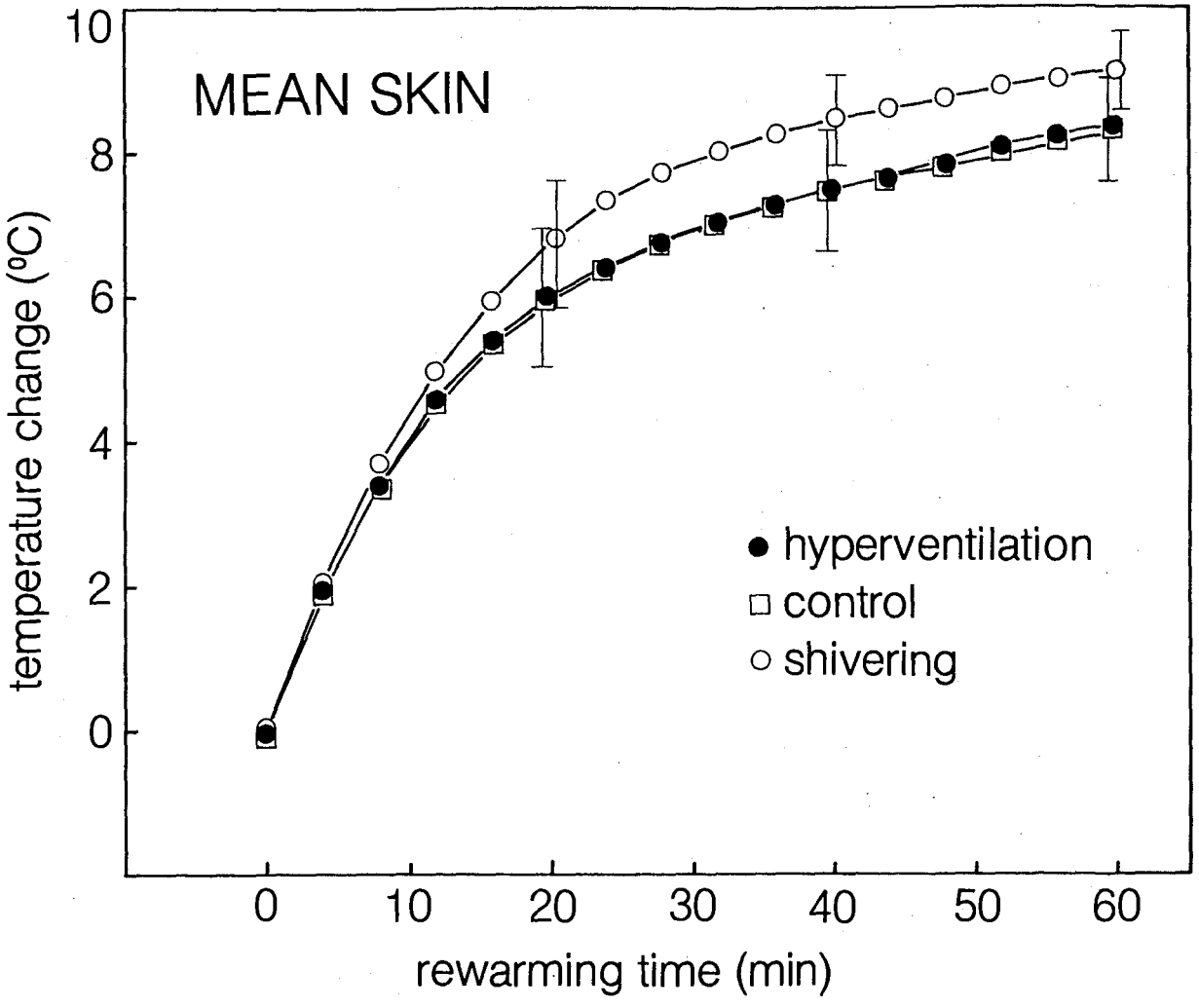

MEAN SKIN
temperature change (°C)
rewarming time (min)
hyperventilation
control
shivering
0
2
4
6
8
10
0
10
20
30
40
50
60

TABLE 9

COMPARISON OF SKIN TEMPERATURES
DURING REWARMING FROM HYPOTHERMIA

		Shivering	Control	Hyperventilation
CHEST	Tzero	25.4 ± 0.8	26.0 ± 0.7	25.7 ± 0.8
	T60	9.9 ± 0.7	8.7 ± 0.8	9.2 ± 1.1
THIGH	Tzero	23.9 ± 0.7	24.7 ± 0.7	24.4 ± 0.7
	T60	10.5 ± 0.6	9.6 ± 0.6	9.7 ± 0.9
ARM	Tzero	22.1 ± 0.4	22.6 ± 0.5	22.9 ± 0.5
	T60	9.1 ± 0.6	8.7 ± 0.4	8.6 ± 0.7
CALF	Tzero	20.4 ± 0.6	20.4 ± 0.7	20.6 ± 0.3
	T60	6.7 ± 0.6	5.9 ± 0.5	6.5 ± 0.3
MST	Tzero	23.1 ± 1.4	23.6 ± 1.5	23.6 ± 0.6
	T60	9.2 ± 0.9	8.3 ± 1.1	8.4 ± 0.8

Core Temperatures

Core temperatures were normalized, as in the field study, relative to the temperature at the start of rewarming. The temperature changes were then calculated at two minute intervals. The average values of initial temperature (Tzero), magnitude of afterdrop (Tad), final temperature (T60), time to maximum afterdrop (tad) and duration of afterdrop (to') for each rewarming method are shown in Tables 10 (Tympanic) and 11 (Rectal).

There were no significant differences between methods for initial tympanic temperature (Tzero), magnitude of tympanic afterdrop (Tad), and final tympanic temperature (T60). The time taken to arrest tympanic afterdrop (i.e. dT/dt=0) was faster ($P < 0.05$) for hyperventilation than for shivering or control. The duration of tympanic afterdrop was longer ($P < 0.05$) for shivering than for either control or hyperventilation. The averaged tympanic temperature variation with time during rewarming is shown in Figure 12.

Figure 12. Comparison of tympanic temperature changes (°C) during rewarming from hypothermia by shivering thermogenesis (shivering), normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 8.

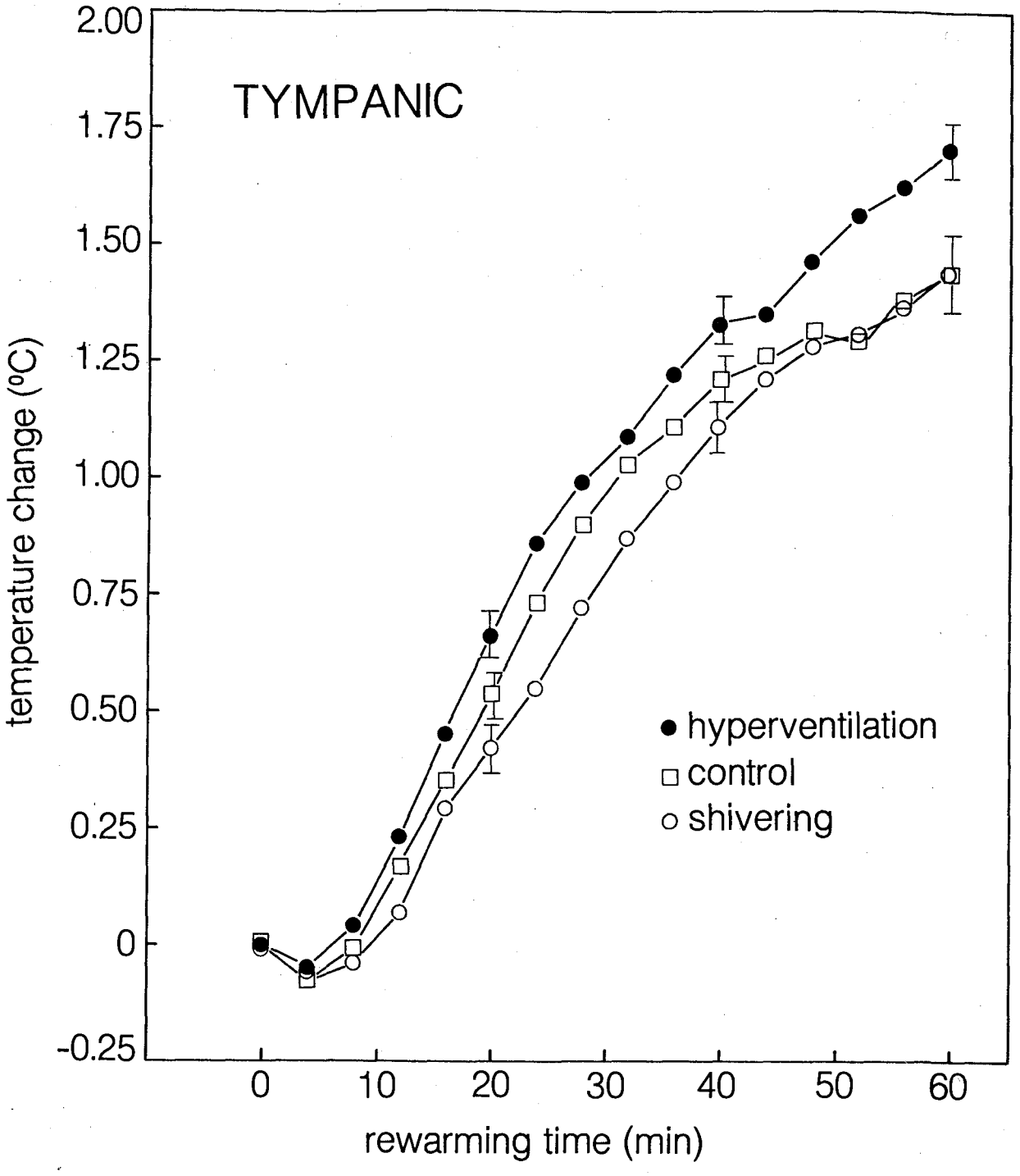

TYMPANIC
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0
-0.25
temperature change (°C)
0
10
20
30
40
50
60
rewarming time (min)
● hyperventilation
□ control
○ shivering

TABLE 10

COMPARISON OF TYMPANIC TEMPERATURE VARIABLES DURING REWARMING FROM HYPOTHERMIA

	Shivering	Control	Hyperventilation
Tzero (°C)	34.5 ± 0.3	34.7 ± 0.3	35.0 ± 0.3
Tad (°C)	- 0.13 ± 0.03	- 0.14 ± 0.04	- 0.11 ± 0.05
T60 (°C)	1.4 ± 0.2	1.4 ± 0.2	1.7 ± 0.1
tad (min)	5.1 ± 1.0	4.8 ± 0.8	3.6 ± 0.8
to' (min)	11.0 ± 2.3	8.8 ± 1.8	6.7 ± 1.7

Shivering recorded both a greater magnitude (Tad) and duration (to') of rectal temperature afterdrop than the two active rewarming methods ($P < 0.05$). Hyperventilation provided a greater rectal temperature gain (T60) than either shivering or control ($P < 0.05$). The rectal temperature gain recorded by control was greater ($P < 0.1$) than that recorded by shivering. The averaged rectal temperature variation with time during rewarming is shown in Figure 13.

Figure 13. Comparison of rectal temperature changes (°C) during rewarming from hypothermia by shivering thermogenesis (shivering), normal inhalation rewarming (control) and hyperventilation inhalation rewarming (hyperventilation). Other conditions as in Figure 8.

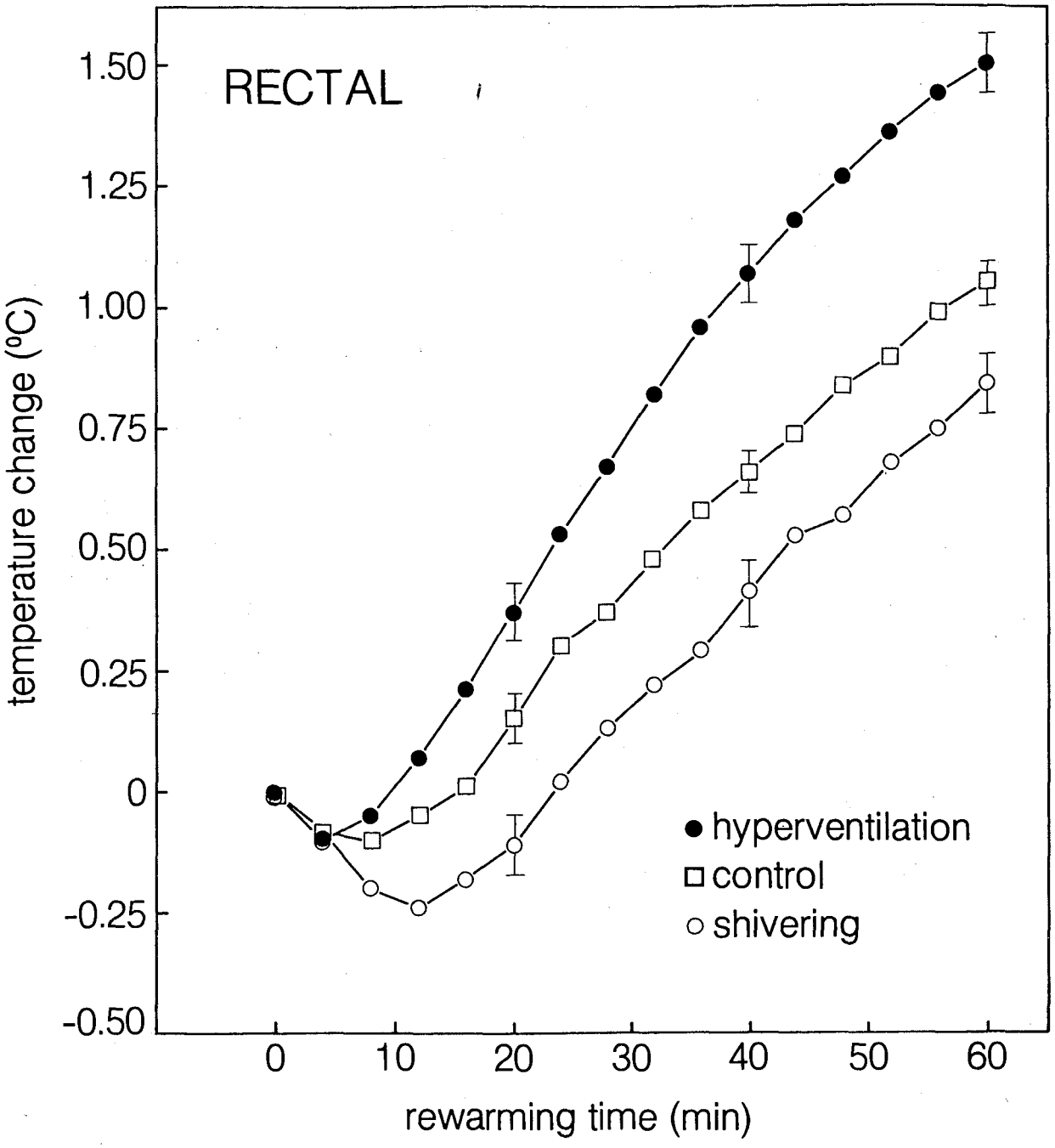

RECTAL
1.50
1.25
1.00
0.75
0.50
0.25
0
-0.25
-0.50
temperature change (°C)
0
10
20
30
40
50
60
rewarming time (min)
hyperventilation
control
shivering

TABLE 11

COMPARISON OF RECTAL TEMPERATURE VARIABLES
DURING REWARMING FROM HYPOTHERMIA

	Shivering	Control	Hyperventilation
Tzero (°C)	34.8 ± 0.1	34.9 ± 0.2	34.9 ± 0.1
Tad (°C)	- 0.40 ± 0.11	- 0.22 ± 0.11	- 0.22 ± 0.10
T60 (°C)	0.8 ± 0.2	1.1 ± 0.1	1.5 ± 0.2
tad (min)	10.4 ± 2.0	6.5 ± 1.7	6.0 ± 2.0
to' (min)	27.0 ± 6.9	15.1 ± 3.8	9.7 ± 2.8

IV. Discussion

In general, results obtained from the laboratory study, with the control and hyperventilation rewarming methods, were similar to results obtained from the field study. Differences between the two studies most probably result from different environmental and experimental conditions.

Ventilation for the hyperventilation method was reduced from approximately 50 l/min in the field study to 40 l/min in the laboratory study. The reduced ventilation in the laboratory study was caused by modifications made to the respiratory rewarming apparatus which reduced inspired carbon dioxide levels. The reduced ventilation for the laboratory hyperventilation method reduced respiratory heat input to the subject. Therefore, it was expected that core temperature gains for the laboratory hyperventilation method would be slightly less than core temperature gains for the field hyperventilation rewarming method. However, the inspired gas temperatures used in the laborarory study were slightly higher than those used in the field study (47°C in the laboratory study verus 44°C in the field study) and this would tend to compensate for the lower ventilation.

Rectal temperature gains for control and hyperventilation in the laboratory study after 30 minutes of rewarming were almost identical to those observed in the field study. Tympanic temperature gains in the laboratory study were similiar for control but were smaller for hyperventilation than those observed in the field study. Also, in the laboratory study, rectal and tympanic core temperature afterdrops were larger.

It is thought that the smaller afterdrops seen in the field study were due to more subject movement before the start of rewarming. Thus, in the field study, most of the afterdrop occurred before rewarming was initiated. It is hypothesised that the smaller tympanic temperature gain observed in the laboratory hyperventilation rewarming method was due to reduced respiratory heat input.

The chest and calf skin temperature gains in the laboratory study, after 30 minutes of rewarming, were larger to those observed in the field study. The higher skin temperature gains observed in the laboratory study were thought to be a result of improved body insulation and reduced heat losses and lower initial skin temperatures.

Three 'inhalation rewarming factors' were calculated for the laboratory study using rectal temperature as the measure of core temperature; one for each pairwise comparison between methods. These 'inhalation rewarming factors' were:

1. Hyperventilation-Shivering = 2.8×10^{-4} °C/liter
2. Hyperventilation-Control = 3.4×10^{-4} °C/liter
3. Control-Shivering = 2.0×10^{-4} °C/liter

These values were smaller than the inhalation rewarming factor calculated in the field study. A possible explanation is that due to the longer duration of this experiment core temperatures were no longer increasing in a linear fashion and rewarming rates were decreasing and thus converging as the core approached normal temperature (Figures 12 and 13) . If 'inhalation rewarming factors' were calculated after 30 minutes of rewarming (core temperatures showed linear increases to 30 minutes) then close agreement between the field and laboratory study occurs.

It should be noted that the calculation of core rewarming rates assumes linear increases in core temperature. However, physiological systems are inherently non-linear. In the field study, the linear model for core rewarming was reasonable as normal body temperatures were not closely approached. In the

laboratory study, due to the longer rewarming period the rate of gain of core temperature decreased as normal core temperature was approached. Hence a linear model of core rewarming could not be applied. Non-linear modelling of core temperatures, mean skin temperature and oxygen uptake during rewarming is presented in Appendix 1.

The only treatment difference between the three rewarming techniques used in the laboratory study was respiratory heat input. Contrary to the assumption made in the field study and the findings of Marcus (1978), metabolic heat production (ie. shivering thermogenesis) was significantly reduced ($P < 0.05$) by respiratory heating. Using the data summarized in Table 12, a negative correlation was calculated between mean respiratory heat input (RH) and mean metabolic heat production (MH) as described by the following equation:

$$MH\ (kcal/hr) = 207.6 - 1.41\ RH\ (kcal/hr) \qquad r=0.99 \qquad (9)$$

It is assumed that this reduction in MH was caused by changes in RH as mean skin temperatures were similiar during each rewarming method. Thus the reduced MH indicates a more rapid rewarming of the central cold receptors located in the hypothalamus and in the spinal cord. This would occur by conduction from the nasopharynx and circulation of warmed

arterial blood (Hayward and Steinman, 1975; Collis, Steinman and Chaney, 1977).

The calculation of MH assumes that, under the conditions of this experiment, the contribution of anaerobic metabolism to the total metabolic heat production were small and any differences among methods were not significant. It is recognized that anaerobic metabolism does occur in severe hypothermia as evidenced by the low pH often recored in such cases (Black, Vanderanter and Cohn, 1976). However, no data is available for mild hypothermia. The difficulty in obtaining venous blood samples, due to the intense vasoconstriction during hypothermia, made this procedure undesirable. In this study mean skin temperatures rose rapidly during rewarming (Figure 11) and differences in mean skin temperatures among methods were small. Thus, the rapid restoration of peripheral blood as shown by the rapid rise in mean skin temperature indicates that substantial anaerobic heat production was unlikely. If anaerobic metabolism did occur to any significant degree, the lack of differences in mean skin temperature among methods suggests that anaerobic metabolism occured to a similiar degree in all methods and therefore would represent a constant error.

Equation 9 implies the total heat available for rewarming (TH) would be reduced as RH is increased. Additionally equation 9 implies that, on average, for every kcal of heat supplied via the respiratory tract, 1.4 kcal of MH is forfeited. It is remarkable therefore that RH enhanced the core temperature recovery from hypothermia as shown in Tables 10 and 11. If RH is of equal or less value than MH in causing core temperature to increase, then it would be expected that as RH is increased core temperature gains would decrease.

Core temperature gains were not reduced by increased RH despite reductions in MH and TH. For example, using the hyperventilation-shivering differences (Table 12), hyperventilation with an additional 40 kcal of RH produced greater gains in core temperature than shivering, despite a reduction in MH of 71 kcal and a reduction in TH of 31 kcal. Also, using the hyperventilation-control differences, hyperventilation with an additional 20 kcal of RH produced greater gains in core temperature than control, despite a reduction in MH of 36 kcal and a reduction in TH of 16 kcal. Finally, using the control-shivering differences, control with an additional 20 kcal of RH produced a greater gain in rectal core temperature and a similar gain in tympanic core temperature to shivering, despite a reduction in MH of 35 kcal and a reduction in TH of 15 kcal.

TABLE 12

COMPARISON OF HEAT GAINS AND CORE TEMPERATURE INCREASES DURING REWARMING FROM HYPOTHERMIA

	Shivering	Control	Hyperventilation
RH (Kcal/hr)	- 10 ± 1	20 ± 2	40 ± 3
MH (Kcal/hr)	218 ± 6	183 ± 5	147 ± 5
TH (Kcal/hr)	218 ± 6	203 ± 6	187 ± 7
T60r (^{o}C)	0.8 ± 0.2	1.1 ± 0.1	1.5 ± 0.2
T60t (^{o}C)	1.4 ± 0.2	1.4 ± 0.2	1.7 ± 0.1

These results suggest that RH is more effective in producing core temperature gains than MH. This is likely explained by RH being delivered directly to the central core (ie. head and chest) while MH from shivering is produced largely in the periphery.

To quantify the contributions of RH, MH and TH to core temperature gain, the core heat input (CH) necessary to cause the observed rectal temperature increases were calculated using Burton's (1935) estimate of core mass.

$$CH = T60r \times 0.83 \times \text{core mass} \quad (10)$$

where T60r = rectal temperature increase during rewarming

0.83 = specific heat of the body (kcal/°C/kg)

core mass = 0.46 x body weight

The percentage of TH supplied to the core increases from 10.7% during shivering to 14.7% during control and to 24.9% during hyperventilation. These results again suggest that RH is more effective in producing core temperature gains than MH alone.

In order to calculate the efficiency of RH in terms of core heat gain it was assumed that the same percentage of MH was supplied to the core in the control and hyperventilation procedures as in the shivering case, where TH is entirely metabolic heat. The difference between the metabolic contribution (i.e. 10.7% of MH) and CH is that supplied by RH. The efficiency of RH is then expressed by the following equation:

$$\text{Efficiency of RH} = \{(CH - 0.107\ MH) / RH\} \times 100\% \qquad (11)$$

In the control treatment, it was estimated that 47.7% of the RH was supplied to the core and, in the hyperventilation treatment, it was estimated that 65.1% of the RH was supplied to the core. When these efficiencies are compared with the 10.7% efficiency of MH, then, in the control treatment, RH was 4.5 times as effective as MH in elevating core temperature and, in the hyperventilation treatment, RH was 6.1 times as effective as MH in elevating core temperature.

The accuracy of Burton's (1935) estimate of core mass is justified in Appendix 2. It should be noted however, that the relative efficiency of RH to MH is relatively insensitive to the value of core mass chosen. The observation that the %TH supplied to the core increases as RH increases is significant regardless

of the weighting assigned to core mass ($P < 0.05$).

A considerable body of evidence suggests that in cases of severe hypothermia active peripheral rewarming can be hazardous, and circulatory collapse is common in the early post-rescue phase (Truscott, Firor and Clein, 1973; Tansey, 1973; Keatinge, 1969; Golden, 1973; Burton and Edholm, 1955; Gregory and Doolittle, 1973; Marcus, 1979). The reason generally given is peripheral vasodilation. Peripheral vasodilation allows cold, acidotic blood trapped in the periphery to return to the core thereby accentuating "afterdrop" of core temperature. The major reasons inhalation rewarming has been promoted as a therapy for hypothermia are that as inhalation rewarming rewarms the core before the periphery it should avoid or reduce hazards of afterdrop, the method is compatible with first aid (field) application by non-medical personnal and is safe for all levels of hypothermia. However, Golden and Hervey (1977) claimed that core temperature afterdrop is a simple conduction of heat down a physical gradient and not due to peripheral vasodilation. Cooper and Ross (1960) found that rapid active rewarming will effect the duration of core temperature afterdrop but not its magnitude.

Marcus (1978) showed no differences in the magnitude or duration of afterdrop of tympanic temperature between inhalation rewarming, shivering thermogenesis, hot bath rewarming and piped suit rewarming. A study by Hayward and Steinman (1975) comparing hot bath rewarming and inhalation rewarming showed no differences in rectal or tympanic temperature afterdrop. Collis, Steinman and Chaney (1977) confirmed the findings of Hayward and Steinman (1975). Additionally however, they showed significant reductions in the magnitude of rectal and tympanic temperature afterdrop and the duration of tympanic temperature afterdrop when comparing inhalation rewaming to shivering thermogenesis. The present study also showed significant reductions in the magnitude and duration of rectal temperature afterdrop and in the duration of tympanic temperature afterdrop when comparing inhalation rewarming tc shivering thermogenesis.

Therefore in terms of reducing the duration of afterdrop it would appear that inhalation rewarming is as effective as hot bath rewarming. The present study and the study conducted by Collis, Steinman and Chaney (1977) both demonstrated significant differences in core afterdrop between inhalation rewarming and shivering thermogenesis alone. While Marcus (1978) was unable to demonstrate significant differences in tympanic temperature afterdrop between any of the rewarming techniques he studied, it is noted that inhalation rewarming produced the smallest

tympanic temperature afterdrop, both magnitude and duration, of any technique used.

An additional benifit of inhalation rewarming can be anticipated on the basis of our results. The lower metabolic rate caused by inhalation rewarming (Figure 9) reduces shivering thermogenesis and therefore the metabolic demands of the periphery. One of the hazards associated with rewarming from hypothermia is in meeting the metabolic demands of the periphery before the hypothermic heart muscle can respond to treatment (Truscott, Firor and Clein, 1973). Thus, a lower metabolic rate in turn lowers the perpheral cardiac output requirement thereby reducing the risks of cardiovascular collaspe from overtaxing the hypothermic heart.

The core temperatures monitored in this study (rectal and tympanic) were selected to provide an account of the changes that occur in the thoracic core and central nervous system during rewarming. However, it has been suggested that rectal and tympanic temperature are not adequate measures of the heart and chest blood temperature during rewarming and that esophageal temperature offers better agreement with pulmonary artery temperature during rewarming from hypothermia in conscious man (Hayward, 1979). It would be expected from the results of Hayward and Steinman (1975) that the differences between

treatments shown in this study would be even greater had esophageal temperature been used as a monitor of core temperature.

In conclusion, increasing the respiratory heat input to a mildly hypothermic subject will cause an increase in rectal and tympanic core temperature elevation. The core temperature elevation occurs despite a reduction in metabolic heat production and in the total heat available for rewarming. The percentage of the total heat supplied to the core must therefore increase as respiratory heat input is increased. Theoretical consideration indicated that respiratory heat is approximately 4 to 6 times as effective as metabolic heat in producing core temperature elevations. Also, inhalation rewarming reduced core temperature afterdrop compared to shivering thermogenesis.

E. SUMMARY

The following main points were deduced as a result of the work carried out.

1. The increase in core temperature due to inhalation rewarming was estimated to be between 2×10^{-4} and 5×10^{-4} °C for each litre of warm, saturated air ventilated.
2. Increasing respiratory heat input to mildly hypothermic subjects increased the core temperature gain during rewarming, despite reductions in metabolic heat production and in the total heat available for rewarming.
3. Heat provided to mildly hypothermic subjects via the respiratory tract was 4 to 6 times more effective in elevating core temperature than metabolically produced heat.
4. Inhalation rewarming was a significant improvement over shivering thermogenesis alone as a therapy for hypothermia. In addition to being more efficient in rewarming the core, core afterdrop was reduced.

APPENDIX 1

Exponential Modelling of Laboratory Rewarming Data

All data selected from the laboratory study was modelled by either single or double exponentials. Mean skin temperature and oxygen uptake were modelled by single exponentials. Mean skin temperature was modelled by an exponential curve of the form

$$T = A(1 - \exp(-kt)) \qquad (12)$$

where T = temperature at time t

A = predicted final MST at t=infinity

k = exponential rate constant

t = time

The only difference between the exponentials which describe MST (Table 13) during the three rewarming methods was the predicted final MST. The predicted final MST for shivering was larger than for either control or hyperventilation. This implies a faster rate of mean skin temperature gain in shivering and also implies final skin temperature would be greater. However, as the body approachs normothermia other physiologic mechanisms (cessation of shivering and skin vasodilation) would affect final skin temperature. In addition, the predicted final MST was close to the experimentally observed final MST and in analyzing the experimental data no significant differences could be found among methods for final MST. Thus the predicted final MST has dubious value as a predictor. Based on the shape of the observed MST curves (Figure 11) the predicted final MST would appear too

low. It may be that a single exponential is not complex enough to truely define MST during rewarming.

Oxygen uptake was modelled by an exponential curve of the form

$$\dot{V}O_2 = A(\exp(-kt)) + B \quad (13)$$

where $\dot{V}O_2$ = oxygen uptake at time t

A + B = value of $\dot{V}O_2$ at t=0

k = exponential rate constant

B = resting metabolic rate (RMR)

The exponentials modelling oxygen uptake (Table 13) verify the analysis made on the raw data. The predicted initial value of oxygen uptake is higher for shivering than the other two methods but it may be artifically high due to a plateau at maximum shivering intensity. The rate constants show that oxygen uptake declines most rapidly during hyperventilation, followed by control and then shivering. It is also noted that the predicted RMR is highest for hyperventilation, followed by control and then shivering. This may reflect differences in the work of breathing in the case of continued hyperventilation or may be random deviation of the predicted RMR obtained from the data sets or may be due to the higher body temperatures produced by the active rewarming methods (Q10 effect).

TABLE 13

SINGLE EXPONENTIAL MODELLING OF MEAN SKIN TEMPERATURE AND OXYGEN UPTAKE DURING REWARMING FROM HYPOTHERMIA

		A	K	B	Function	r^2
MST	Hyperventilation	8.33	-0.0633		$MST = A(1 - e^{-kt})$	1.00
	Control	8.24	-0.0639			1.00
	Shivering	9.24	-0.0644			1.00
VO_2	Hyperventilation	1.35	-0.118	0.302	$VO_2 = Ae^{-kt} + B$	1.00
	Control	1.31	-0.0628	0.285		0.99
	Shivering	1.69	-0.0554	0.250		0.94

Single exponential modelling was not attempted on the core temperature data because the afterdrop phenomena could not be included in such a model. While the temperature increase phase of the core data could be modelled by a single exponential different time intervals would have applied to the curve fit of each method thus making comparison difficult. To model the complete core temperature curves during rewarming a double exponential was fitted to the mean data (Table 14). The first exponential represents the warming function while the second represents the cooling or afterdrop function.

$$T = A(1 - \exp(-at)) - B(\exp(-bt) + 1) \qquad (14)$$

where T = temperature at time t

A = asymtote for warming exponential

a = exponential rate constant for warming

B = asymtote for cooling exponential

b = exponential rate constant for cooling

A - B = predicted final core temperature

In general, the model offers a good fit to the experimental results. For rectal temperature, hyperventilation has the highest predicted final temperature (A - B) followed by control and then shivering. The model predicts the magnitude and

duration of rectal temperature afterdrop is greatest for shivering and least for hyperventilation. For tympanic temperature, hyperventilation has the highest predicted final temperature, followed by shivering and then control. Differences in tympanic temperature afterdrop are not apparent.

The model is difficult to intrepret beyond 60 minutes, perhaps because the model is too simple. As normal body temperature is approached several physiological responses occur, the most important of which are peripheral vasodilation, increased skin blood flow and increased body heat losses. It is doubltful this simple model can account for all the physiological changes which occur as normal body temperature is approached, as they are not fully represented within the time period of the experimental data, but rather would tend to materalise at times greater than 60 minutes in response to normothermia being attained.

TABLE 14

DOUBLE EXPONENTIAL MODELLING OF RECTAL AND TYMPANIC TEMPERATURES DURING REWARMING FROM HYPOTHERMIA

		A	B	K_1	K_2	A-B	r^2
RECTAL	Hyperventilation	3.09	-0.91	-0.0255	-0.148	2.18	1.00
	Control	2.68	-1.08	-0.0260	-0.101	1.50	1.00
	Shivering	6.29	-5.00	-0.0387	-0.0597	1.29	1.00
TYMPANIC	Hyperventilation	2.77	-0.83	-0.0376	-0.201	1.94	1.00
	Control	10.00	-8.54	-0.0777	-0.0979	1.46	1.00
	Shivering	10.74	-9.11	-0.0589	-0.0736	1.63	1.00

APPENDIX 2

Calculation of Mean Body Temperature and Changes of Body Heat Content

To verify the applicability of Burton's (1935) estimate of core mass to the present study the weighting coefficients of mean body temperature were calculated. Mean body temperature (MBT) is generally given by the equation:

$$MBT = (x)\,Tr + (1 - x)\,MST \qquad (15)$$

where Tr = rectal temperatue

MST = mean skin temperature

Several studies have been carried out to determine the value of (x). Burton and Edholm (1955) found (x) to be 0.7, while Hardy and Dubois (1938) found (x) to be 0.8. Stolwijk and Hardy (1966) confirmed the value of (x) to be 0.8 in a in a hot environment. Livingstone (1967) and Colin, Timbal, Houdas, Boutelier and Guieu (1971) have demonstrated that the relative masses of core and peripheral tissues can vary according to the heat load.

The most appropriate value of (x) for the laboratory study was determined by the following procedure:

1. Three values of (x) 0.50, 0.65 and 0.80 and the measured gains in Tr and MST (Tables 9 and 11) were used in equation 15 to compute the increment in MBT (ΔMBT). This value was then substituted into equation 16 to calculate the total heat input

(THc) necessary to elevate MBT by the computed increment.

$$THc = \Delta MBT \times 0.83 \times \text{Body weight} \quad (16)$$

Applying a total heat balance according to the equation:

$$THc = MH + RH - HL \quad (17)$$

where HL represents heat loss from the skin surface, then the correct value of THc should be that neccesary to obtain equilibrium.

2. A linear regression analysis of differences between THc and (MH +RH) (Table 12) and the chosen values of (x) was then calculated.

3. The best estimate of (x) was taken to be the value which gave a difference (THc - (MH +RH)) of 20 kcal, representing the estimated heat loss during rewarming (i.e. HL = 20 kcal). Heat loss estimates were obtained from three subjects using four heat flow transducers (Thermonetics, HFT-A) placed over the skin at the same sites used for skin temperature measurement. Differences in heat losses between methods were assumed to be small due to the similiarity of mean skin temperatures and environmental conditions during all rewarming experiments. The details of this analysis are shown in Table 15. The appropriate value of (x) thus obtained was 0.75, giving the equation

TABLE 15

DETERMINATION OF WEIGHTING COEFFICIENTS FOR MEAN BODY TEMPERATURE

	Difference between measured TH and TH calculated for MBT increase			
X	Shivering	Control	Hyperventilation	Mean
.50	84.4	79.1	117.4	93.6
.65	9.0	13.5	53.5	25.3
.80	-66.4	-52.2	- 10.4	-43.0
x for -20 Kcal	0.71	0.73	0.82	0.75

$$MBT = 0.75Tr + 0.25MST \quad (18)$$

The above analysis was used to check the validity of Burton's (1935) estimate of core mass under the conditions of the present study.

Burton (1935) estimated that the body was 46% core and 54% periphery. Burton further assumed that mean peripheral temperature was half-way between core (rectal) and mean skin temperature. Thus it can be deduced that mean body temperature must be

$$\begin{aligned} MBT &= 0.46Tcore + 0.54Tperiphery \quad (19) \\ &= 0.46Tr + 0.54\ (0.50Tr + 0.50MST) \\ &= 0.73Tr + 0.27MST \end{aligned}$$

The above formula, based on the assumptions of Burton (1935) is in close agreement with that derived directly from the experimental data for mean body temperature based on total body heat balance (equation 18). It would appear therefore from the above analysis, for the conditions of this experiment, the use of Burton's estimate of core mass is justified.

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