Whole Head Submersion and its Effect on the Rate of Cooling of Body Core Temperature

by

Dorathea Pretorius

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

Department of Physical Education & Recreation Studies

University of Manitoba

Winnipeg

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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Of

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To my Mother who taught me to live every day to its fullest
and Nora who never had the opportunity to do so.

ACKNOWLEDGEMENTS

Writing this thesis and everything preceding it, was one of the most wonderful privileges life has granted me.

I want to acknowledge my husband, Jassie, for providing me with such a carefree life that I was able to go back to school as a full time student. I also admire him for his infinite knowledge of not only physiology but also the basic sciences. For my two daughters, Chrismarie and Marissa, I know it has not always been easy to have a student as a mother, but they were always so understanding and supportive. It is great to have them as a family.

To Dr Gordon Giesbrect I am greatly in debt for taking me as a student. Being a former teacher I admire him for his brilliant and creative teaching skills. He impressed me not only with his knowledge but also with his passion for everything he believes in. This laboratory and everything surrounded by it is a reflection of his passion for his career and it was a privilege to be part of it. Everything that I know about thermoregulation and research today, I have learned from him, and also much more than that. I also appreciate that he acted as a subject in this study and personally helped in most of the other experiments.

I want to acknowledge my other two committee members, Dr Alan Steinman and Dr Greg Gannon, for their input this study. My greatest appreciation also goes to Dr Gerry Bristow, the physician who provided medical support and lots of help during the studies. His cheerful character brought some relief during the very tense experiments. I also want to thank Dr Johan Jacobs for the one experiment that he assisted us in.

I also want to acknowledge Doug Evans from One Stop Diving and Sherwood Scuba (Niagra Falls), for the provision of the regulator and Jeremy Stewart of the Fresh Water Institute for the use and the filling of the SCUBA tanks for the study. For funding I want to acknowledge the National Science and Engineering Research Council and the Randy Chipperfield Hypothermia Research Fund.

I am deeply in debt to my subjects. I admired them for their cooperation in the studies. Apart from the three hours that it took to do the experiments, they had to sacrifice the rest of the day due to the high dose of meperidine that was used in this study.

For Perry Schwark and Andre Worms from this faculty – I always appreciated the promptness and willingness with which they have responded to my many requests.

Lastly I want to acknowledge the support I got from my family in South Africa. My mother, although the study itself did never make too much sense to her, always enquired about the progress. Elsi, my twin knows what it takes to do a study like this and Chrisma knows about the demands of a family. For both of them and their families, thank you for the continuing interest in what I do.

……and lots of thanks to our Heavenly Father who created the human body so masterly and mysteriously so that we can have fun detangling the details of it.

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ABSTRACT

Background: This study was conducted to determine the effect of whole head submersion in 17°C water, on the cooling rate of body core temperature. Previous studies have shown that immersing the back of the head in cold water had a significant core cooliIng effect if the body was exposed to the cold water but insignificant when the body was insulated from the water. Methods: Six healthy individuals were studied under four conditions. They were either immersed from neck down, or completely submerged, in 17°C water for 45 minutes or until the esophageal temperature (T_{es}) reached 34°C. Meperidine and buspirone were used to inhibit shivering heat production to isolate the effect of cutaneous heat loss through the body and/or head on the rate of core cooling. The four different conditions were: Two conditions where the body was insulated, once with the whole head above the water and covered with a fleece cap, and once with the whole head exposed to the water; and two conditions where the body was exposed to the water, once with the whole head above the water and covered with a fleece cap, and once with the whole head exposed to the water. Results: Body core temperature dropped significantly from baseline values in all four conditions. The difference increased from body-insulated, head-out (0.63 ± 0.2°C) condition to body-insulated, head-in (1.08 ± 0.2°C) condition and further increased in the body-exposed, head out (1.42 ± 0.7°C) and body-exposed, head-in (1.91 ± 0.6°C) conditions. Head submersion did not significantly increase the drop in core temperature in either of the sub-conditions. The rate of cutaneous heat loss was greater in the body-exposed sub-conditions throughout with a greater heat loss in the head-in condition after 15 minutes. In the body-insulated sub-conditions heat loss in the head-in conditions were greater throughout. Head submersion significantly increased head heat loss from 8.7 ± 1.5 W in the head-out sub-conditions to 43.99 ± 11.2 in the head-in sub-conditions. For all other areas (arms, trunk and legs) heat loss was significantly higher in the body-exposed conditions than in the body-insulated conditions throughout immersion/submersion. Total absolute heat loss was about 2.5 times greater in the body-exposed (964.19 ± 105.8 kJ) conditions than in the body-insulated (379.95 ± 53.5 kJ) conditions ($p < 0.001$) with heat loss from the head six times greater in the

head-in (101.6 ± 18.2 kJ) conditions than in the head-out (16.90 ± 2.8 kJ) conditions ($p < 0.001$). Metabolic heat production was similar for all conditions during the baseline and up to 15 minutes of immersion. In the body-insulated sub-conditions there was a decrease in metabolic heat production towards the end of the experiments due to the suppressing effect of meperidine and buspirone. In the body-exposed conditions, metabolic heat production did not differ significantly throughout the experiment. This is an indication that shivering heat production was significantly suppressed throughout the experiment. Conclusions: These data demonstrate that whole head exposure to 17°C water in both insulated and non-insulated sub-conditions only had a minimal effect on body core cooling. Body composition only played a role in the insulated sub-condition and it was found that the higher the subject BMI and weight, the smaller the differences in core temperature drop between the head-in and head-out conditions.

INTRODUCTION

Many recreational, commercial and military activities present the risk of human exposure to cold water and the consequent development of accidental hypothermia. Several studies have been done to try to understand the effect of cold water immersion[1] on the rate of body core cooling. Factors that have been investigated include body composition (21,33,58), movement (25), body position (24), nutritional state (30,61), exhaustion (30,45,51), the effects of drugs and alcohol (31) protective clothing and sea state (50). Most of this work involves immersion of only the body in cold water but few studies have included exposure of the head. Three cold water studies on humans have exposed the dorsal head to cold water (1,16,35) while none have exposed the whole head.

IMPORTANCE OF THE STUDY

Knowledge on this topic could be applied to better the understanding of the onset of hypothermia when someone is exposed to cold water. Search and rescue personnel could benefit by understanding the effect of dorsal head cooling and this could help in the survival time prediction for cold-water victims. Design of personal flotation devices may determine whether the dorsal head is exposed to the cold water or not. Knowledge of the effect that whole head exposure has on core cooling can help with the development of protocols for insulation in cold-water SCUBA divers and long distance swimmers in order to prevent hypothermia. It can also help to explain the mechanisms of brain cooling in the event of cold-water near-drowning[2] that serves as protection against ischemic brain damage.

Head cooling is also used for the induction of hypothermia for the benefits it has in some clinical conditions. Hypothermia is used for prevention of brain damage in patients suffering from stroke (57), brain injury (39) or cardiac arrest (2). The mechanism by which the brain is protected by cooling might be linked to a reduced metabolic rate (38) as well as reduction in biosynthesis, release and uptake of neurotransmitters (6).

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[1] Part of body and head under the water
[2] Survival after suffocation by submersion in cold water

Alexander (1) reported on unethical studies that were done by two German investigators during the Second World War in concentration camps in Dachau. The investigators compared cooling rates in 2 - 4ºC water between three different conditions – two conditions where the body was exposed, once with the back of the head and the neck in the water and once with the back of the head and neck out of the water. In the third condition only the body was exposed to the cold water. They found that the effect of cooling of the dorsal head and neck on rectal temperatures was minimal when the body was not cooled, compared to the much greater effect when the whole body as well as the dorsal head was exposed to the cold water. Similar results were seen in a study done by Lockhart et al. (16) in 10ºC water, measuring esophageal temperature. This study compared two personal flotation devices, which either kept the dorsal head and chest in or out of the water. This study was repeated using meperidine to suppress shivering to isolate the effect of surface cooling by Giesbrecht et al. (36).

Xu et al. (59) explained brain cooling using a 2-dimensional mathematical model that illustrated the avenues of heat loss through the human head during submersion. It showed that most heat was lost through convection by aspirated water in the lungs. Convection and conduction through the scalp had a minimal predicted effect on the rate of core cooling (59). Parts of this model were based on studies done on shaven, anesthetized dogs that were submerged[3] in different conditions (7). This was verified by experiments on human cadavers (irrigating the nasopharyngeal area) and one experiment on one human subject whose head was submerged in cold water (59).

In the three previous human studies (1,16,35) dorsal head cooling increased the rate of body core cooling. Although Xu's mathematical model (59) predicts little effect of whole head cold-water submersion on body core cooling, there have been no systematic studies of whole head cold water submersion in humans.

[3] Whole body and head under the water

STATEMENT OF THE PURPOSE OF THIS STUDY

To determine the effect of whole head submersion in cold water on the rate of decrease of body core temperature in humans.

PROTOCOL

Six healthy individuals were studied under four conditions. They were either submerged or immersed from neck down in 17ºC water for 45 minutes or until the esophageal temperature (T_{es}) reached 34ºC. Meperidine and buspirone were used to inhibit shivering heat production to isolate the effect of cutaneous heat loss through the body and/or head on the rate of core cooling.

The four different conditions were:

Two conditions where the body was insulated:

<u>Body-insulated, Head-out</u> - The whole head was above the water and covered with a fleece cap.

<u>Body-insulated, Head-in</u> - The whole head was exposed to the water.

Two conditions where the body was exposed to the water:

<u>Body-exposed, Head-out</u> - The whole head was above the water and covered with a fleece cap.

<u>Body-exposed, Head-in</u> - The whole head was exposed to the water.

HYPOTHESIS

The effect of whole head exposure on the rate of body core cooling would be maximal if the body is exposed and minimal if the body is insulated from the cold water.

ASSUMPTIONS

1. The core temperature is reflected in the esophageal temperature.
2. An increase in metabolic heat production, higher than the average resting values is an indication of shivering heat production.
3. Subjects did not consume anything other than the prescription drugs and a moderate breakfast before the trial.
4. Subjects did not smoke before the trial.
5. There was no drastic change in sleeping habits from one experiment to the next.
6. There was no vigorous exercise done on the day of the experiment.
7. The posterior head probe was positioned on top of the hair and tightened by a mesh hood. The assumption was made that this configuration provides an accurate value of skin temperature and heat flux.

LIMITATIONS

1. Healthy male volunteers between the ages of 18 and 46 participated in this study, which may limit the generalizability of the results to this specific group.
2. Insulation provided by a dry suit and fleece undergarment did not constitute perfect insulation; therefore body-insulation conditions still allowed some heat loss from the body.

REVIEW OF RELATED LIERATURE

INTRODUCTION

This review gives a background on the basic physiology underlying thermoregulation and cold-water immersion as well as mechanisms that may play a role in the survival of cold-water near-drowning. It also gives a summary of related studies done on heat loss through the head, a brief description of the drugs used in this study and the technical issues of breathing compressed air under water.

HEAT BALANCE

Homeothermic species like humans require a relative constant body core temperature (T_{co}) for optimal metabolic function. The human core temperature is maintained within 0.5°C from the normal, which is generally considered to be 37°C (48).

The homeostasis depends on a balance between heat loss and heat gain. Physical mechanisms through which the body loses heat are radiation from the skin surface, conduction due to a temperature gradient between the body and its surroundings, evaporation of sweat or wettedness from the skin surface and convective heat loss due to movement of air or water around the body. Heat loss from the body surface is regulated through vasomotion (to regulate radiative heat loss) and insulation (to regulate conductive heat loss).

Heat is gained through metabolic heat production (general metabolic function, shivering and exercise) and donation from the exterior. Metabolic heat is produced within the cells and then transferred to the surroundings. This process occurs passively through conduction, due to the thermal gradient between the cell and its surroundings and convectively through movement of blood throughout the body (43).

THERMOREGULATION

Thermoregulation occurs in three phases (48). First, afferent thermal sensing from peripheral sensors in the skin and central sensors in the deep central tissues (abdomen and thorax), the spinal cord, the hypothalamus and other parts of the brain. The peripheral sensors are particularly rate sensitive whereas the central response is a direct reflection of the absolute temperature of tissues as well as the returning blood from the peripheral area.

The hypothalamus is the main central regulator of body core temperature. It responds to an integrated thermal input from the afferent stimuli via response mechanisms that alter heat loss to the environment or increase metabolic heat production.

Efferent responses to integrated thermal input include behavioral and physiological responses.

Responses to warm temperature will be sweating and vasodilatation to increase the heat loss from the body surface to the environment and responses to neutral temperature will not trigger any regulatory response.

The initial responses to cold are behavioral and might include changed body position, the addition of clothing to increase insulation and decrease heat loss or avoiding the cold exposure. Cutaneous vasoconstriction is the first physiological response to a cold environment and will decrease heat loss from the body surface. This reaction does not require much energy (43). If the body loses more heat it will increase its metabolic heat production mainly through shivering which can increase heat production by 400-500% in adults (13).

Vasoconstriction and shivering are referred to as the secondary responses to cold (23,44) and occur when neural thermoregulation of the body is intact. An increase in metabolic heat production due to shivering is accompanied by an increase in oxygen consumption ($\dot{V}O_2$), minute ventilation ($\dot{V}_E$), heart rate (HR), cardiac output ($\dot{Q}$), and mean arterial pressure (MAP).

In moderate to severe cases of hypothermia[4] shivering ceases and the primary responses to cold can be seen (44). These include a decrease in tissue

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[4] Tco < 32

metabolism and gradual inhibition of neural transmission and control. This is reflected as a decrease in $\dot{V}O_2$, $\dot{V}_E$, HR, $\dot{Q}$ and MAP.

RESPONSES TO COLD-WATER IMMERSION.

When someone is immersed in cold water, the 'Cold Shock' response occurs within the first 1-2 minutes. This is possibly provoked by a massive nervous stimulus (8) from the cold sensors in the skin and results in vasoconstriction, the gasp reflex, tachycardia, hypertension, hyperventilation and a consequent reduction in arterial P_{CO2}[5] (8,26,32,53). These responses significantly increase the workload of the myocardium, which in addition to a massive sympathetic discharge may lead to cardiac arrest and death. The intensity and duration of this response depends on the initial skin temperature (T_{sk}), and the rate of change of T_{sk} (8) which will be affected by the temperature of the water, insulation value of clothing and level of entry (4).

Shivering starts due to the rapid cooling of the skin and cool blood from the periphery to the core that stimulates the central cold receptors. Significant cooling of the peripheral tissues continues to occur for the first 30 minutes of immersion with a decrease in neural transmission and control that is most prominent in the hands and feet (54).

There are several internal factors that have an effect on rate of cooling of the core temperature in cold water. Body composition (%body fat, height and weight) has shown to have the greatest effect of these factors. At a given skin temperature shivering heat production will be less in humans with greater amounts of subcutaneous fat (21,33,58). The bigger the skin surface area: body mass ratio, the faster the rate of core cooling (19). Gender was not shown to have an effect on the decrease in core temperature due to cold water submersion of young humans. However when both age and gender were considered, older men were more susceptible to cold environments than women and younger men (20,56).

[5] Partial pressure of CO_2 in the blood

Pugh (45) concluded that when cold stress, fatigue and discomfort are combined, the point of exhaustion is reached earlier than when the stresses operate in isolation. This would suggest that with the same cold stress, individuals who are more fatigued would have less defense against core cooling. Jacobs (30) showed a negative relationship between blood glucose levels and rate of core cooling when humans are immersed in cold water. Young et al. (61) conducted a study on eight young males to determine the effect of exertional fatigue and chronic negative energy balance on thermoregulation. Military trainees were subjected to severe training while they were deprived from sleep and food. They had an average negative energy balance of ~ 850 kcal/day, lost 7.4 kg body weight and had an average of 12% body fat at the end of the training period. They were then subjected to cold exposure for four hours on three occasions: immediately after the course; 48 hours later, after a period of rest and energy repletion; and 109 days after the course. Immediately after the course no one could endure the cold for the entire 4 hours while only five of the eight subjects could complete the trial 48 hours later. On the third trail, when an average of 12.8 kg lean and fat body mass were restored (average body fat was 21%) everyone could complete the trail. This was likely because of the added metabolic capacity of regained body mass and the increased thermal insulation of the new fat mass.

In a study done on alcohol consumption and thermoregulatory responses it was shown that it is unlikely that moderate alcohol consumption qualitatively alters human thermoregulation nor predisposes individuals to hypothermia (31). Although, Freund (14) stated in a review paper that alcohol causes an increased rate of body core cooling during cold exposure. The magnitude of reduction is related to blood alcohol concentration. According to this review, the increased rate of core cooling appears to be due to impairment of shivering thermogenisis caused by alcohol induced hypoglycemia rather than increased vasodilatation as commonly believed.

External conditions affecting rate of cooling are water temperature (1), clothing and insulation (52), body position and activity level (25). It was shown that minimizing both voluntary activity and the exposure of major heat loss areas of the skin to the cold water is the best way of minimizing the drop in core temperature.

Sagawa et al. (47) showed that the lowest water temperature in which humans could maintain normal core temperature through muscular activity was 25°C. Steinman et al. (50) reported faster cooling rates (50 – 100%) for subjects in rough water compared to calm water when loose fitting, wet garments (boat crew overalls) were worn The same effect was not seen in conditions where clothing had better insulation value.

COLD-WATER NEAR-DROWNING

The remarkable survival of cold-water near-drowning victims (3) with intact neural outcome focused attention on cold-related mechanisms which protect the brain from ischemic injury. For a long time it has been attributed to the decreased cerebral metabolic requirements (CMR_{O2}) according to the Q_{10} principle [6]. Mitchenfelder (38) has shown that the Q_{10} of the brain increases from 3 between 37ºC and 27ºC to 4.8 between 27ºC and 17ºC. If the brain could survive an ischemic insult for 5 minutes at 37ºC, it would provide 15 and 72 minutes respectively at 27ºC and 17ºC. The implication of this is that the brain had to cool at a very fast rate (more than 10ºC in 5 minutes) or the victim had to be severely hypothermic[7] at the point of submersion to explain these survival case studies.

However, several of these case reports (34,42) showed that the core temperatures of these patients were higher than what was required for the protection based on the decreased CMR_{O2} alone. These results indicate that there were other mechanisms providing brain protection. Today it is known that even mild hypothermia[8] protects the brain from ischemic injury (5,6,39,40). The mechanisms involve suppression of neurotransmitters (glutamate and dopamine) and free fatty acids (6), the protection of the blood brain barrier (9) and reduction of hydroxyl radical production (22).

[6] Change of physical and chemical rate of reactions with a 10ºC change in temperature
[7] Tco < 28ºC
[8] 35 >Tco > 32ºC

HEAT LOSS THROUGH THE HEAD

Xu et al. (60), used a mathematical model to predict the rate of human brain cooling during cold–water submersion. His model was based on research done by Conn (7) on anesthetized, shaven dogs that were submerged in cold water under different conditions. The model distinguished between two boundaries through which heat was lost from the head – the outer boundary (skull and soft tissues) between the brain and the cold water, and the inner boundary, which is an interface between the brain and the upper airways in the nasopharyngeal region and, in part, the interface between the brain and the rest of the neck and head. The model demonstrated the significance of each of these avenues during submersion when one or both of them were exposed to the 2ºC water. Predicted conductive brain cooling through the outer boundary was minimal (< 1ºC) within the first ten minutes of cooling. The effect of the inner boundary was greater – a drop of 4ºC in 10 minutes was predicted when both the inner and outer boundaries were cooled. The contribution of the inner boundary was thus 3ºC in the first 10 minutes.

Conn (7) found that the dogs were breathing water for several minutes after submersion. Flushing of the lungs with cold water, cooled the pulmonary blood, which had a circulatory cooling effect on the whole body, including the brain. The application of these findings on the human head was validated with data obtained from human cadavers where the nasopharynx was irrigated with ice water and another subject that cooled his outer boundary with cold water of different temperatures (12 and 18ºC).

According to this model, heat loss through the head during submersion occurs mainly through the convective heat loss to the circulating blood. A drop of 7ºC in 10 minutes was predicted if all the contributions to brain cooling were considered.

Predictions of Xu on the effect of cooling of the outer boundary are consistent with results of Mellergard (37) who observed changes in human brain temperature with different cooling methods. All the patients had severe brain injuries and were unconscious. Brain temperature was measured directly with a thermocouple introduced through an intraventricular catheter that was used to monitor intracranial pressure.

Some patients were cooled with a gel cap with which blocks of frozen liquid were wrapped around the head. The temperature of the gel cap was 0ºC and the temperature beneath the helmet was 10 - 14ºC after 2 hours of cooling. These patients showed no significant decrease in brain or rectal temperatures over a period of 2.5 hours. Other patients were cooled with a cooling helmet covering the head and part of the neck. The helmet had a system of thin plastic channels on the inside, through which 5ºC water was circulated. Cooling with this helmet showed very little decrease in brain and rectal temperature (0.5 - 0.6ºC) over a period of more than 4 hours.

Lockhart et al. (16) tested two personal flotation devices and their effect on rate of core cooling (T_{co}) in 10°C water. The flotation devices differed in the way that they held the body in the water. One device kept the body vertical with the head out and the other device held the body in a recumbent position so that the dorsal head was immersed. A control condition, where only the dorsal head was immersed, resulted in a cooling rate of 0.18°C/h over a period of 35 minutes. When only the body was immersed, and the head was out, the cooling rate was 1.63°C/h over the same time period of time. The combined dorsal head and body immersed condition had a core cooling rate of 2.6°C/h which was 87% greater than the body exposed head out condition. It was explained by the different blood flow patterns in the different conditions (55). In the condition where only the head was in the cold water, there was a large volume of perfused tissue. Any cooled blood from the head would quickly be dissipated through the perfused tissue and have a small effect on the core temperature. In the condition where the whole body was in the water, the blood vessels of the extremities were maximally constricted. The cold blood returning from the head was distributed into a smaller tissue volume, causing the greater drop in core temperature.

The conditions of the study by Lockhart (16) were repeated in a follow-up study by Giesbrecht et al. (16) where the thermal effects of dorsal head cold water immersion were studied. This time the confounding effect of shivering heat production was minimized by the use of meperidine and the water temperature was 12ºC. The results in this study showed that when the body was insulated, dorsal head immersion did not result in a significant decrease in T_{es} (0.5ºC) compared to the head out condition (0.7ºC). However, in the body-exposed conditions T_{es} decreased more after 30 minutes of immersion in the dorsal head-immersion condition (2.5ºC) than in the head-out condition (1.8ºC). The results in this study did not confirm that heat loss from the head was greater per surface area compared to other areas of the body. The difference in the effect of dorsal head cooling on body core temperature in the different conditions was again explained by the difference in volume of perfused tissue.

These findings were consistent with reports from Alexander (1) who reported on gruesome studies that were done by two German investigators during the Second World War in concentration camps in Dachau. They found that the effect of cooling of the dorsal head in 2-4ºC water on rectal temperatures was minimal when the body was not exposed, compared to the much greater effect when the whole body as well as the dorsal head was exposed.

In a recent study done by Wang et al. (57) brain temperature was reduced with a cooling helmet which encased the patients head and neck. The helmet was designed for the purpose of emergency treatment for patients with anoxic brain injury. The brain cooling rate was an average of 1.84ºC (±0.9) in the first hour. What is interesting about this study is that it reports no changes in core temperatures (measured in the bladder) in an average of three or four hours after starting treatment. The average age of the subjects was high and they suffered from stroke. Busto et al. (5) demonstrated that rectal temperature unreliably reflects brain temperature during brain ischemia in rats.

Froese et al. (15) and Rasch et al. (46) studied heat loss from the head during rest and exercise respectively. Although the studies used different techniques they were consistent in indicating that a powerful heat sink exists on the head. These studies showed an inverse relation between ambient temperature (T_a) and heat loss through the head. Froese (15) concluded that heat loss from the head might be a large portion of total heat loss in a cold environment. Based on skin temperature measurements he concluded that very little vasoconstriction exists with a decrease in T_a, even when the rest of the body is in a general state of vasoconstriction.

Hertzman and Roth (28) indicated that there was an absence of vasoconstrictor reflexes in the forehead circulation. They used a plethysmograph to illustrate the selective character of vasomotor activity in the skin. This would suggest that the heat loss from the unprotected head might be excessive during exposure to low temperatures.

THE SUPPRESSION OF SHIVERING HEAT PRODUCTION THROUGH MEPERIDINE PLUS BUSPIRONE

The goal of this study is to isolate the effect of exposing the total head surface to cold water on the rate of core cooling. Heat production through shivering is the main defense of the body against core cooling and will therefore confound the effect of the exposed body parts. Shivering may also be different in the four different conditions, as each condition will be exposing a different surface area to the cold water. It is therefore necessary to suppress shivering heat production in order to isolate the primary effect of the exposed body parts on core cooling.

Meperidine is an opioid that suppresses cold induced vasoconstriction (29) and shivering heat production (16,18,49) and will consequently increase rate of core cooling (18). The effect of meperidine is far greater than equianalgesic doses of other opioids such as morphine and fentanyl which act primarily on μ-recptors (50). Its antishivering effect appears to be related to the activity at μ and kappa opioid receptors (29, Sessler, 1994 #1953). Meperidine also has a sedative effect and suppresses respiration.

Buspirone, an anti-anxiety agent, has a little specific effect on cold induced shivering. However it has been shown that buspirone and meperidine synergistically increase the shivering threshold while causing little sedation or respiratory suppression (41).

BREATHING COMPRESSED AIR UNDER WATER

Due to the fact that the subjects were fully submerged in a vertical position in two of the conditions, with the top of head just under the surface of the water, the lungs were 40-50 cm below the surface. The pressure at this depth was considerably higher than that of the atmosphere, from which they would breathe if they would have used a snorkel. This would increase the work of breathing and therefore subjects breathed compressed air from a SCUBA tank.

Breathing compressed gas under water presents the risk of barotrauma – a rupture of airway or lung tissue. This pressure-induced injury to the lungs could be fatal.

Volume and pressure are inversely related at constant temperatures and constant amounts of gas (Boyle's law). More air is thus required to fill the lungs to the same volume at an increased depth. If a breath is taken at a certain depth and the airways are closed while ascending to the water surface, the decreased outside pressure will result in an increased lung volume. Barotrauma occurs if this increase in volume causes overdistension and rupturing (12).

The subjects in this study therefore all were certified SCUBA divers who understood that they should not hold breath under water and they should not surface quickly.

METHODS

SUBJECTS

Following approval from the Educational/Nursing Research Ethics Board, six people were studied after giving written informed consent. Subjects had to be healthy divers, physically active and between the age of 18 and 46 years. They were screened with a Par – Q questionnaire prior to inclusion and questioned by a physician to ensure that they were free of any conditions that could be worsened by exposure to cold water. Subjects with cardio-respiratory diseases, Raynaud's Syndrome or a history of asthma were not allowed to participate in the study. All the subjects were males.

ANTHROPOMETRIC DATA

Height (h), weight (w), age and four measurements of skin fold thickness were determined.

Body Mass index (BMI) was calculated as follows: BMI = $w \cdot h^{-2}$ (36).

Body density (D_b) was estimated from four skin folds by the equation: D_b(kg/l) = 1.1631 – 0.0632 · $\text{Log}_{\text{base}10}$ (bicep + tricep + subscapularis + suprailiac skin folds). It should be noted that the quantitative values recorded in this equation are age specific and that slight deviations from these values exist for differing age groups (11). After obtaining an estimate of body density using the above equation, this value was then applied to the Siri equation as shown in the study of Durnin and Womersley (1974) to calculate the fat percentage of the body: % Body Fat = $4.95/D_b - 4.5 \times 100$ (11).

Body surface area (BSA) was calculated according to the equation of DuBois: BSA (m^2) = $0.20247 \times \text{Height(m)}^{0.725} \times \text{Weight(kg)}^{0.425}$ (10).

See Table 1 for anthropometric data for all subjects.

Table 1. Descriptive data for six subjects

Subject	Sex	Age (yr)	Height (cm)	Mass (kg)	BMI	BSA (m^2)	Sum of four skin folds (mm)	% Body Fat
1	M	46	183	86	25.7	1.94	46.5	17.99
2	M	35	184	90	26.6	1.98	67.7	22.60
3	M	22	182	78.5	23.7	1.86	43.0	17.04
4	M	34	172.5	78	26.2	1.78	82.1	25.00
5	M	31	176	110	35.5	2.09	130.0	30.82
6	M	33	182	120	36.2	2.22	124.0	30.21
MEAN		33.50	179.92	93.75	28.99	1.98	82.22	23.94
SD		7.71	4.59	17.37	5.43	0.16	37.56	5.87

BMI and BSA were calculated from height and weight measurements (10)
Four skin fold measurements were from biceps, triceps, subscapularis and suprailiac crest.
% Body fat was estimated from these four skin folds (11).

INSTRUMENTATION

For each trial subjects wore a swimsuit while being instrumented in a room at an ambient temperature of ~23°C.

Single-channel electrocardiogram was monitored and heart rate (HR) was recorded at 30-second intervals.

Twelve heat flux transducers (sites listed below) were taped to the skin (Figure 1), measuring temperature and cutaneous heat transfer (Concept Engineering, Old Saybrook, CT) according to the standard procedures used in this laboratory. Serial data from the transducers were acquired on an electronically isolated Macintosh computer at 30-second intervals. The results were averaged for every 30-second period and recorded in a spreadsheet format on a hard disk. The software used to process this data is LABVIEW graphical signal processing software (National Instruments, Austin, T_X).

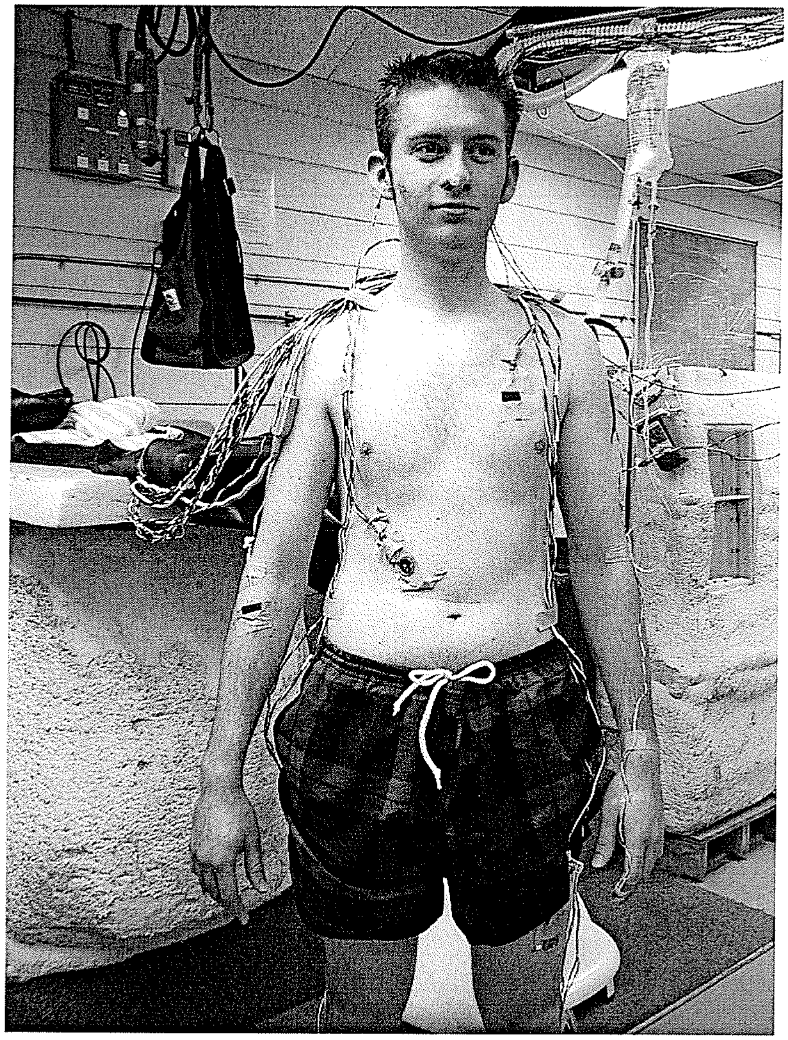

Figure 1. Twelve heat flux transducers taped to the skin

Core temperature was monitored with a disposable esophageal thermocouple inserted through the nose down the esophagus to the level of the heart. This is a standard procedure in our laboratory and provides the best non-invasive measure for intra-cardiac temperature (27).

An intravenous line was started before and maintained during trials to administer meperidine (demerol) to inhibit shivering. The insertion site was covered with Tegaderm, a transparent, waterproof dressing so that the broken skin was never directly exposed to the water.

Oxygen consumption ($\dot{V}O_2$) and the respiratory exchange ratio (RER) were measured with an open-circuit method from measurements of expired minute volume and inspired and mixed expired gas concentrations sampled from a mixing box (V_{max} 229 by Sensormedics, Yorba Linda, Ca). When subjects were submersed, the lungs were 40 to 50 cm below the surface of the water. The pressure at this depth made it difficult to breathe through a snorkel, and therefore subjects were breathing compressed air from a SCUBA tank through a regulator (Blizzard by Sherwood Scuba, Niagra Falls, N.Y.) and a mouth piece. The subjects inhaled through a one way valve on the regulator which opened on demand when inhalation caused a negative pressure in the chamber of the regulator. Gasses were exhaled through another one way valve and the regulator was modified so that all expired gasses could be collected and transported to a flow transducer and mixing box. A solid, plastic fitting (inner diameter 2.8 cm) was glued to the chamber of the regulator, to facilitate connection to the mixing box by a 5.4 cm of light-weight, flexible tubing.

During submersion of the head, the mouth and regulator were 30 - 40 cm below the water surface. At this depth, the pressure in the expiratory chamber of the regulator was much higher than the pressure in the tube collecting the exhaled air, so that the air kept flowing through the one-way valve into the tube, without closing in between expirations. To increase the resistance against which the subjects were breathing, another one way resistance valve was placed near the regulator. A plastic cylinder (8 cm in length) connected the plastic fitting on the regulator to the resistance valve which was directly connected to the plastic tubing. All of these connections were secured with metal hose clamps (Figure 2).

This was standard procedure for all the trails. To add more resistance during submersion, water was added to the tube so that the level of water in the tube was the same as the surface level of the water in the cold water tank. This created equal pressures in the tube and the expiratory chamber of the regulator so that the valve, separating the air in the regulator from the air in the tube, closed during inspiration.

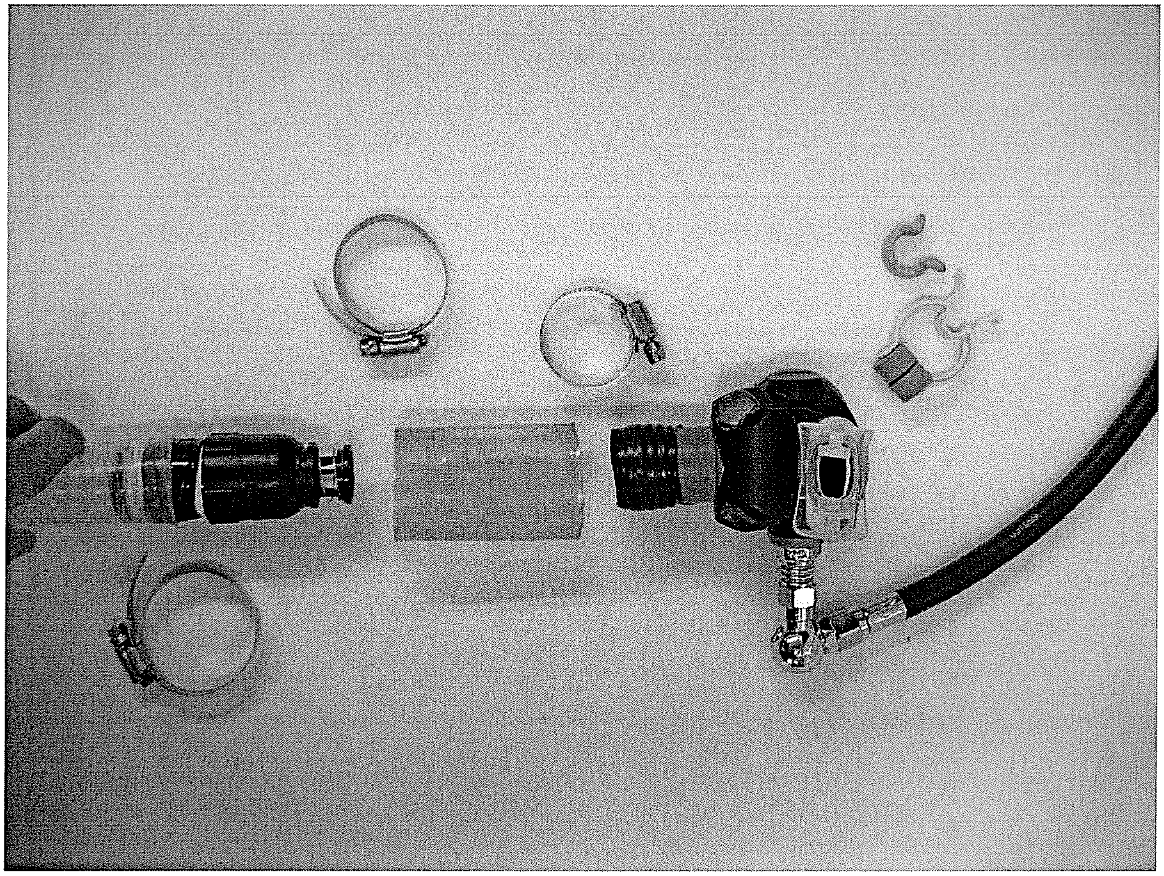

Figure 2. Modified regulator with resistance valve

Gas analyzers were calibrated against gases of known concentration prior to each session.

Oxygen saturation of the blood was measured at the forefinger using a pulse oximeter (Datex Ohmeda, Louisville, Kentucky). Due to the fact that meperidine suppresses breathing, subjects had to be monitored to ensure that blood O_2 saturation stayed above 95%. If the saturation dropped too low they were aroused and requested to take deep breaths which always increased O_2 saturation. Vasoconstriction caused by the cold stimulus and slight compression of the oximeter, caused occlusion of blood flow to the forefinger so that a false low measurement was obtained during some of the experiments. Placement of the probe on another finger of the same hand solved the problem.

PROTOCOL

The subjects arrived at the laboratory at least 60 minutes prior to submersion/immersion in order to administer the first dose of buspirone. One tablet (10 mg) was taken 60, 30 and 5 minutes before the start of the test (a total of 30 mg). The ECG leads and heat flux transducers were taped to the skin after which the esophageal probe was inserted and the intra venous line started.

During the trial, meperidine was administered by the physician. A total of 2.5mg/kg was diluted in saline so that the volume of the injection was 10 ml (0.25mg/kg/ml). The total amount of meperidine was administered in ten small boluses of 0.25mg/kg to each subject in all four of the trails. Baseline values were recorded for 20 minutes. Five of the meperidine-doses were administered during the second ten minutes of baseline at 2-minute intervals. Administration of meperidine during the baseline was done while the subjects were sitting in the initial experiments. Due to a drop in blood pressure as a consequence of meperidine some of the subjects experienced nausea. One subject (subject # 4) got nauseous after the second dose of meperidine in baseline and was lowered into the water to get the effect of hydrostatic pressure to support his blood pressure. To prevent the drop in blood pressure in the remaining experiments, subjects were laid down on a stretcher (Figure 3) for the second half of baseline, which had the desired effect of preventing nausea. Two minutes after the fifth dose of meperidine the subjects were lowered into stirred water at 17°C.

Each subject was exposed to all four conditions. The four different conditions were:

<u>Two conditions where the body was insulated from the cold water</u>:

Insulation consisted of two fleece garments, two pairs of wool socks, one wool glove for the hand that was in the water and a dry suit (Figure 3), including a waterproof glove. The hand with the intra venous line was kept out of the water and the oximeter was clipped onto one of these fingers.

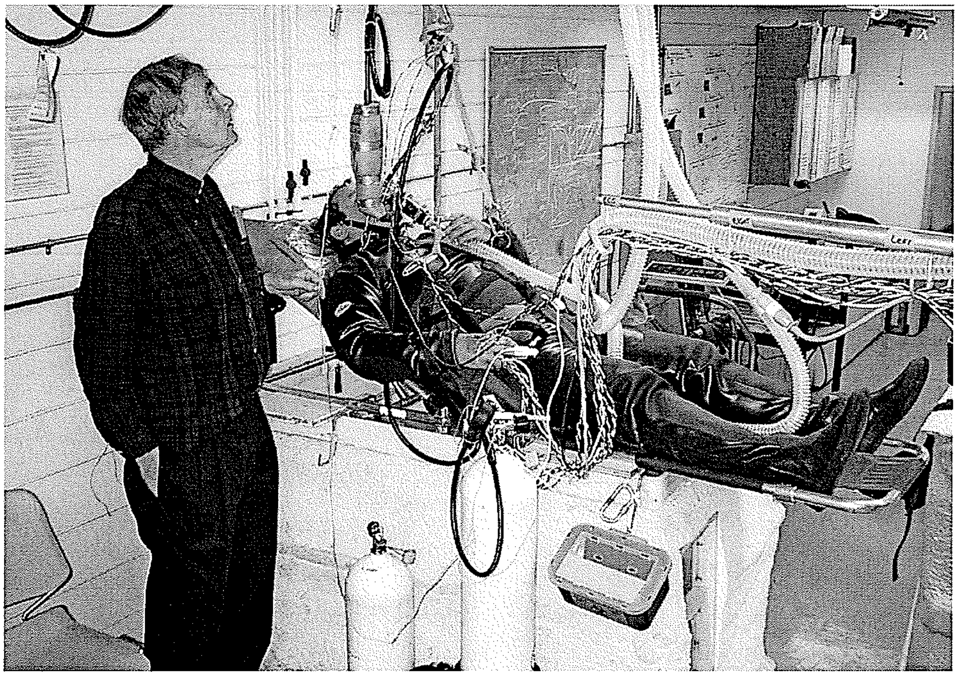

Figure 3. Dry suit and stretcher

<u>Body-insulated, Head-out</u> - The body was only immersed to the neck with the whole head positioned above the water and covered with a fleece cap. The cap also kept the posterior head heat flux disk in place. A nose clip prevented exhaling through the nose (Figure 4).

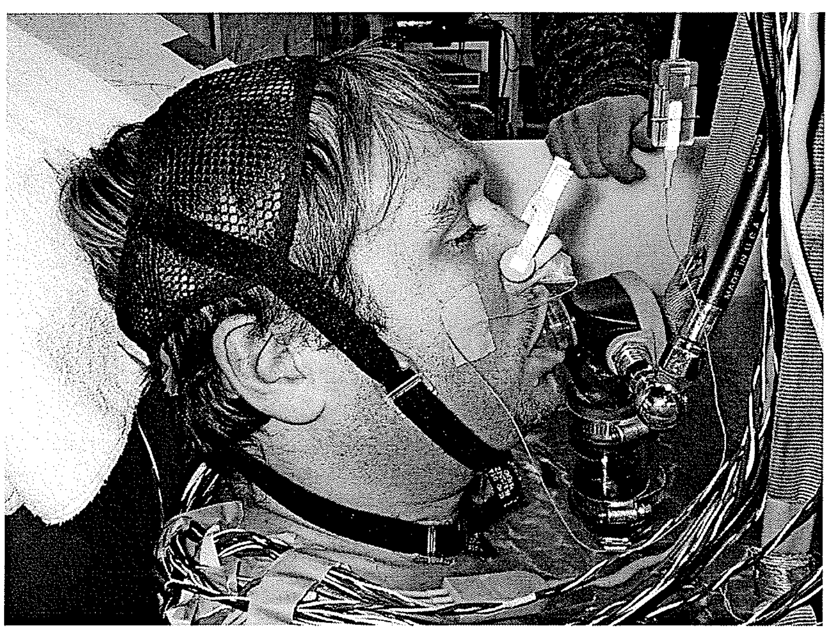

Figure 4. Head-out position

Body-insulated, Head-in - The whole head was exposed to the water during submersion (Figure 5), while a diving mask and a nose clip were worn. A mesh hood was worn to position the posterior head heat flux disk (Figure 5).

Figure 5. Head-in condition

Figure 6. Mesh hood keeping the posterior probe in position

Two conditions where the body was uninsulated and exposed to the water:

Body-exposed, Head-out – The body was only immersed to the neck with the whole head positioned above the water and covered with a fleece cap. The cap also kept the posterior head heat flux disk in place. A nose clip prevented exhaling through the nose.

Body-exposed, Head-in - The whole head was exposed to the water during submersion, while a diving mask and a nose clip were worn. A mesh hood was worn to position the posterior head heat flux disk.

For the body–insulated trails the initial ten minutes were recorded with all the insulation except for the dry suit and the second fleece garment that was only pulled up to the knees. The head heat flux disks were not in place either. Recording was paused after this period to put the dry suit on and to tape the disks to the head.

Subjects were then suspended in a harness and lowered by an electronically isolated hoist so that the top of the head was fully submerged and the lungs were about 40 to 50 cm below the surface of the water in the submerged conditions. Two weight belts were needed to keep them in this position – one around the waist and the other one over the thighs. Water was added to the tube collecting the exhaled gasses. In the immersed conditions the subjects were lowered so that the head was positioned above the surface of the water. One weight belt around the waist was enough to keep them in this position.

After entering the water meperidine was given as required to suppress shivering for the first experiment (a body-exposed condition) done on the first three subjects. In the experiments that followed for these subjects, meperidine was administered at the exact time as in the first experiment. The average of these times were calculated so that a protocol could be set for the approximate administering of meperidine to the three remaining subjects who then did their body-insulated trails first in order to maintain a balanced order. Meperidine was given at the same times as the first experiments except if shivering occurred in which case the next dose was given. The maximum cumulative amount of meperidine was 2.5 mg/kg. Shivering occurred in 4 experiments in the body-exposed conditions after the maximum amount of meperidine was given.

Subjects were in the water until either body core temperature decreased to 34ºC or 45 minutes of immersion/submersion elapsed, whichever came first. Subjects had the option of getting out at any time they wished to do so, but none of them requested to get out before at least one of the two criteria was met, neither did the physician stop an experiment for health or safety reasons.

After the body-exposed experiments the subjects were actively warmed by entering a warm bath of 41 - 43ºC. They were always given this option in the body-insulated conditions, but in most of these experiments, covering by a sleeping bag adequately rewarmed them. Subjects were observed in the laboratory for about 30 minutes after the experiment for possible adverse effects of meperidine and stayed there until they were picked up by someone to take them home as they were not allowed to drive for the rest of that day.

DATA ANALYSIS

Power analysis determined that six subjects should be required to determine an inter-condition difference in T_{es} of 0.5ºC when alpha is 0.05 (16).

The following variables were calculated for all four conditions:

Rate of T_{es} cooling (ºC/min) is the slope of ΔT_{es} data between 10 (T_{es} only started to drop after 10 minutes in the body-insulated studies) and 30 minutes of immersion/submersion when n = 6.

Baseline T_{es} ($T_{es\ (base)}$) (ºC) is the esophageal temperature just before entering the water.

Final T_{es} ($T_{es\ (final)}$) (ºC) is the esophageal temperature at the maximum time that each subject has spent in the water in all four of the conditions. (Subject #1: 39 minutes; subject # 2, 4 and 5: 45 minutes; subject # 3: 32.5 minutes and subject #6: 37 minutes)

Drop in T_{es} (ΔT_{es}) = $T_{es\ (base)}$ - $T_{es\ (final)}$

Flux values for each transducer ($W \cdot m^2$) were converted into W/region as follows:

$Flux_{region}$ (W) = transducer flux ($W \cdot m^{-2}$) x BSA (m^2) · regional percentage

The following regional percentages were assigned based on Layton et al. (Layton et al. 1983): forehead 4%, posterior head 3%, chest 8.75%, back 17.5%, abdomen 8.75%, upper arm 12%, forearm 7%, posterior thigh 9.5%, anterior thigh 9.5%, posterior calf 6.5%, anterior calf 6.5%, foot 7%.

Heat flux of the head (HF_h) (W) = forehead + posterior head

Heat flux of the trunk (HF_t) (W) = chest + back + abdomen

Heat flux of the arm (HF_a) = upper arm + forearm

Heat flux of the leg (HF_l) = posterior thigh + anterior thigh + posterior calf + anterior calf + foot

Total cutaneous heat flux HF_T (W) = $HF_t + HF_h + HF_a + HF_l$

During some experiments there were one or more faulty heat flux readings. In these cases the fraction value of the missing site was added to the fraction value of the closest working site in the same region.

Average skin temperature (T_{SKavg})

T_{SKavg} (ºC) = anterior head · 0.04 + chest · 0.0875 + back · 0.175 + abdomen · 0.0875 + posterior upper arm · 0.1 + forearm · 0.09 + anterior thigh · 0.095 + posterior thigh · 0.095 + posterior calf · 0.065 + anterior calf · 0.065 + foot · 0.07 + posterior head · 0.03

The fractions were based on Layton et al. (Layton et al. 1983).

Metabolic rate in Watts was determined for every 30 seconds:

$$M\ (W) = \dot{V}O_2\ (l/min) \times 69.7(4.686 + [(RER - 0.707) \times 1.232])$$

Energy production (E_{30min}) in kilojoules was determined for the first 30 minutes of immersion/submersion of each experiment:

E_{30min} (kJ) = M (W) x 1.8 where M (W) was the average over the 30 minutes.

The respiratory heat loss (RHL) was calculated in dependence of the energy production:

RHL (kJ) = 0.09 x E_{30min} (kJ)

Total Energy Loss (kJ) for each condition during the first 30 minutes of immersion/submersion was calculated by adding HF_T (kJ) and RHL (kJ):

Total Energy $Loss_{30\ min}$ (kJ) = HF_T (W) x 1.8 + RHL (kJ).

HF_T (W) was taken as the average over the first 30 minutes of immersion/submersion. The same calculations were made to obtain the heat loss for each region over 30 minutes in kJ.

For all parameters data for the four trails were compared using repeated measures analysis of variance. The same method was used when different periods of the experiment were compared. Post hoc analysis for significant differences between treatments and between periods was accomplished using the Holm-Sidak test. Results are reported as means ± SD; $p < 0.05$ identified significant differences.

RESULTS

Core Temperature Response

All subjects did not stay in the water for equal lengths of time as experiments were terminated when the core temperature reached 34°C. Exit time for all the trials in both the body-insulated conditions was 45 minutes. The average exit time for the body-exposed, head-out condition was 43.5 ± 3 minutes and for the body-exposed, head-in condition was 40.9 ± 5 minutes.

The rate of core cooling was less in the body-insulated, head-out (0.02 ± 0.0°C/min) condition than in both the body exposed (head-out: -0.04 ± 0.1 °C/min and head-in: -0.05 ± 0.1°C/min) conditions ($p < 0.01$) (Table 2).

Table 2. Slopes of decline in temperature for each subject in each condition from 10 – 30 minutes immersion/submersion.

Subject	Body-insulated, Head-out	Body-insulated, Head-in	Body-exposed, Head-out	Body-exposed, Head-in
1	-0.0096	-0.0324	-0.0284	-0.0660
2	-0.0186	-0.0201	-0.0224	-0.0435
3	-0.0203	-0.0292	-0.0292	-0.0465
4	-0.0240	-0.0306	-0.0379	-0.0288
5	-0.0203	-0.0216	-0.0176	-0.0208
6	-0.0297	-0.0409	-0.0934	-0.0687
MEAN	-0.0204 *	-0.0291	-0.0382	-0.0457
SD	0.0066	0.0076	0.0279	0.0193

* Cooling rate is less than both the body-exposed conditions ($p < 0.03$)

Body core temperature dropped significantly from baseline values in all four conditions. There was a tendency for a larger drop in T_{es} from baseline as more of the body was exposed to the cold water (Figure 7). The difference increased from body-insulated, head-out (0.63 ± 0.2°C) condition to body-insulated, head-in (1.08 ± 0.2°C) condition and further increased in the body-exposed, head out (1.42 ± 0.7°C) and body-exposed, head-in (1.91 ± 0.6°C) conditions. There were only significant differences between the body-insulated, head-out and the two body-exposed conditions ($p < 0.008$) and the body-insulated, head-in and the body-exposed, head-in condition ($p = 0.011$).

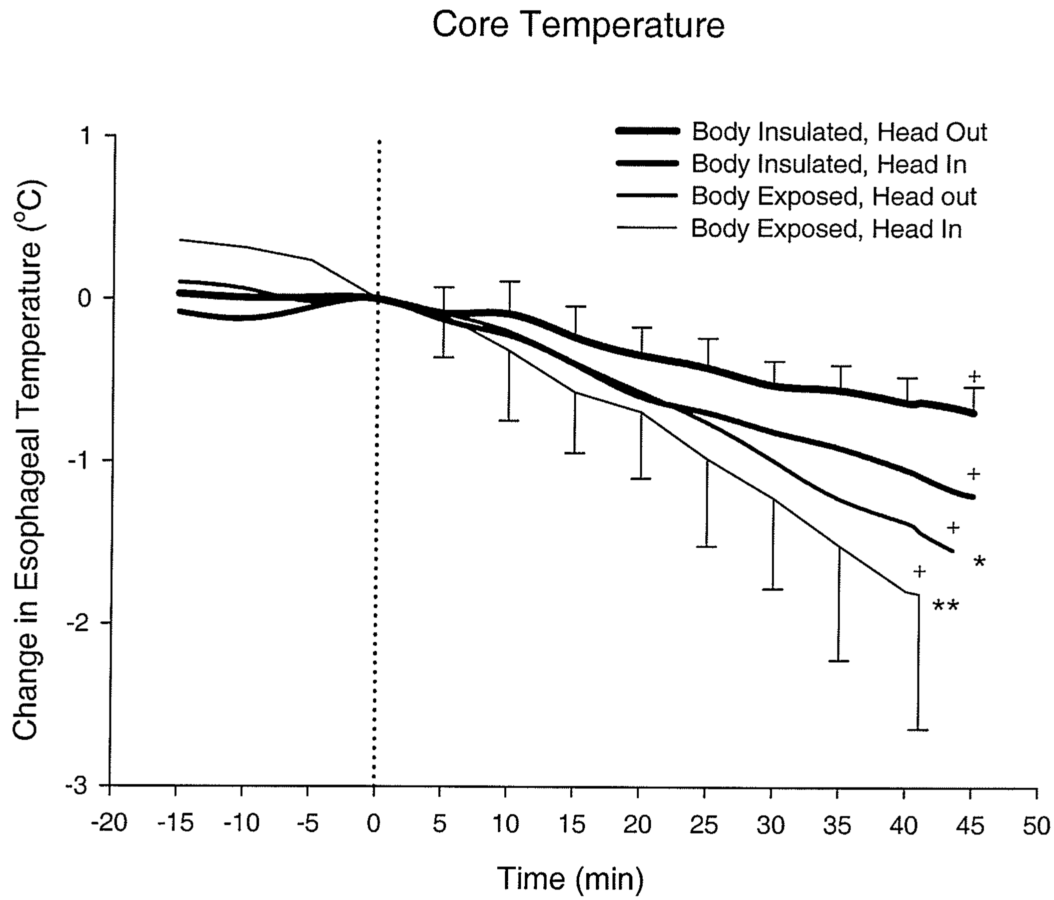

Figure 7. Change in core temperature throughout each trial. Time 0 indicates the time that the chest was immersed in the head-out sub-condition and the time that the head was submersed in the head-in sub-condition. Twenty minutes of baseline includes 5 meperidine injections (0.25mg/kg each) at 2-minute intervals from minutes -10 to -2. Exit time in both the body-insulated conditions was 45 minutes. The average exit time for the body-exposed, head-out condition was 43.5 ± 3 minutes and the average exit time for the body-exposed, head-in condition was 40.9 ± 5 minutes.
* Lower than body-insulated, head-out condition
** Lower than both body-insulated conditions
+ Significantly lower than baseline

In the body-exposed subcondition there was no significant difference between the head-in and head-out conditions. Even though three subjects cooled much quicker when their heads were immersed, head immersion had no effect on the other three. Therefore a subsequent analysis was conducted to determine if any body composition factors could explain why some subjects showed a difference while some did not. A previous study (17) demonstrated that the difference between the rate of core rewarming between different rewarming techniques was accentuated in high fat subjects but attenuated in low fat subjects.

Within each of the body-insulated and body-exposed sub-conditions, the effect of head submersion on the drop in core temperature ($\Delta T_{es\ Head\text{-}in}$ - $\Delta T_{es\ Head\text{-}out}$) was plotted against subject BMI, weight and height. A line of best fit was drawn and r^2 values > 0.57 determined significant correlations ($p < 0.05$). In the body-insulated conditions the effect of head submersion on drop in core temperature was inversely correlated with BMI (r^2 = 0.7557) and weight (r^2 = 0.7005). In the body-exposed conditions no significant correlations were found (Figure 8).

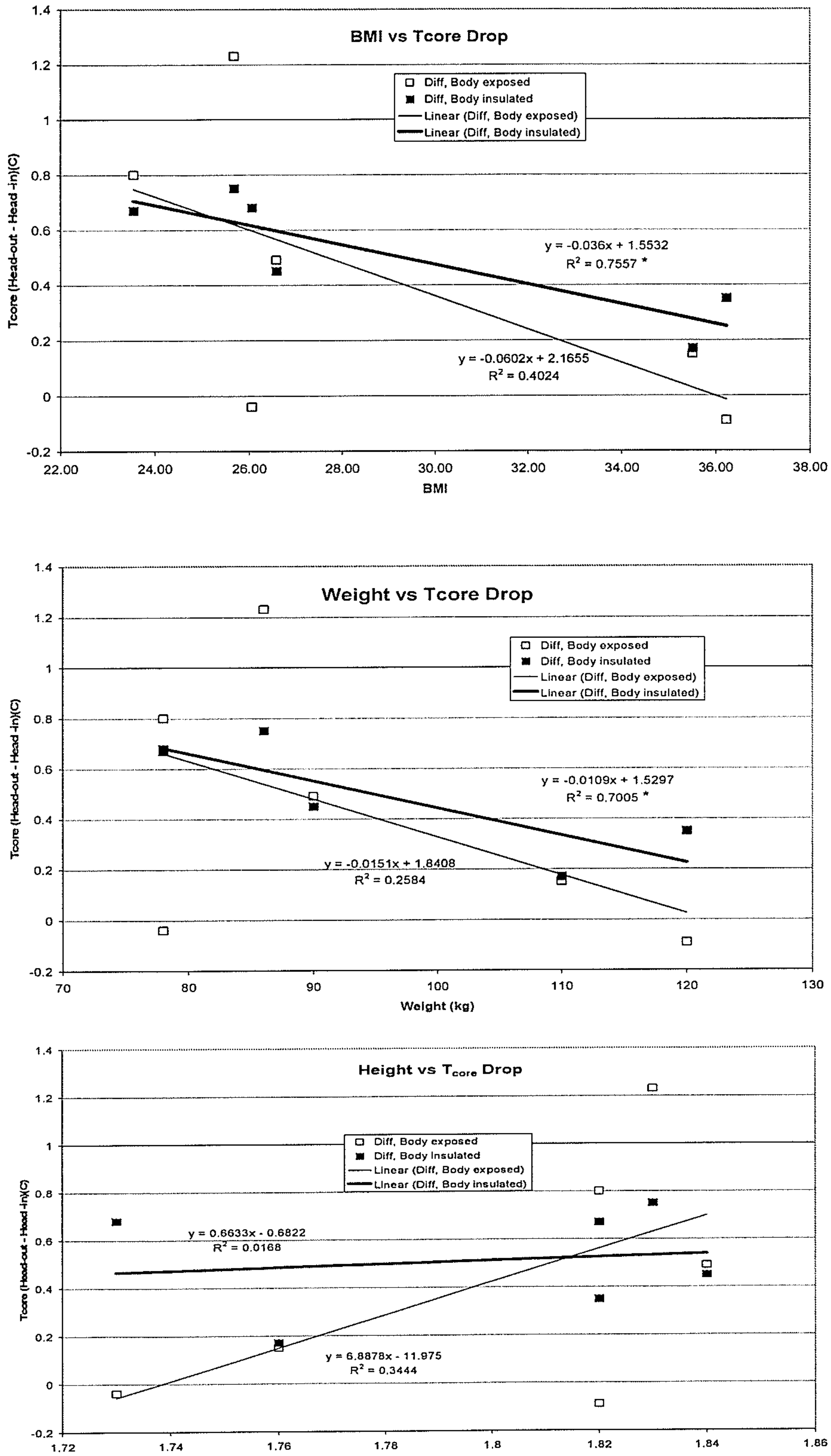

Figure 8. The effect of head on the drop in core temperature (Tes head-out - Tes head-in) was plotted against subject BMI, weight and height. A line of best fit was drawn and r2 values > 0.57 determined significant correlations ($p < 0.05$).

* Inverse correlation between BMI (r2 = 0.7557) and weight (r2 = 0.7005) in the body-insulated sub-conditions.

Cutaneous Heat Loss

In both the body-exposed sub-conditions there was an initial large increase in cutaneous heat loss (1350.9 ± 145.0 W) which gradually decreased to 341.51 ± 59.4, as the gradient between the water and the skin temperatures decreased (Figure 9). Cutaneous heat loss was greater in the body-exposed conditions throughout with a greater heat loss in the head-in condition at 15 minutes. In the body-insulated sub-conditions heat loss in the head-in conditions were greater throughout.

Total Cutaneous Heat Loss

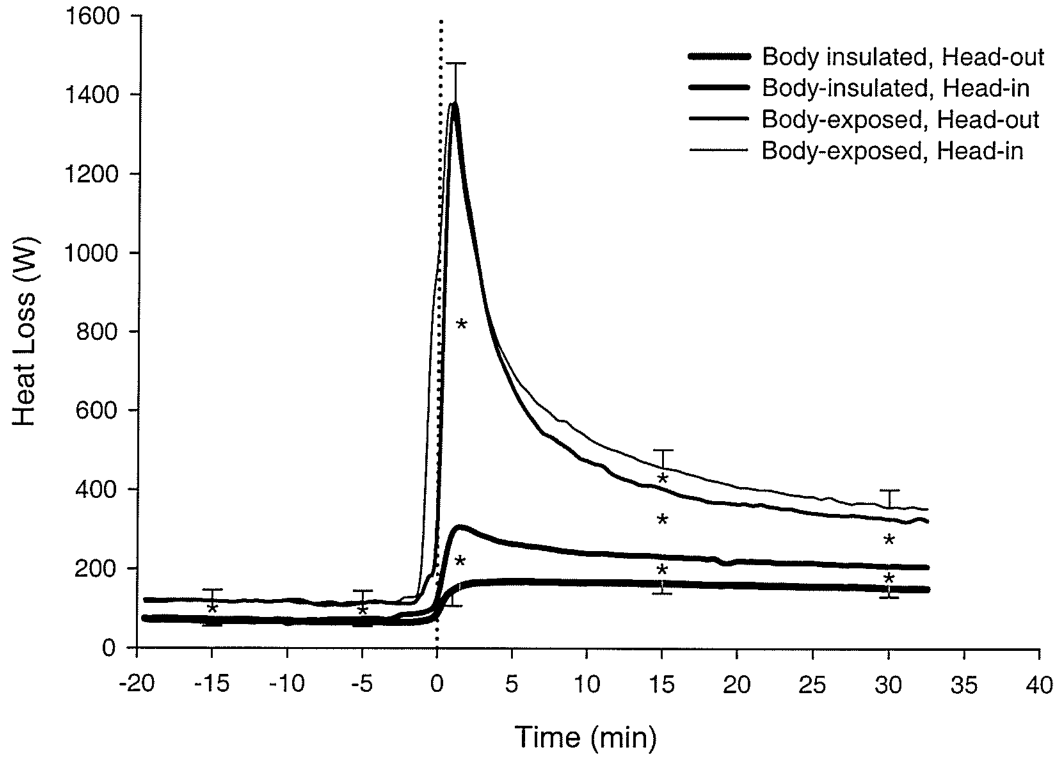

Figure 9. Average cutaneous heat loss for baseline (20 min) and immersion/submersion (32.5 min). Time 0 indicates the time that the chest was immersed in the head-out sub-condition and the time that the head was submersed in the head-in sub-condition.
* Separates conditions that are significantly different at -15 minutes, -5 minutes, 1 minute, 15 minutes and 30 minutes of the experiment.

Head submersion significantly increased head heat loss from 8.7 ± 1.5 W in the head-out sub-conditions to 43.99 ± 11.2 in the head-in sub-conditions (Figure 10).

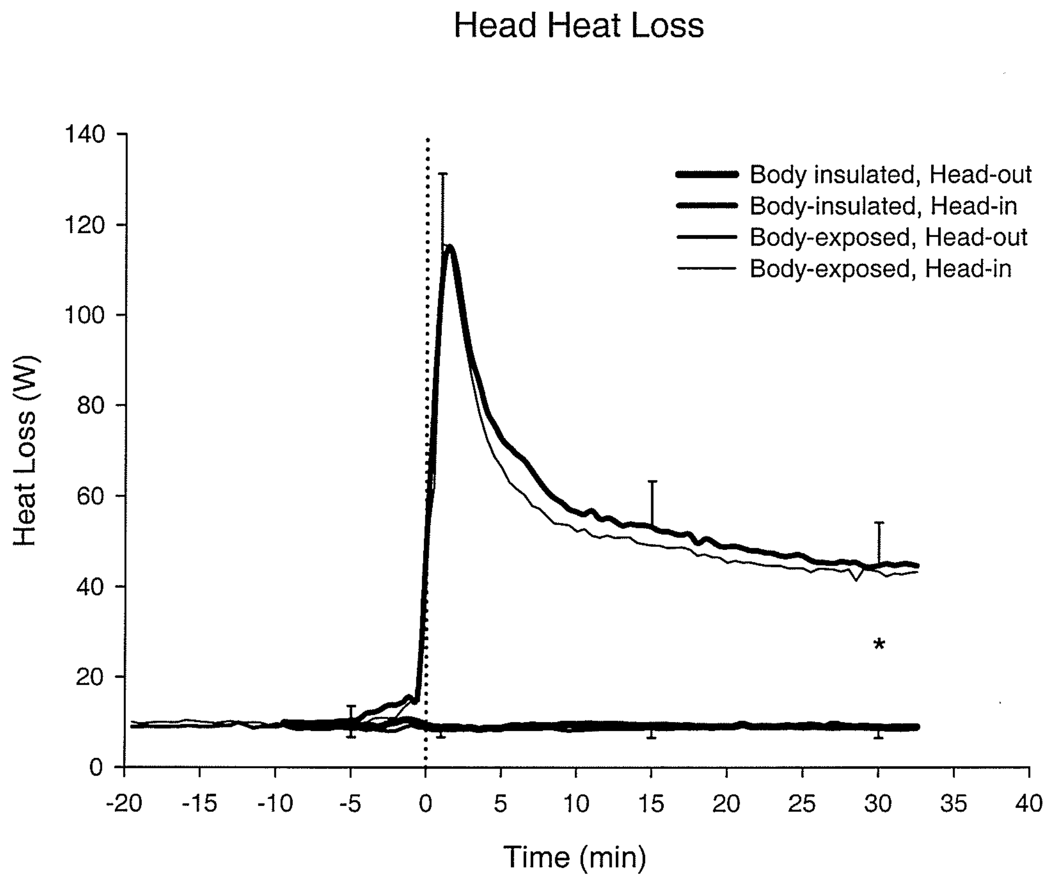

Figure 10. Average cutaneous head heat loss for baseline (20 min) and immersion/submersion (32.5 min). Time 0 indicates the time that the chest was immersed in the Head-out conditions and the time that the head was submersed in the Head-in conditions.
* Separates conditions that are significantly different at 30 minutes of immersion/submersion.

For all other areas (arms, trunk and legs) heat loss was significantly higher in the body-exposed conditions than in the body-insulated conditions throughout immersion/submersion (Figures 11 - 13).

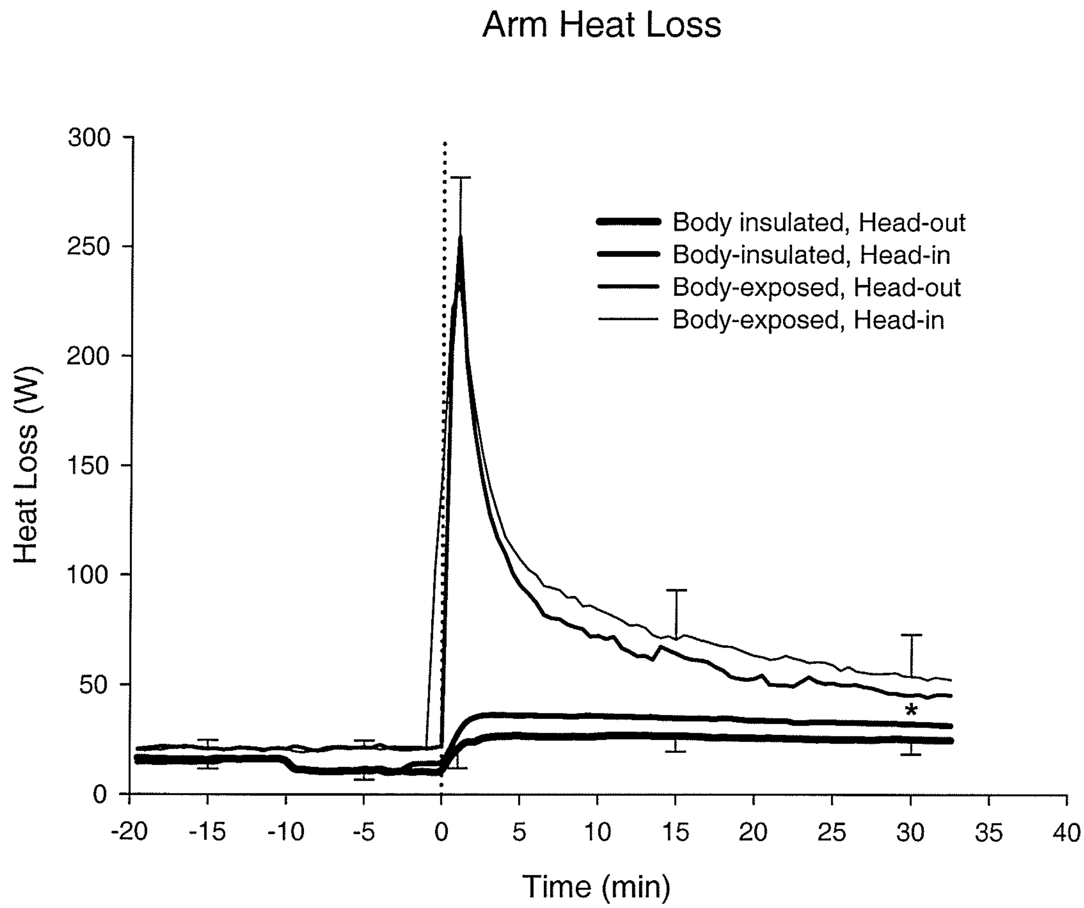

Figure 11. Average cutaneous arm heat loss for baseline (20 min) and immersion/submersion (32.5 min). Time 0 indicates the time that the chest was immersed in the head-out sub-conditions and the time that the head was submersed in the head-in sub-conditions.
* Separates conditions that are significantly different at 30 minutes of immersion/submersion.

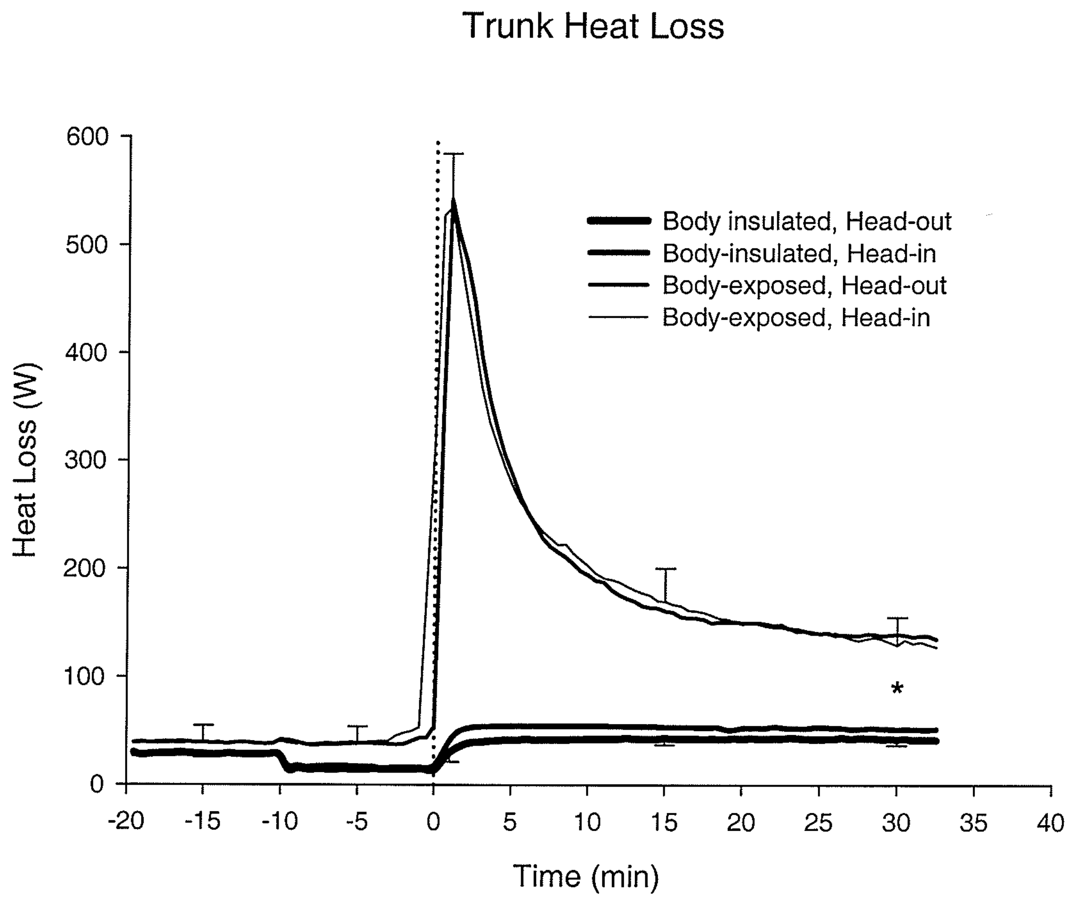

Figure 12. Average cutaneous trunk heat loss for baseline (20 min) and immersion/submersion (32.5 min). Time 0 indicates the time that the chest was immersed in the head-out sub-condition and the time that the head was submersed in the head-in sub-condition.
* Separates conditions that are significantly different at 30 minutes of immersion/submersion.

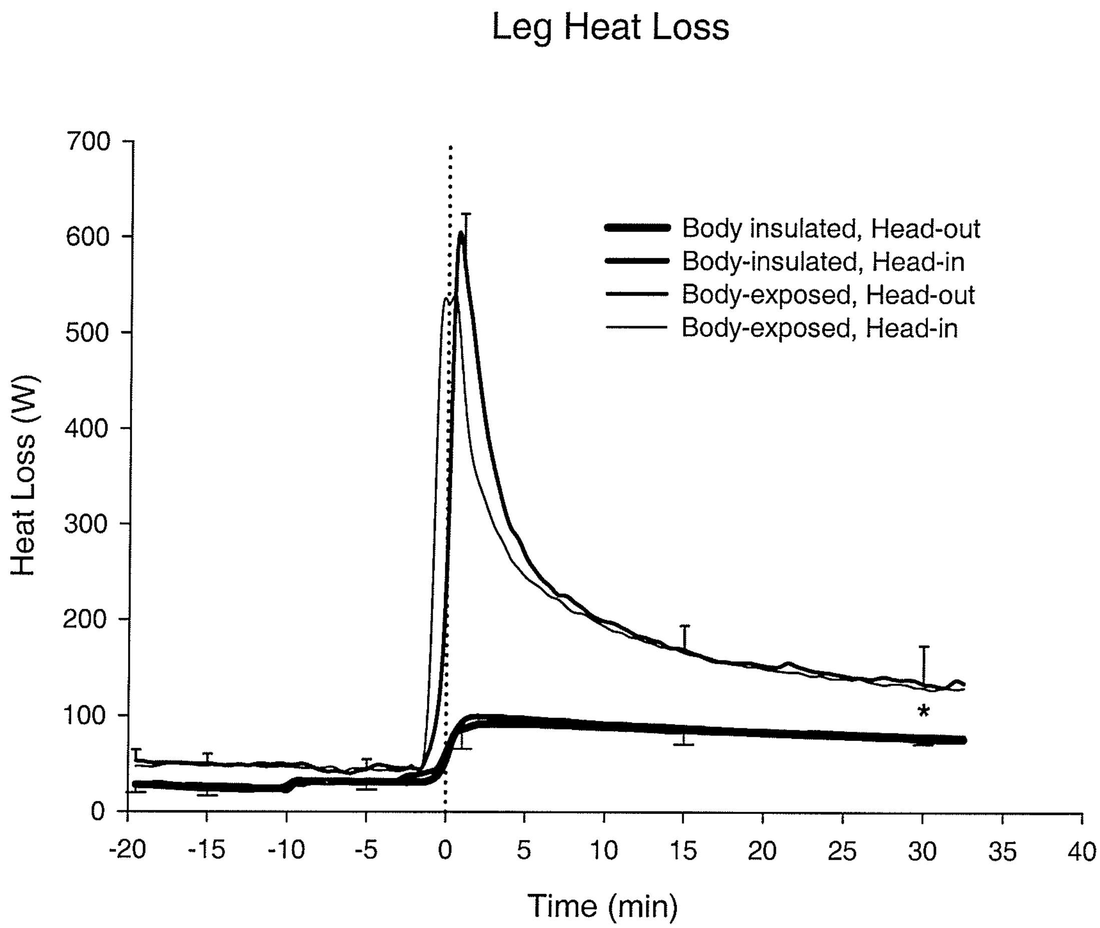

Figure 13. Average cutaneous leg heat loss for baseline (20 min) and immersion/submersion (32.5 min). Time 0 indicates the time that the chest was immersed in the head-out sub-condition and the time that the head was submersed in the head-in sub-condition.

* Separates conditions that are significantly different at 30 minutes of immersion/submersion.

Average Skin Temperature

T_{SKavg} values were higher in the body-insulated (33.6 ± 0.7°C) conditions during the second half of baseline when the total amount of insulation was added compared to body-exposed (31.2 ± 0.8°C) values ($p < 0.001$) and throughout immersion/submersion (body-insulated (31.0 ± 0. 8 °C) conditions vs body-exposed (19.3 ± 0.4 °C) conditions ($p < 0.001$)). See Figure 14.

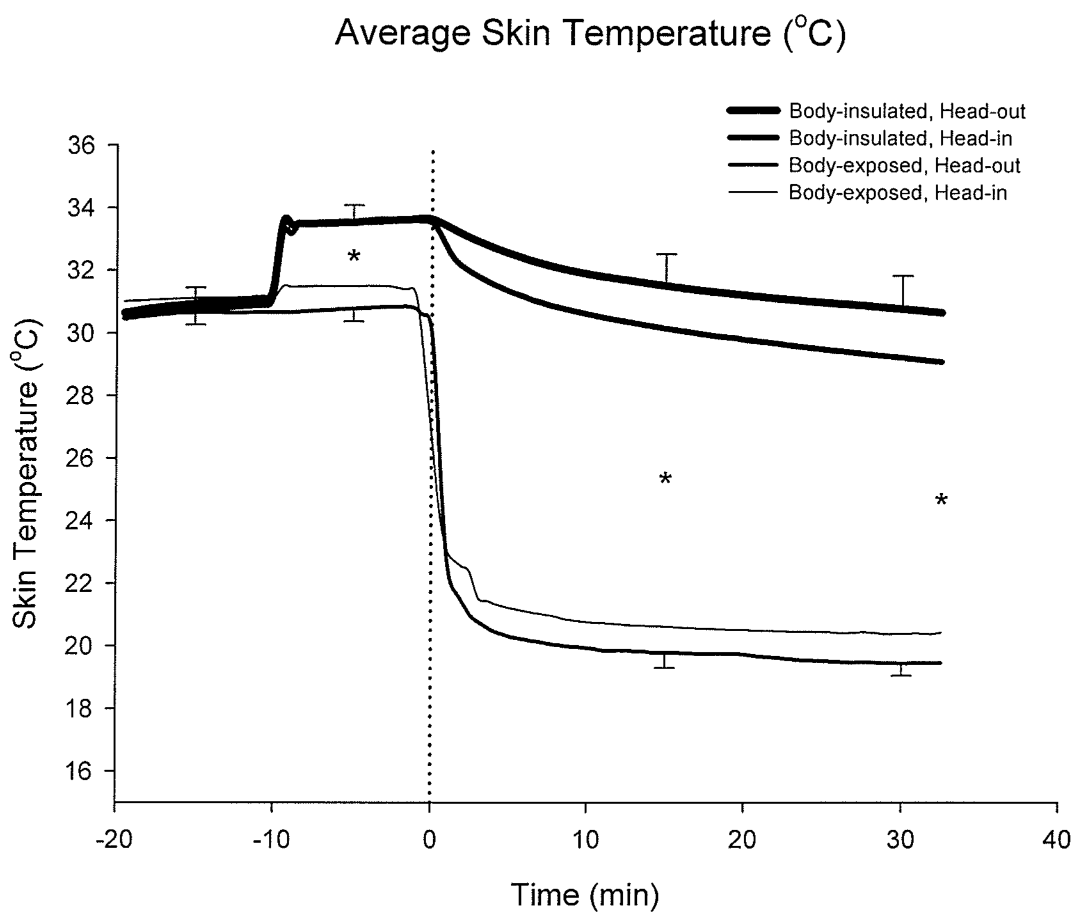

Figure 14. Average skin temperature for baseline (20 min) and immersion/submersion (32.5 min). Time 0 indicates the time that the chest was immersed in the head-out sub-condition and the time that the head was submersed in the head-in sub-condition.
* Separates conditions that are significantly different at -5minutes, 15 minutes and 32.5 minutes.

Metabolic Responses

Metabolic heat production was similar for all conditions during the baseline and up to 15 minutes of immersion.

Figure 15 shows that in the body-insulated sub-conditions there was a decrease in metabolic heat production towards the end of the experiments due to the suppressing effect of meperidine.

In the body-exposed conditions, metabolic heat production did not differ significantly throughout the experiment. Although 4 subjects started to shiver in the body-exposed conditions, heat production only increased slightly with 18% from the first 30 minutes of immersion (167.61 ± 44.1 W) to the end of the experiment (198.84 ± 84.5 W), opposed to a 400-500% increase that would be expected in the case of severe shivering (13).

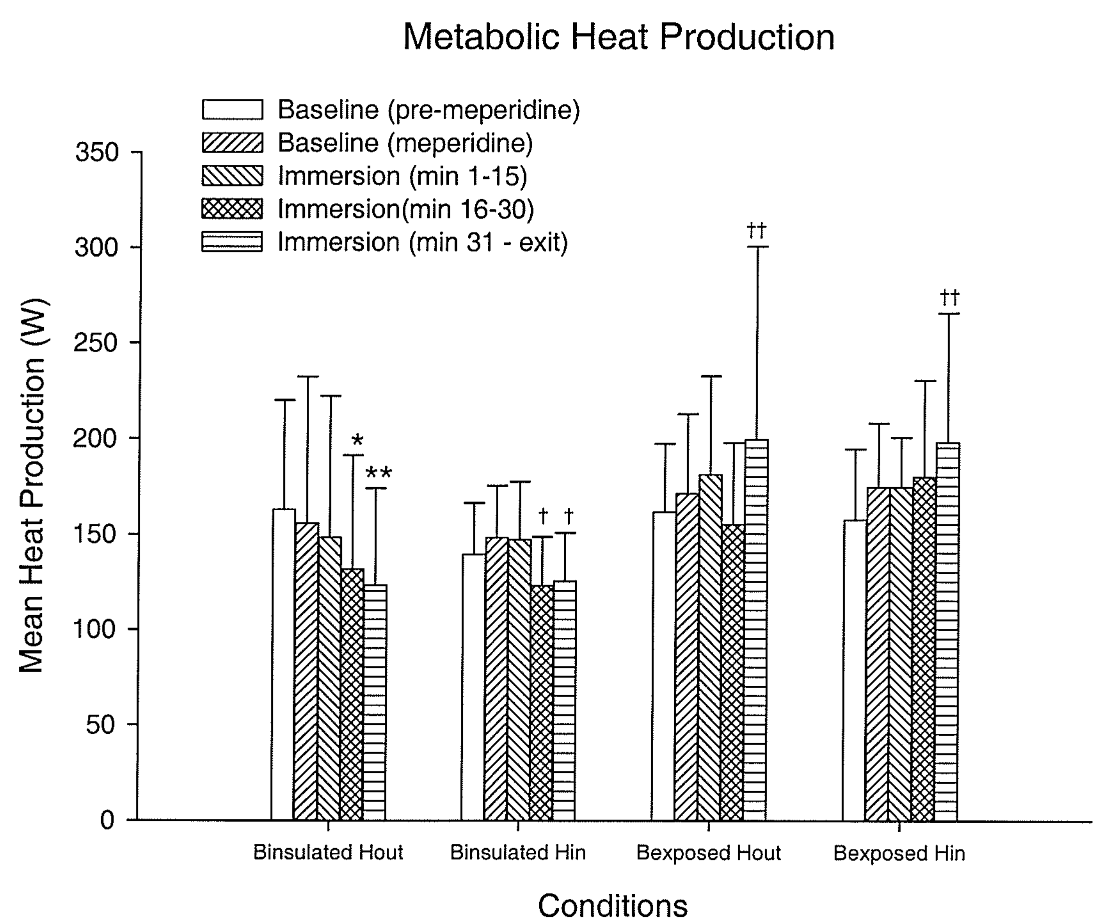

Figure 15. Metabolic heat production as calculated from oxygen consumption (l/min) and respiratory exchange ratio measurements.
* Less than pre-meperidine period in same condition.
** Less than pre-meperidine and meperidine period in same condition.
† Less than baseline meperidine and 1-15 min period in same condition.
†† Greater than body-insulated conditions during min 31 to exit period.

Energy Balance

Total heat loss from the body (heat loss from the skin and respiratory heat loss) and energy production are presented in absolute terms (kJ). Figure 16 shows that total heat loss was about 2.5 times greater in the body-exposed [9](964.19 ± 105.8 kJ) conditions than in the body-insulated [10](379.95 ± 53.5 kJ) conditions ($p < 0.001$) with the greatest loss seen in the body-exposed, head-in (1004.30 ± 91.3 kJ) condition. Heat loss through the head was 6 times greater in the head-in [11](101.6 ± 18.2 kJ) conditions than in the head-out [12](16.90 ± 2.8 kJ) conditions ($p < 0.001$). Heat loss was greater in all areas during the body-exposed conditions ($p< 0.001$) except for the head, in the body-exposed, head-out condition.

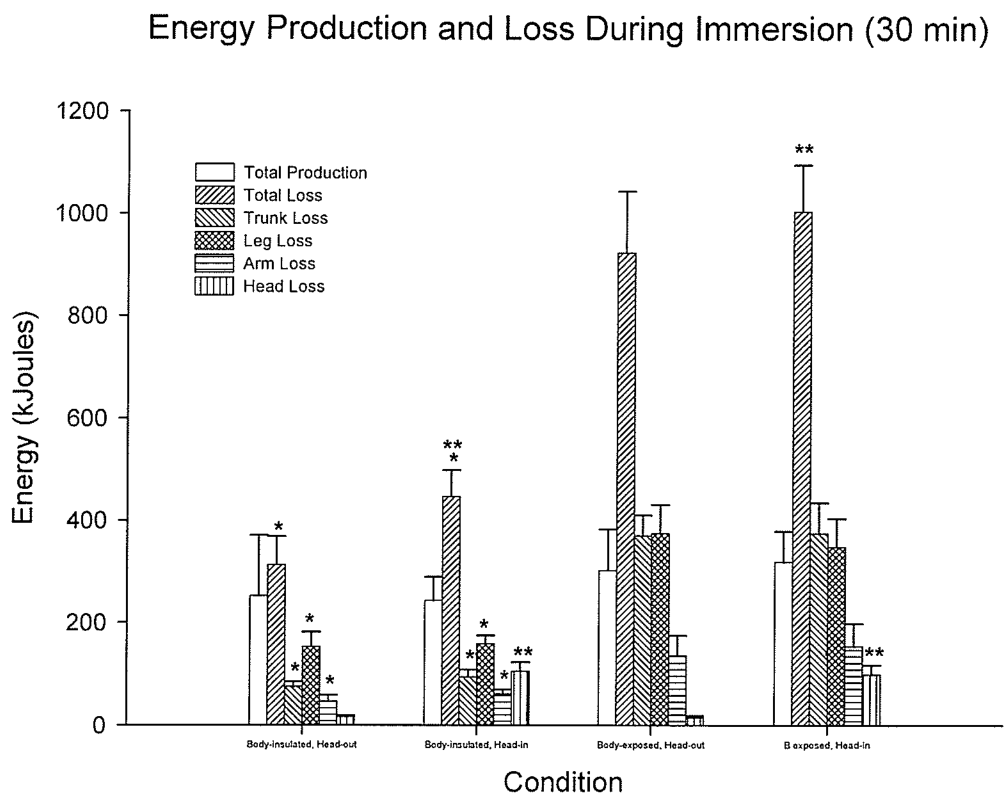

Figure 16. Energy production and loss during 30 minutes of immersion in 17 °C water. Heat production is calculated from oxygen consumption (l/min) and respiratory exchange ratio measurements. Total heat loss includes cutaneous and respiratory heat loss (9% of heat production).

- * Less than body-exposed conditions
- ** Greater than head-out conditions

[9] Mean value of the two body exposed conditions
[10] Mean value of the two body insulated conditions
[11] Mean value of the head-in conditions
[12] Mean value of the head-out conditions

Heart Rate Response

There was no difference in heart rate between the four conditions or between any of the stages of any of the four conditions (Figure 17).

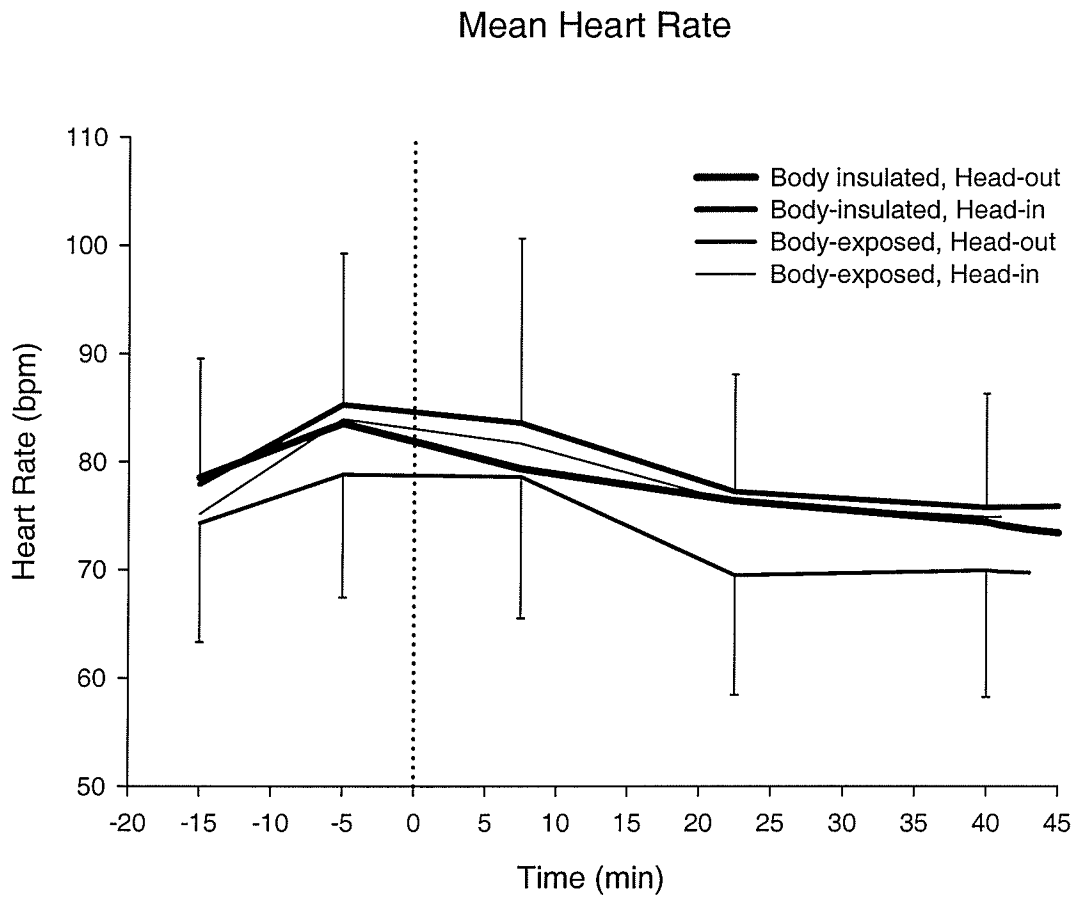

Figure 17. Mean heart rate during baseline (20 min) and immersion/submersion. Time 0 indicates the time that the chest was immersed in the head-out sub-condition and the time that the head was submersed in the head-in sub-condition. Exit time in both the insulated conditions was 45 minutes. The average exit time for the body-exposed, head-out condition was 43 ± 3.27 minutes and the average exit time for the body-exposed, head-in condition was 41 ± 5.06 minutes. There were no significant differences between any of the four conditions.

DISCUSSION

SUMMARY

This was the first ethically approved study where the whole human head was exposed to cold water to study the effect on core cooling. All subjects were exposed to four different conditions to study all the combinations of insulation and non-insulation of the head and the body in 17°C water. In order to eliminate the confounding effect of shivering, equal amounts of meperidine (2.5 mg/kg) and buspirone (30 mg) was administered to each subject in all four conditions. There was only a 18% increase in metabolic rate in both the body-exposed conditions compared to baseline values. Since maximal shivering could increase metabolic rate by as much as 400 – 500% (13), shivering heat production was adequately suppressed by the use of these drugs. An increased drop in core temperature was found when the body was exposed to the cold water, but when the head was exposed in addition to the body (insulated or exposed) only a minimal, insignificant increase in drop in T_{es} was found.

COMPARISONS WITH OTHER STUDIES

Our results from the body-insulated experiments, where the exposure of the head to cold water had a minimal effect on the drop in core temperature, is in agreement with three similar studies (1,16,35), where immersing the back of the head in the water without exposing the body, did not have any significant effect on the core temperature. However, the results in the body-exposed sub-condition in all three of these studies showed a greater drop in core temperature when the back of the head was exposed to the water in addition to the body. Alexander (1) reported that rate of core cooling, in 1 - 2°C water, increased 250% from 3.8 to 9.4 °C/h when the dorsal head was also immersed. Likewise, Lockhart et al. (35), while studying differences between two personal floatation devices (PFDs), discovered an increased core cooling rate of 87% from 1.5 to 2.8 °C/h in 10°C water when the back of the head was exposed in addition to the exposed body. In a follow up study by

Giesbrecht et al. (16) done in 12°C water and with suppression of shivering heat production through meperidine, a significant, increased cooling rate of 39% from 3.6 to 5.0 °C/h was found when the head was exposed to the water. Hayward et al. (24) showed similar relative differences when subjects were physically active in 10°C water. They demonstrated that downproofing (which intermittently submersed the whole head) increased core cooling by 36% to 4.6°C/h, compared to 3.4°C/h while treading water with the head above the water.

This increased cooling rate when the head is exposed in addition to the exposed body, was not seen in the present study, although, during the first 30 minutes of immersion, in the body-exposed, head-in condition heat loss through the head (99.0 kJ) resulted in 10% of the total heat loss (975.6 kJ), which is 1.5 times that of the approximate 7% surface area that the head takes up of total BSA. Our results confirm predictions made by Xu et al. (60), that cooling of the outer boundary of the head during cold water submersion does not have a significant effect on brain temperature.

POSIBLE EXPLANATIONS FOR THE RESULTS

The contribution of isolated whole head immersion to core temperature was of major interest in this study. Blood flow to the head, including the scalp, remains relatively high and constant during cold exposure compared to the rest of the body. Hertzman found that the ratio of head blood flow – to – surface area is 4 to 10 times greater than seen in the trunk and proximal limbs (28). Froese found little or no head skin vasoconstriction in response to cold, whether the cold stimuli came from the head alone or even during cooling of the whole body surface (15). Based on these studies and the studies done by the Germans (1), Lockhart et al. (35) and Giesbrecht et al. (16) one would expect that cooling the whole head should have a significant effect on core temperature cooling.

Explanations for the negative results in this study could be related to technical issues during the head-in conditions. Time delays occurred between the entrance of the body and the entrance of the head into the water due to the practical issues such as leaking equipment, the addition of water in the tube and sometimes nausea of a subject. Time 0 for these experiments was defined when the head entered the water. If there was a time delay between the times that the exposed body entered the water and when the head entered the water, a substantial amount of heat had already been lost (Figure 9) and the core temperature had already started to drop by the time the head was submersed. This had a blunting effect on the difference in T_{es} from baseline values, and could be the reason for our negative results in the body-exposed conditions.

If, in the previous studies (1,16,35) only the back of the head was exposed to the water or not, one would expect to see a more pronounced drop in core temperature when the whole head is exposed. Although the German studies (1) had the nape of the neck and the back of the head in or out of the water, in the studies done on the PFDs (35), the upper trunk was included in the area that was in or out of the water. The back of the head and the upper trunk respectively contribute to 3% and 17% of the surface area of the body where as the whole head only contributes to 7% of the BSA. Due to the design of the personal floatation devices that were studied, the upper chest was not only out of the water during the body-exposed, head-out condition, but also partially insulated by the PFD itself. Another obvious difference between these studies and the present study is the colder water that was used in the previous studies. In the German studies (1) subjects were immersed in 2 – 4°C water while the Lockhart (35) and Giesbrecht (16) studies respectively used 10°C and 12°C water. The results of the latter two studies were explained by the fact that vasoconstriction during body-exposure results in a smaller blood perfused body mass than in the body-insulated studies (55). Equal amounts of cold blood from the scalp will then have different effects on the differently perfused body cores – the effect on the smaller volume in the body-exposed conditions will be greater.

Vasoconstriction depends on the cold stimulus from the skin (43), a response that is impaired by meperidine (29). In the previous studies, the effect of head cooling on core cooling rate decreased from 250% to 87% as the water temperature increased from 2°C – 10°C and from 87% to 39%, as the water temperature increased from 10°C – 12°C and meperidine was included. The combined effect of these two factors (the temperature of the water and meperidine) in the present study could result in a larger perfused body volume in all conditions, and might explain why the absolute difference in mean cooling rates were smaller (19.6%) and that the tendency was not significant.

PRACTICAL IMPLICATIONS

Because of the specific group of males that were tested the generalizability of the results might be restricted to this group with its specific amount of muscle mass and fat proportion. Meperidine was administered to reduce shivering and therefore isolate the effect of head cooling. It therefore simulated events where the body's normal thermoregulatory responses are impaired such as in the most commonly seen cold water emergencies - severe hypothermia and near–drowning – and could help explain what happens to victims during these events.

FUTURE RECOMMENDATIONS

Because of the diversity in response to the different conditions, more subjects should be tested with extra care taken that there is a minimal time delay between entrance of the body and the head into the water. If, after more subjects were studied and still no difference is found in the body-exposed conditions, the experiments could be repeated in colder water to test the speculation about the perfused body mass.

These experiments should also be repeated without the effect of meperidine to see how the body defends its core temperature when the head is exposed to cold water while the thermoregulatory responses are in tact. Experiments should also be done while subjects are swimming, where a greater portion of the body is perfused with blood to fuel the muscles for the activity, to further test the theory that perfused body mass determines the effect of head cooling on core temperature and to be able to extrapolate the findings to cold water swimmers and divers.

CONCLUSIONS

These data demonstrate that whole head exposure to 17°C water in both insulated and non-insulated sub-conditions only had a minimal effect on both core cooling and core cooling rates. Body composition only played a role in the insulated sub-condition and it was found that the higher the subject BMI and weight, the smaller the differences in core temperature drop between the head-in and head-out conditions. Total heat loss from the skin was only significantly higher throughout immersion in the head-in sub-condition when the body was insulated. This is because of the relative small amount of heat loss from the body in the body-insulated conditions. Although total heat loss from the skin during the body-exposed conditions was only higher at some stages of the head-in sub-condition, head heat loss resulted in 10% of total heat loss during the first 30 minutes of immersion.

Based on these findings, it is concluded that the effect of cooling the surface of the whole head on the rate of core cooling is minimal.

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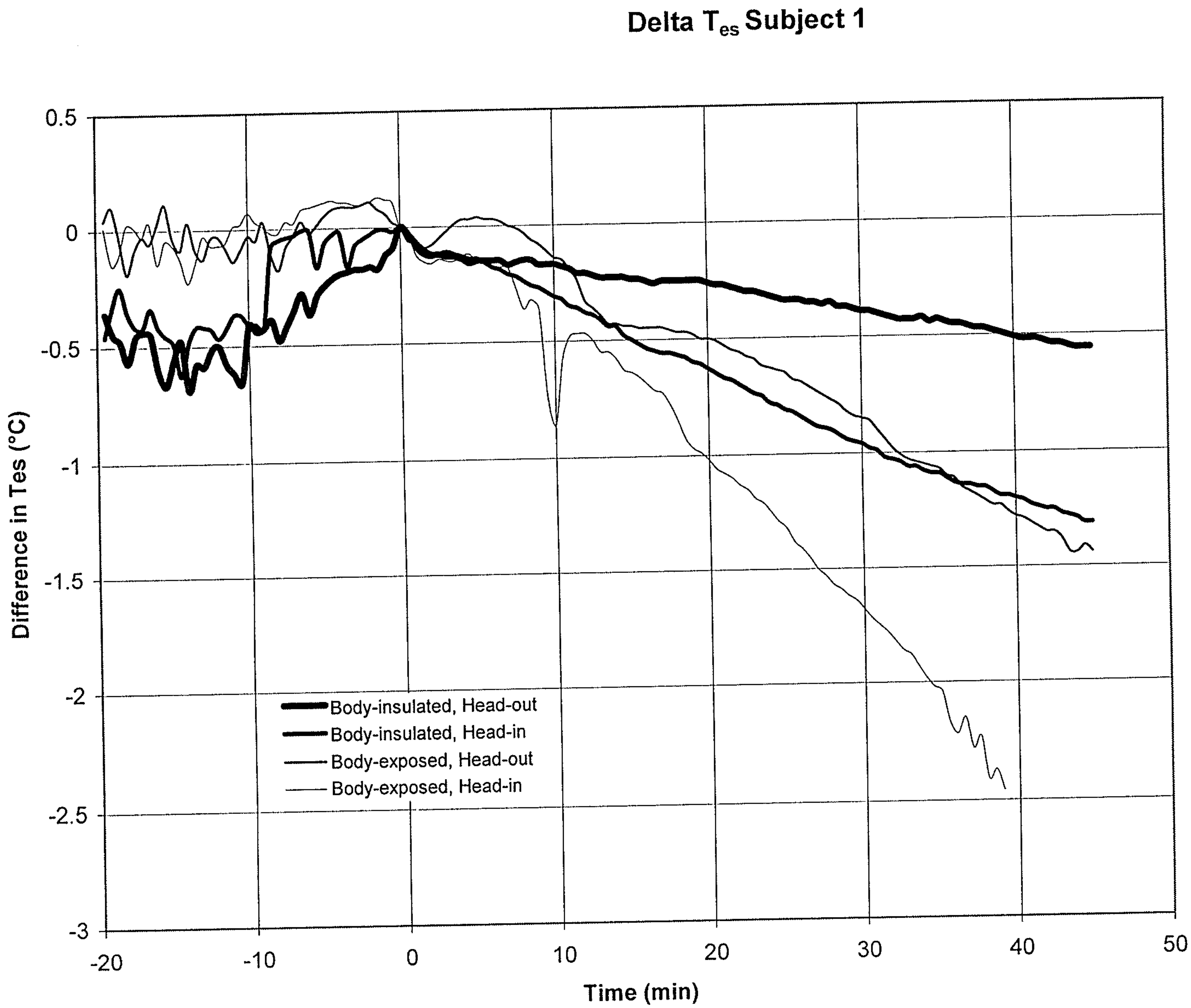
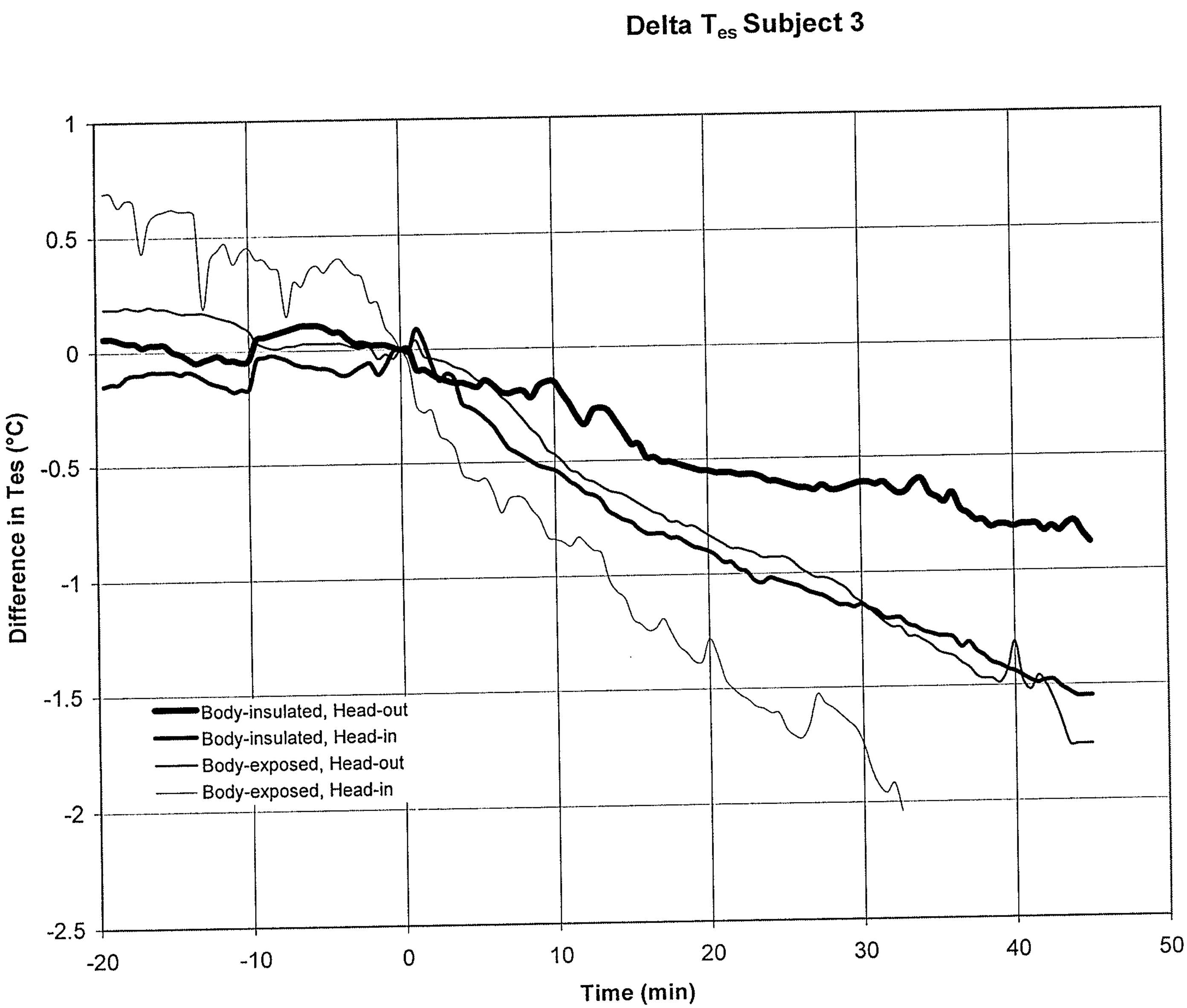
APPENDIX I

Change in core temperature during four conditions for each individual subject (n=6).

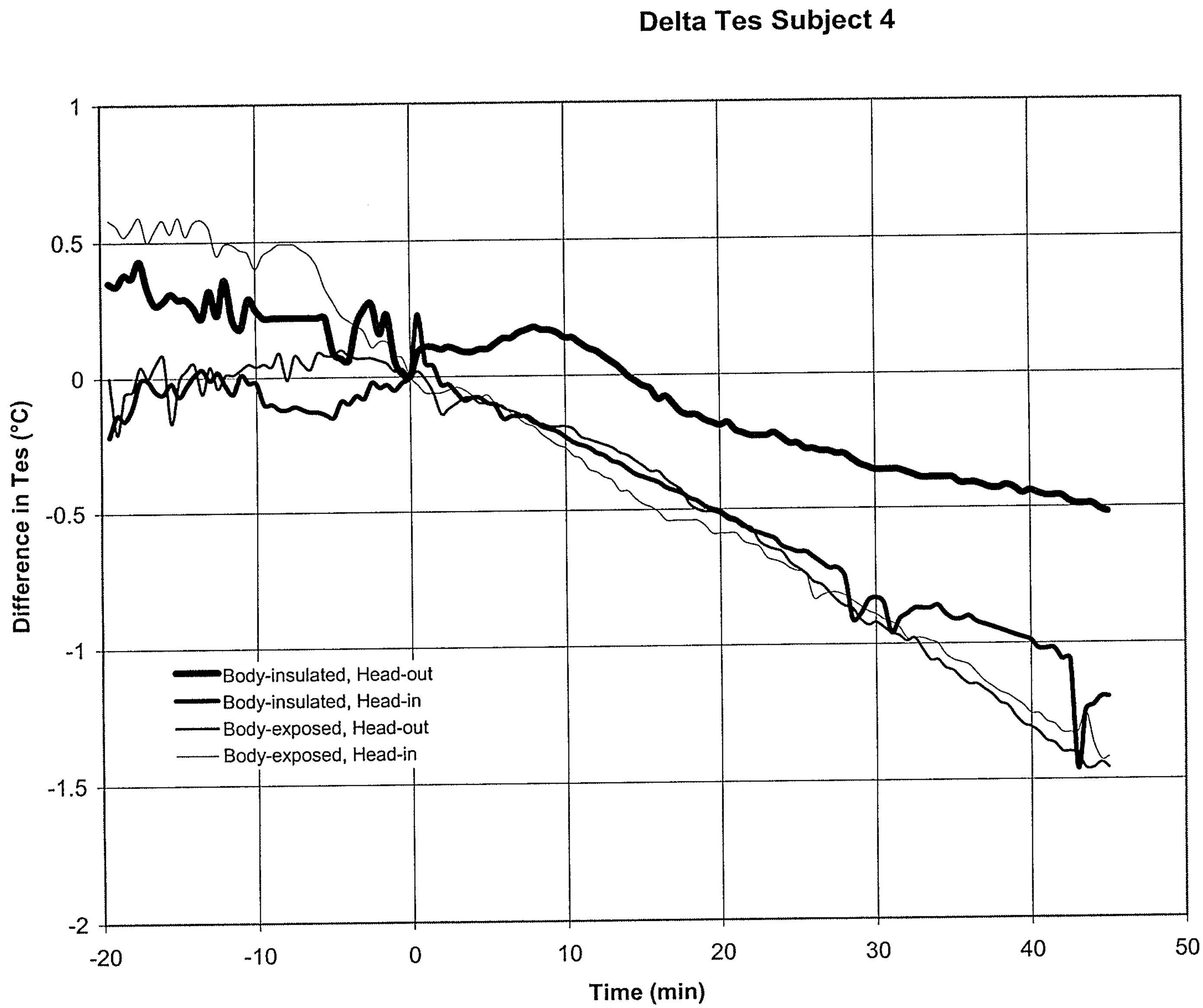
Time 0 and Temp 0 are at the start of chest immersion (head-out sub conditions) and head submersion (head-in sub conditions).


Delta T_{es} Subject 1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
Difference in Tes (°C)
-20
-10
0
10
20
30
40
50
Time (min)
Body-insulated, Head-out
Body-insulated, Head-in
Body-exposed, Head-out
Body-exposed, Head-in

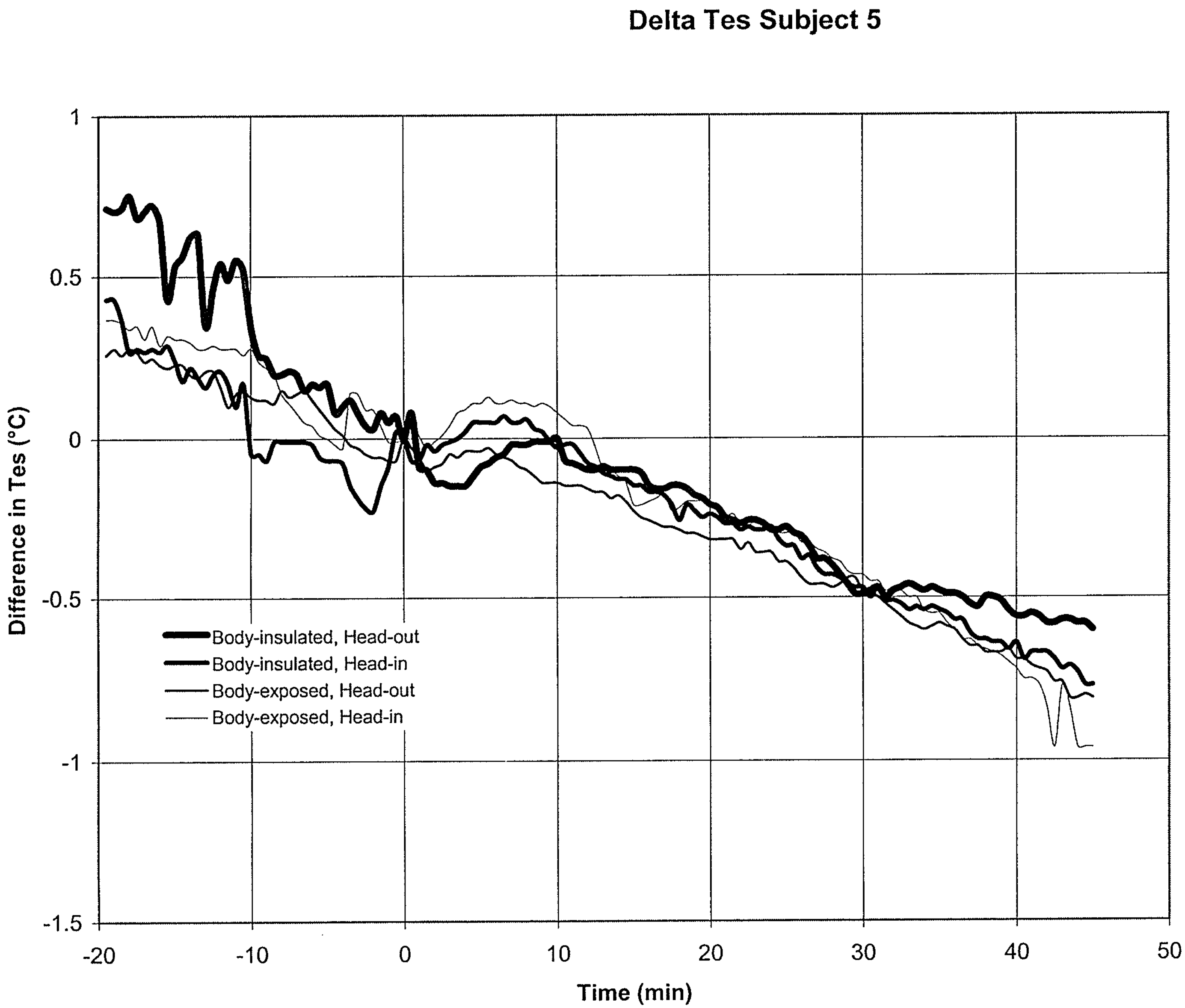
Delta Tes Subject 2
LaytonBiHo
LaytonBiHi
LaytonBeHo
LaytonBeHi
1
0.5
0
-0.5
-1
-1.5
-2
Difference in Tes (°C)
-20
-10
0
10
20
30
40
50
Time

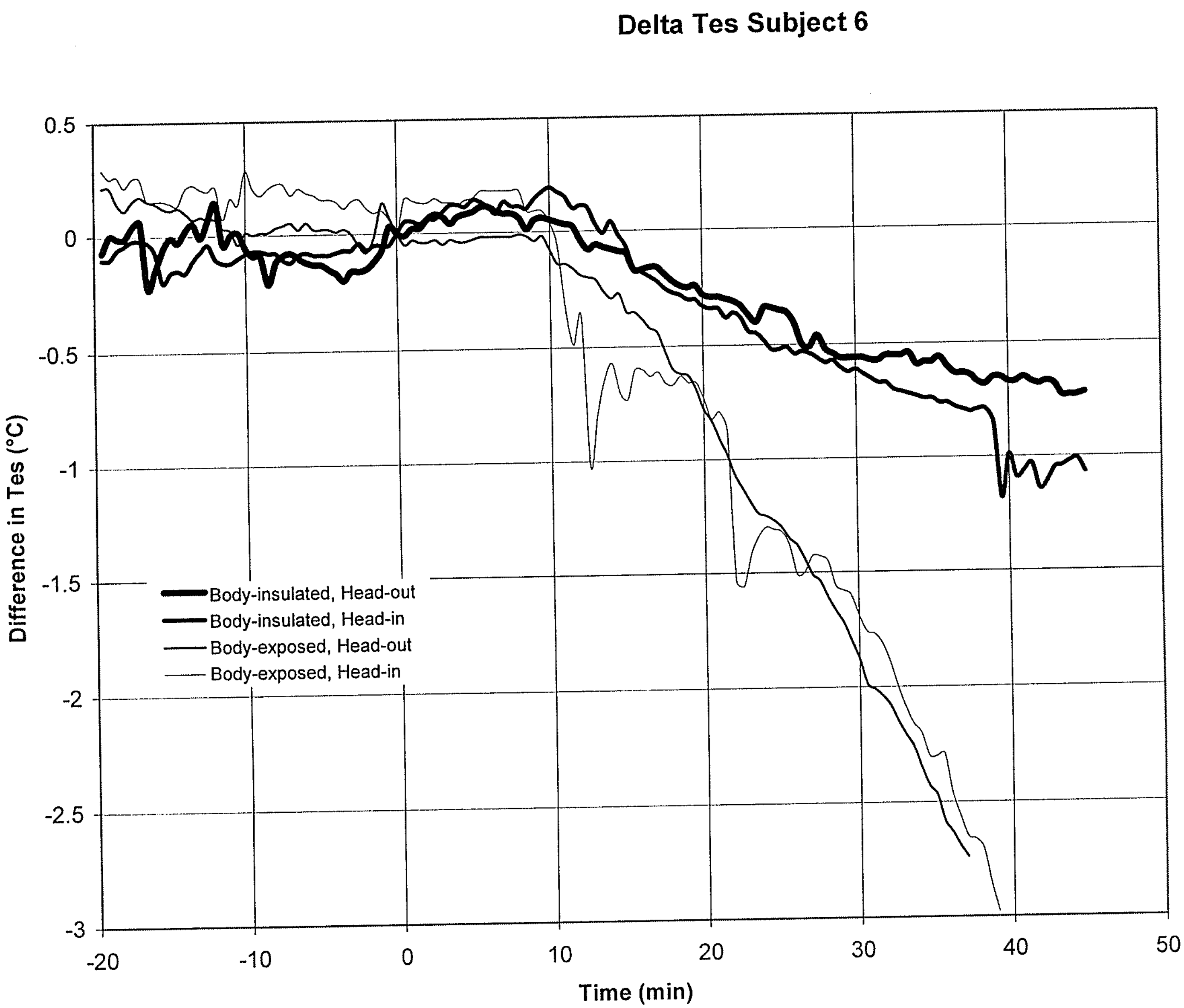


Delta T_{es} Subject 3
Difference in Tes (°C)
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-20
-10
0
10
20
30
40
50
Time (min)
Body-insulated, Head-out
Body-insulated, Head-in
Body-exposed, Head-out
Body-exposed, Head-in



Delta Tes Subject 4
Difference in Tes (°C)
Time (min)
1
0.5
0
-0.5
-1
-1.5
-2
-20
-10
0
10
20
30
40
50
Body-insulated, Head-out
Body-insulated, Head-in
Body-exposed, Head-out
Body-exposed, Head-in

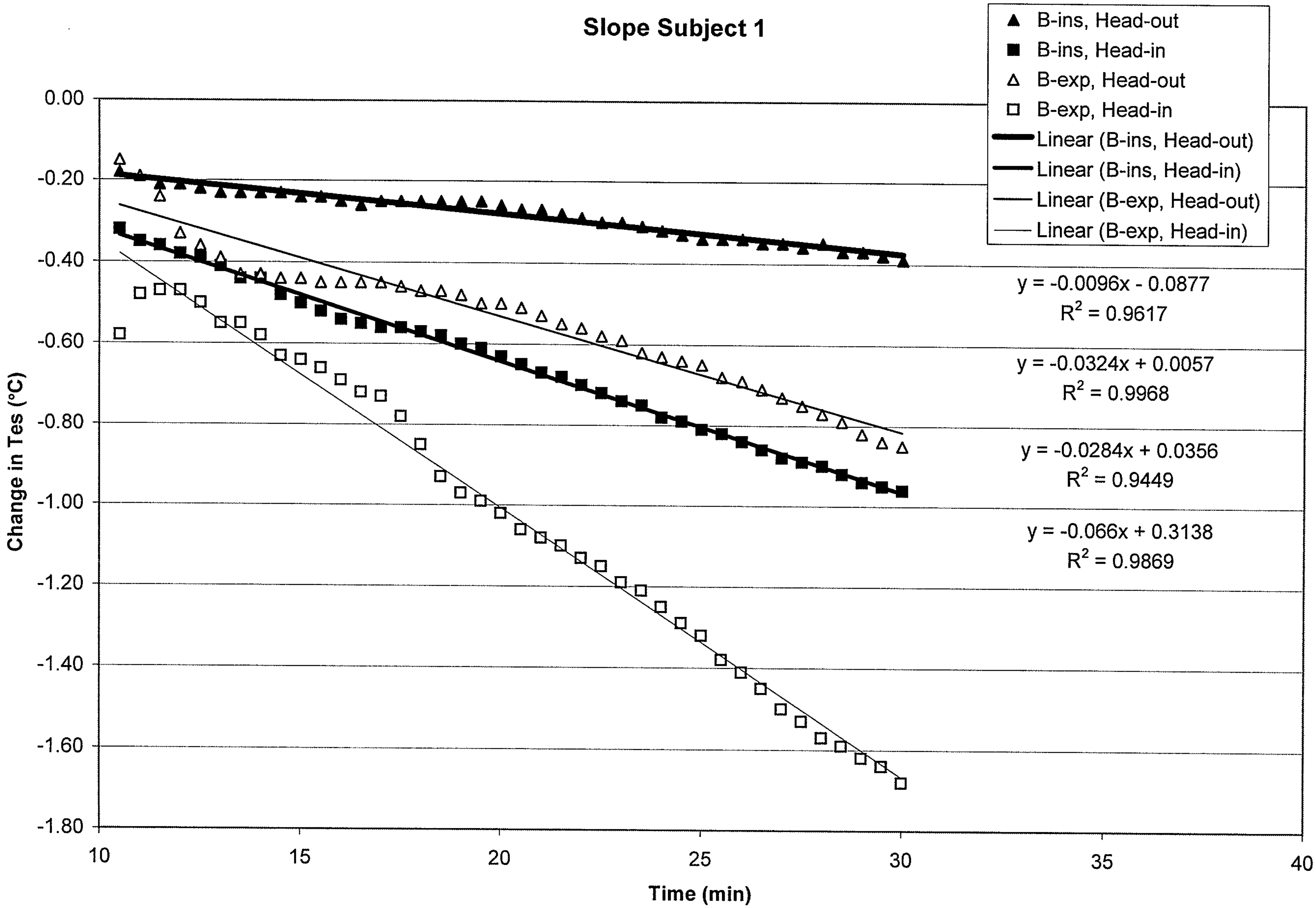

Delta Tes Subject 5
Difference in Tes (°C)
1
0.5
0
-0.5
-1
-1.5
-20
-10
0
10
20
30
40
50
Time (min)
Body-insulated, Head-out
Body-insulated, Head-in
Body-exposed, Head-out
Body-exposed, Head-in



Delta Tes Subject 6
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
Difference in Tes (°C)
-20
-10
0
10
20
30
40
50
Time (min)
Body-insulated, Head-out
Body-insulated, Head-in
Body-exposed, Head-out
Body-exposed, Head-in

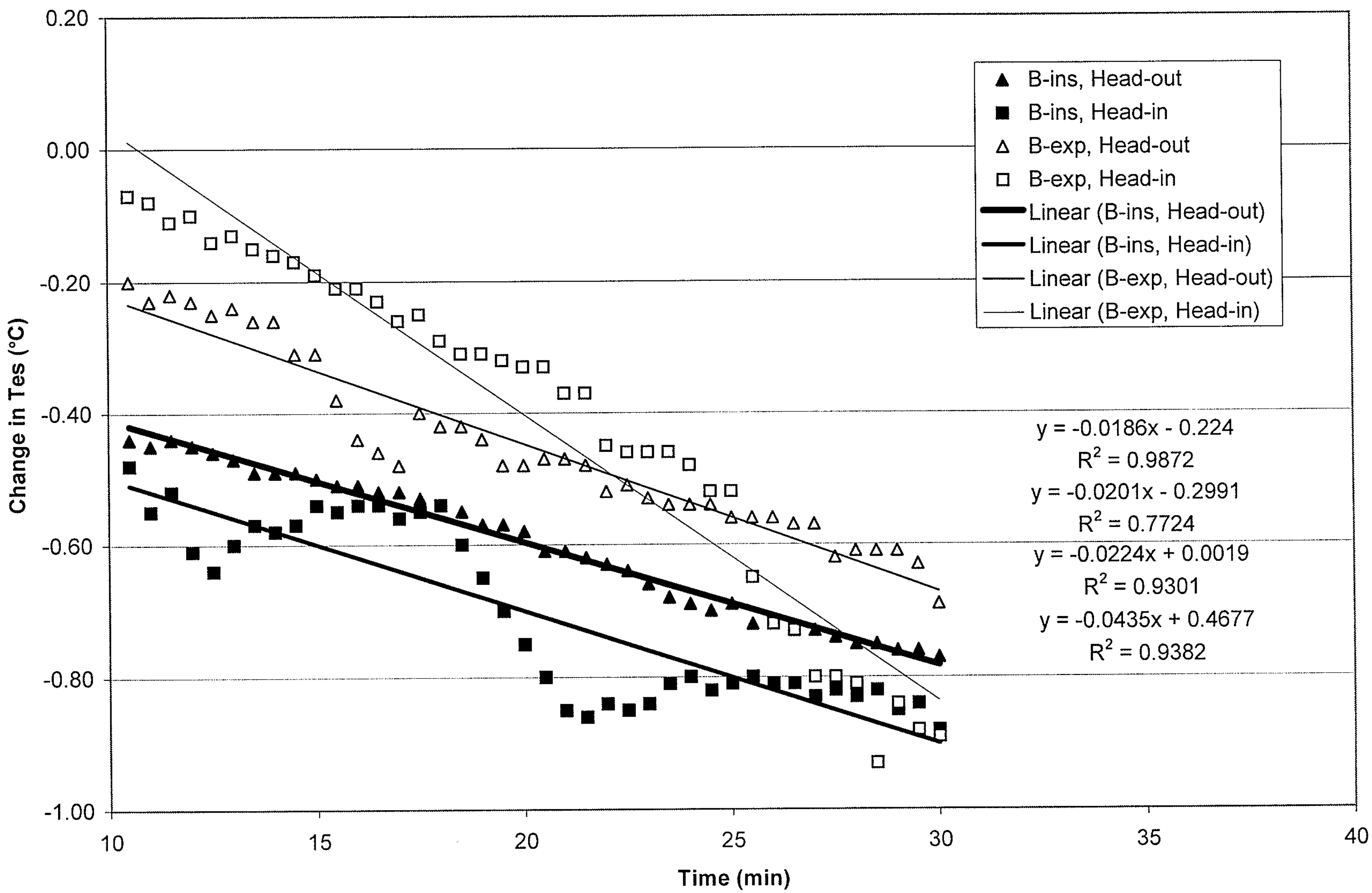
APPENDIX II

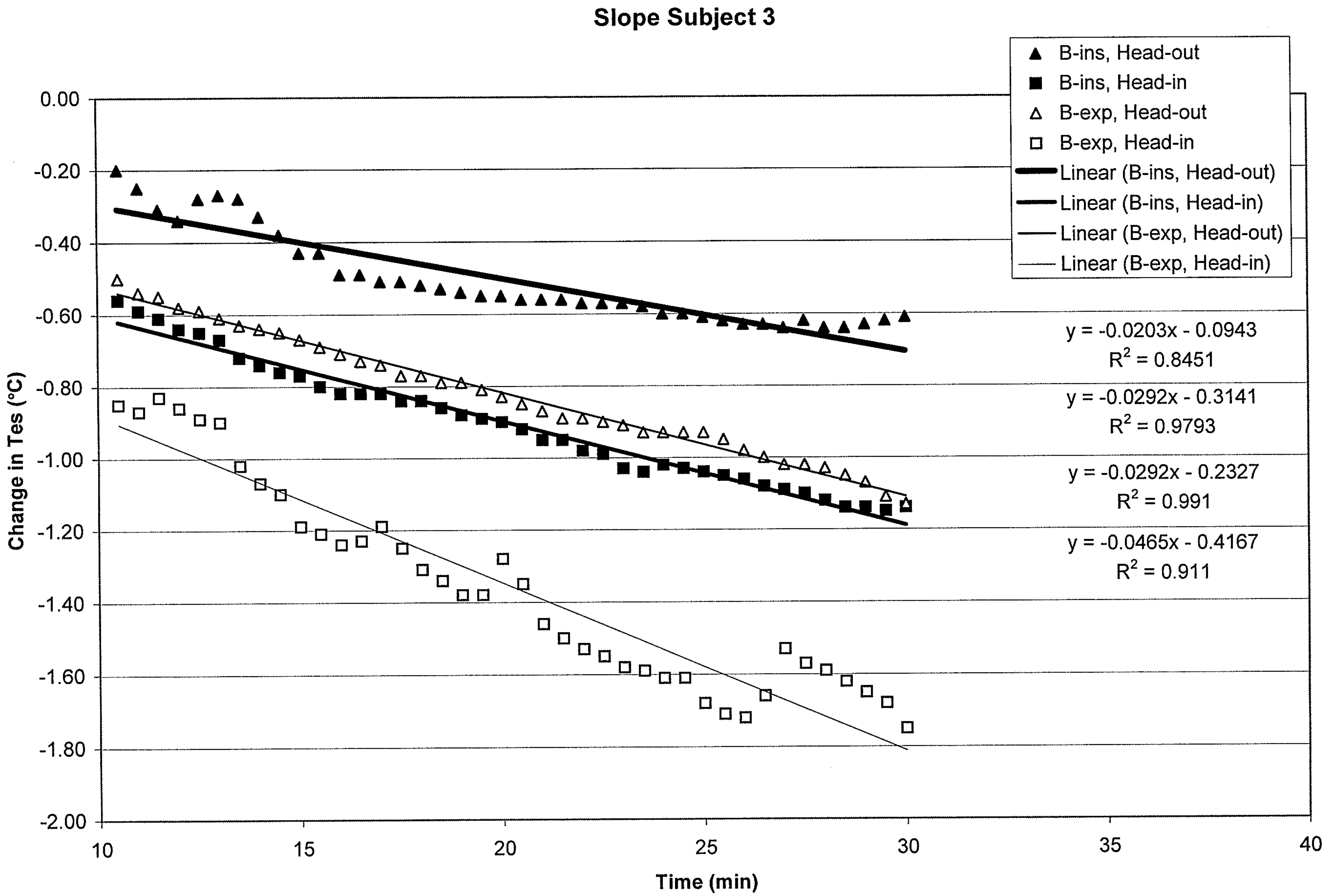
Data for the period 10 to 30 minutes of submersion/immersion in each condition for each subject. For each trial, lines of best fit are presented as well as the slopes and R^2-values.



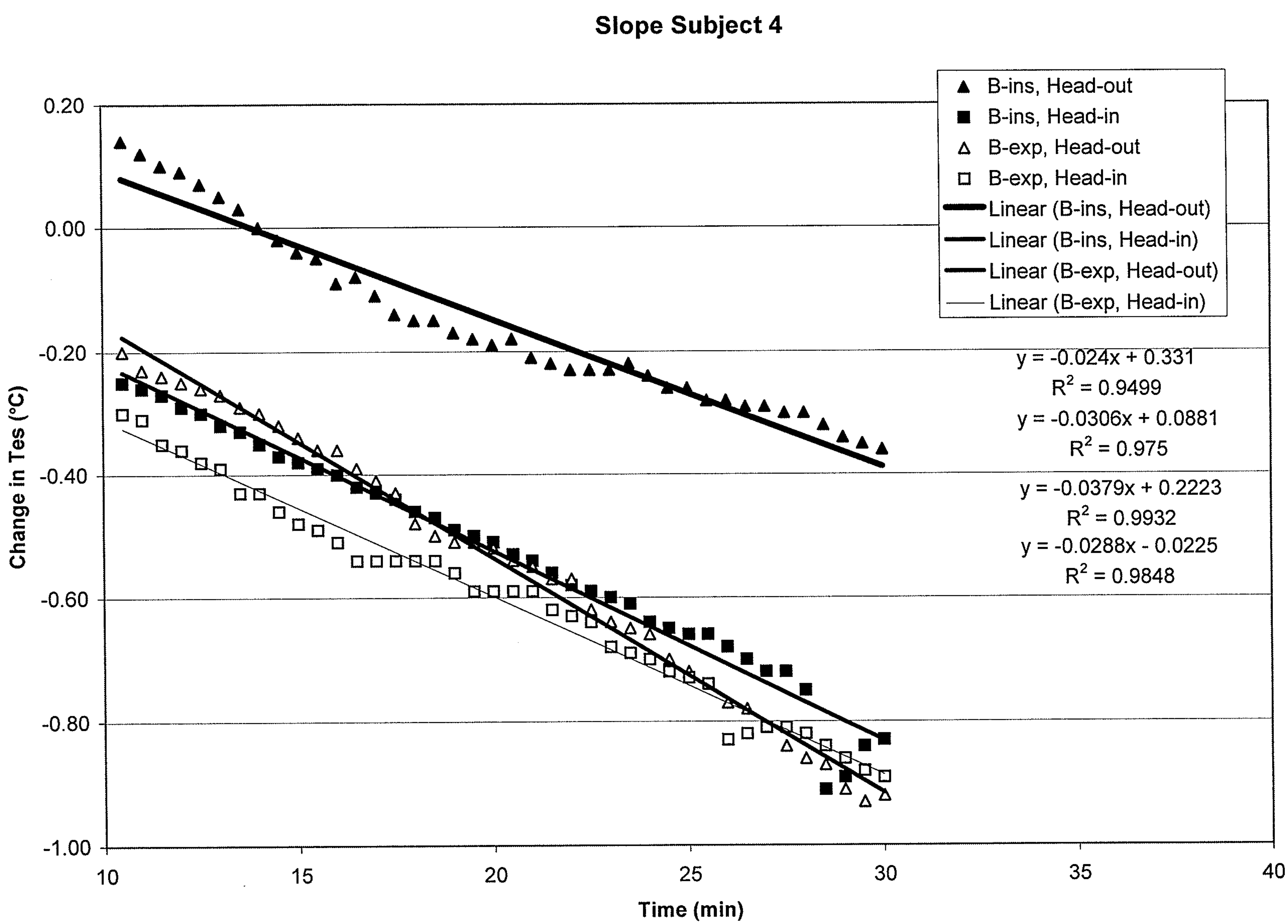
Slope Subject 1
B-ins, Head-out
B-ins, Head-in
B-exp, Head-out
B-exp, Head-in
Linear (B-ins, Head-out)
Linear (B-ins, Head-in)
Linear (B-exp, Head-out)
Linear (B-exp, Head-in)
y = -0.0096x - 0.0877
R2 = 0.9617
y = -0.0324x + 0.0057
R2 = 0.9968
y = -0.0284x + 0.0356
R2 = 0.9449
y = -0.066x + 0.3138
R2 = 0.9869
Change in Tes (°C)
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
10
15
20
25
30
35
40
Time (min)

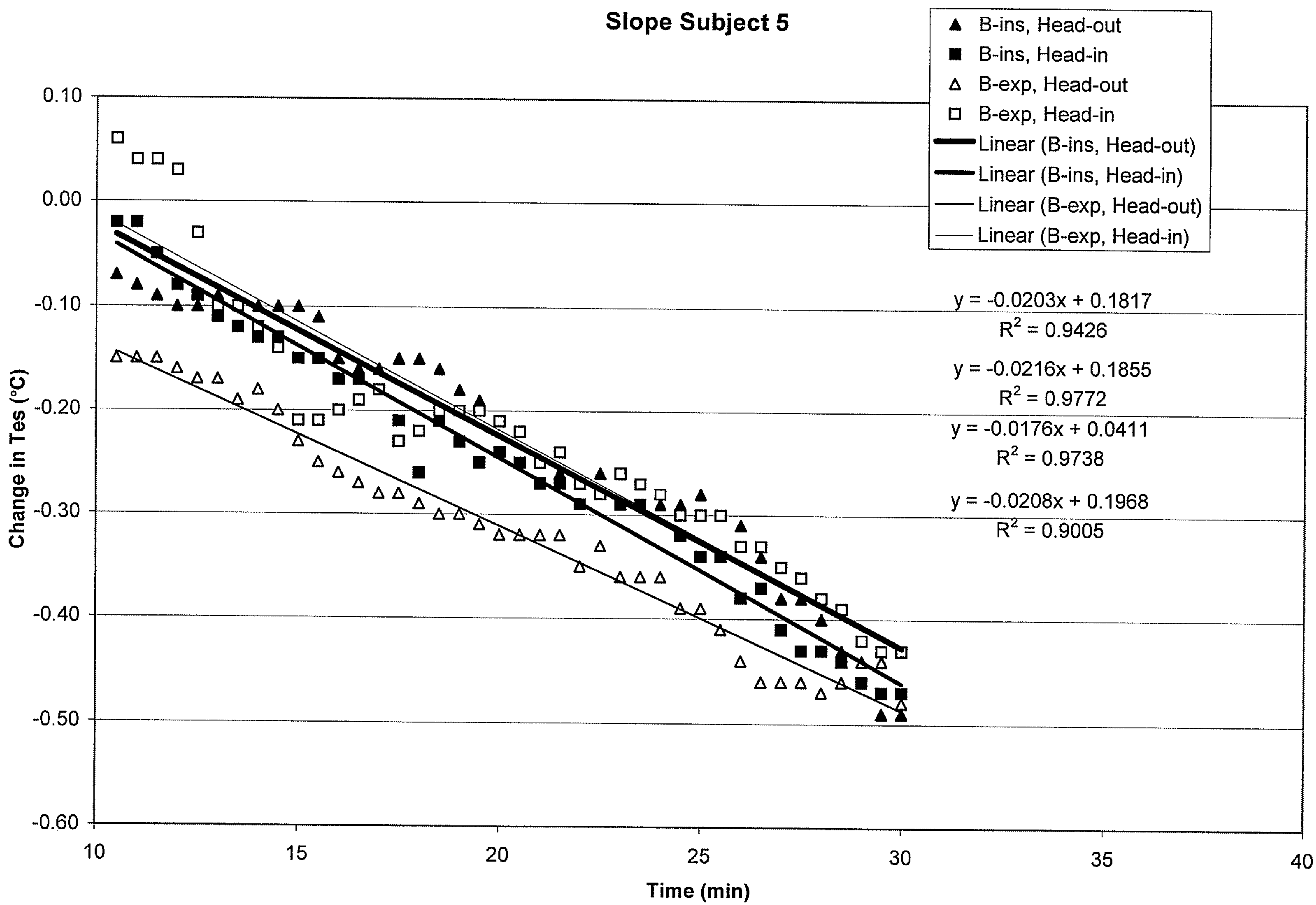
Slope Subject 2



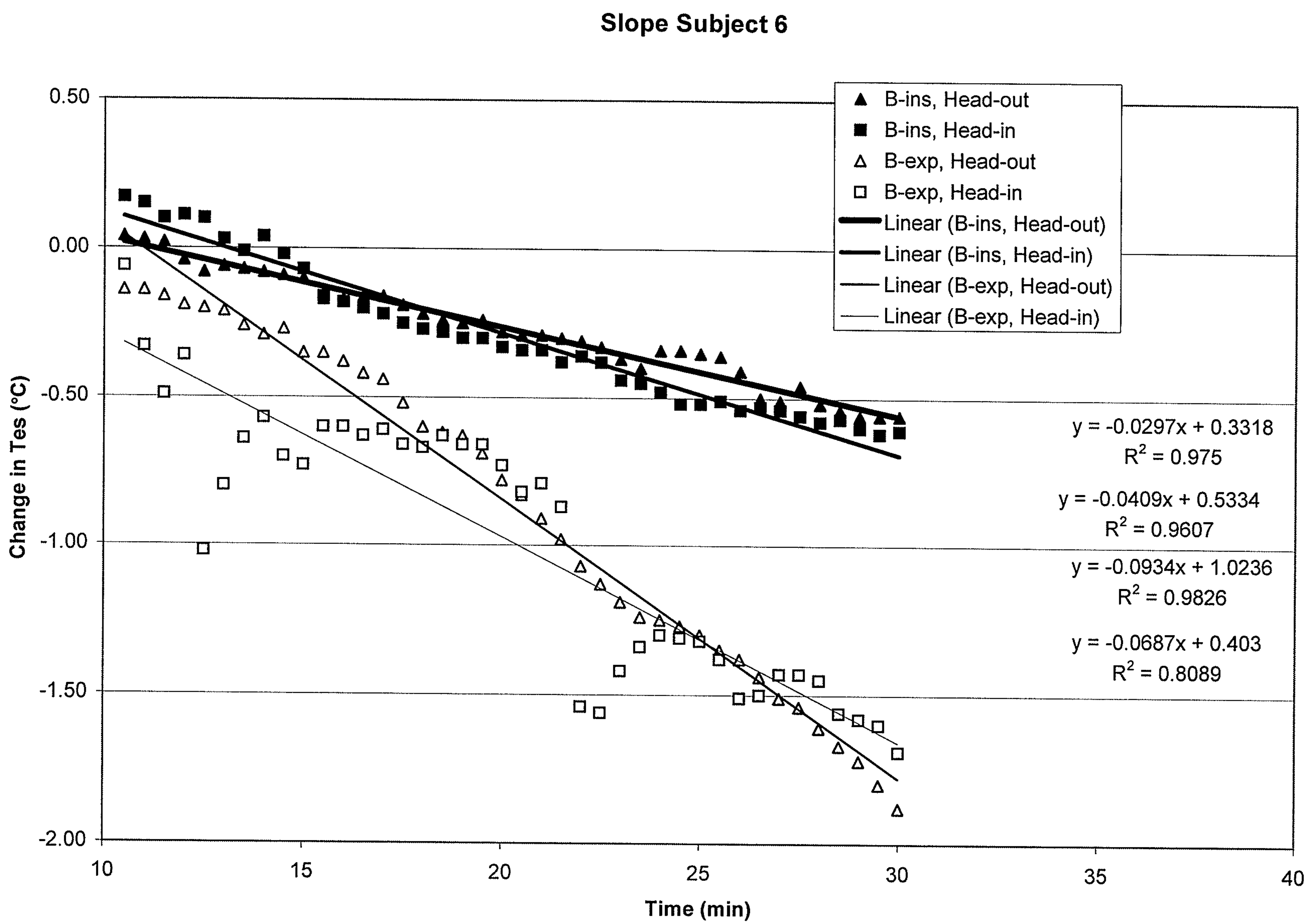


Slope Subject 3
B-ins, Head-out
B-ins, Head-in
B-exp, Head-out
B-exp, Head-in
Linear (B-ins, Head-out)
Linear (B-ins, Head-in)
Linear (B-exp, Head-out)
Linear (B-exp, Head-in)
y = -0.0203x - 0.0943
R2 = 0.8451
y = -0.0292x - 0.3141
R2 = 0.9793
y = -0.0292x - 0.2327
R2 = 0.991
y = -0.0465x - 0.4167
R2 = 0.911
Change in Tes (°C)
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
10
15
20
25
30
35
40
Time (min)


Slope Subject 4
B-ins, Head-out
B-ins, Head-in
B-exp, Head-out
B-exp, Head-in
Linear (B-ins, Head-out)
Linear (B-ins, Head-in)
Linear (B-exp, Head-out)
Linear (B-exp, Head-in)
y = -0.024x + 0.331
R^2 = 0.9499
y = -0.0306x + 0.0881
R^2 = 0.975
y = -0.0379x + 0.2223
R^2 = 0.9932
y = -0.0288x - 0.0225
R^2 = 0.9848
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
Change in Tes (°C)
10
15
20
25
30
35
40
Time (min)



Slope Subject 5
B-ins, Head-out
B-ins, Head-in
B-exp, Head-out
B-exp, Head-in
Linear (B-ins, Head-out)
Linear (B-ins, Head-in)
Linear (B-exp, Head-out)
Linear (B-exp, Head-in)
y = -0.0203x + 0.1817
R^2 = 0.9426
y = -0.0216x + 0.1855
R^2 = 0.9772
y = -0.0176x + 0.0411
R^2 = 0.9738
y = -0.0208x + 0.1968
R^2 = 0.9005
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
Change in Tes (°C)
10
15
20
25
30
35
40
Time (min)



Slope Subject 6
B-ins, Head-out
B-ins, Head-in
B-exp, Head-out
B-exp, Head-in
Linear (B-ins, Head-out)
Linear (B-ins, Head-in)
Linear (B-exp, Head-out)
Linear (B-exp, Head-in)
y = -0.0297x + 0.3318
R^2 = 0.975
y = -0.0409x + 0.5334
R^2 = 0.9607
y = -0.0934x + 1.0236
R^2 = 0.9826
y = -0.0687x + 0.403
R^2 = 0.8089
Change in Tes (°C)
0.50
0.00
-0.50
-1.00
-1.50
-2.00
Time (min)
10
15
20
25
30
35
40