Eur J Appl Physiol (2000) 82: 24–29

© Springer-Verlag 2000

ORIGINAL ARTICLE

Ronald Wallingford · Michel B. Ducharme
Eugene Pommier

Factors limiting cold-water swimming distance while wearing personal floatation devices

Accepted: 8 December 1999

Abstract The influence of body adiposity, arm skinfold thickness, aerobic capacity, and cooling rate were studied in a mock survival swimming situation conducted in water at around 14 °C. Seventeen adult participants wore personal floatation devices on top of seasonal clothing and were asked to swim as far as they could, as if attempting to reach shore following an accidental immersion in cold water. Triceps and patellar skinfold thickness showed a significant correlation with distance covered ($r = 0.70$ and 0.56, respectively), while abdominal skinfold and percent body fat showed no significant correlation. Maximum oxygen consumption ($\dot{V}O_{2max}$) was not significantly related to distance covered. There was a negative correlation between body cooling rate during the swimming period and distance covered. A multiple stepwise regression analysis, however, indicated that the only significant contributor to variance in the distance covered was the triceps skinfold thickness ($r^2 = 0.49$). It was concluded that for a healthy subject accidentally immersed in cold water, triceps skinfold thickness is a stronger predictor of the swimming distance covered than body adiposity, $\dot{V}O_{2max}$, or the drop in core temperature.

Key words Accidental immersion · Adiposity · Aerobic capacity · Cooling rate · Rectal temperature

R. Wallingford
School of Human Kinetics, Laurentien University, Sudbury, Ontario, Canada, P3E 2C6

M. B. Ducharme (✉)
Human Protection and Performance,
Defence and Civil Institute of Environmental Medicine,
Toronto, Ontario, Canada, M3M 3B9
e-mail: michel.ducharme@dciem.dnd.ca
Fax: +1-416-6352186

E. Pommier
Emergency Medicine, St. Joseph's Health Centre, Sudbury, Ontario, Canada, P3E 3B5

Introduction

Swimming in cold water has been reported to accelerate the rate of decrease of core temperature when compared with rates observed during static immersion (Doubt 1991; Hayward et al. 1975; Keatinge 1960, 1961, 1969; Nadel et al. 1974; Sawaga et al. 1988). This observation has led various authors and public safety authorities to recommend that swimming should not be attempted during accidental cold-water immersion, but that the body should be held still to slow the progression into hypothermia, unless the victim is certain to make it to shore (Hayward et al. 1975; Royal Life Saving Society of Canada 1997; The Canadian Red Cross Society 1983, 1995). Furthermore, the work of Hayward et al. (1975) suggested that when victims are wearing lifejackets, the rate of body cooling could be the limiting factor for the swimming distance in cold water. Similarly, Dulac et al. (1987) reported that seven out of ten non-finishers in an outdoor marathon swimming competition in 18.5 °C water stopped because of hypothermia.

Several factors that modify the rate of fall in core temperature during swimming in cold water have been identified, namely the water temperature, water agitation, fitness and fatness of the subject, type of clothing worn and the intensity of the exercise (Golden and Tipton 1987). These factors will all impact on the two key components of the heat balance equation, namely heat production and heat loss. Numerous studies have shown that if no thermally protective clothing is worn, the body's subcutaneous fat thickness is the single most significant factor, other than the water temperature and muscle perfusion, in defining body heat loss (Cannon and Keatinge 1960; Carlson et al. 1958; Keatinge 1960). On the other side of the heat balance equation, heat production during swimming will be defined mainly by the capacity to produce and sustain work, which may be best characterized by the subject's aerobic fitness. Therefore, if the rate of body cooling is the limiting factor for the distance covered during swimming in cold water, body subcutaneous fat thickness and the aerobic fitness of the subject should be significantly correlated to the distance covered during swimming before incapacitation.

Nadel et al. (1974), however, reported that during a maximal swim in 18 °C water, the limiting factor responsible for the termination of the swim was not cardiorespiratory distress or incapacitation by hypothermia, but the inability to contract the muscles and muscle tiredness. This observation is explained in part by the fact that the greatest contribution to propulsion during swimming is provided by the work of the arm muscles (Holmer and Astrand 1972). During swimming, the small muscle groups of the arms are working under anaerobic conditions, even during submaximal work, particularly in untrained swimmers (Holmer 1972). This is probably responsible for the observed increase in blood lactate (Holmer 1972) and the early onset of muscle fatigue of the arms during swimming.

A second factor that may contribute to premature fatigue during swimming in cold water as compared with warmer water is in the cooling of the muscle tissue of the arms. Because of the unfavorable area-to-mass ratio of the arms as compared with the lower limbs, the tissue of the arm can not retain heat as efficiently (Doubt 1991; Golden and Tipton 1987), and consequently its temperature may decrease even during swimming activity. It has been suggested that if muscle temperature is below normal, the muscle perfusion for a given workload will be reduced and the rate of glycolysis and lactate production increased, which would reflect the higher anaerobic contribution to the work effort (Pendergast 1988). Cooled muscles also have a reduced contractile force and an increased rate of fatigue (Blomstrand et al. 1986). If muscle cooling of the arms is indeed a limiting factor to muscle performance during cold-water swimming, it may be expected that any factor that could minimize arm muscle cooling rate, such as a greater subcutaneous fat thickness of the arm, could improve the distance covered.

The objective of the present study was to investigate which of the proposed limiting factors (i.e., body adiposity, subcutaneous fat thickness on the arms, aerobic fitness, or body cooling rate) is the best predictor of the distance covered during swimming in cold water before incapacitation while wearing personal floatation devices. The working hypothesis was that subjects with a greater subcutaneous fat thickness around the upper arm could swim further before incapacitation as compared to subjects with less adiposity around their upper arms.

Methods

Subjects

Five female and 12 male subjects were recruited from a University community to participate in the study. None of the subjects had been previously trained for cold-water swimming. Only one subject (F4; see Table 1) had some training as a Varsity swimmer. The health status of all of the subjects was assessed by a medical

Table 1 Physical and anthropometric characteristics of the subjects, including measurements of skinfold thickness at the triceps, patella and abdomen, and body fat. [A_D Body surface area estimated by the Dubois and Dubois (1916) formula, *F* female, *M* male, *SD* standard deviation]

Subject	Age (years)	Height (cm)	Mass (kg)	A_D (m^2)	Triceps (mm)	Patellar (mm)	Abdominal (mm)	Body fat (%)	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)
F1	22.0	171.0	63.0	1.73	11.6	13.2	12.7	13.9	48.8
F2	21.0	165.0	74.0	1.81	15.7	12.3	7.7	13.8	47.7
F3	20.0	151.0	61.0	1.56	20.0	26.0	10.6	16.1	51.8
F4	21.0	161.0	61.0	1.63	18.2	8.4	12.2	16.0	53.0
F5	22.0	173.7	62.5	1.74	7.1	6.1	4.2	9.9	40.3
Mean (F)	21.2	164.3	64.3	1.69	14.5	13.2	9.5	13.9	48.3
SD	0.8	9.0	5.5	0.1	5.2	7.7	3.5	2.5	5.0
M1	21.0	175.0	73.0	1.88	13.3	12.4	19.8	16.6	49.6
M2	52.0	174.0	71.0	1.86	9.5	15.6	11.1	12.8	47.7
M3	24.0	169.0	72.0	1.83	10.6	9.2	15.4	14.4	57.0
M4	21.0	175.5	76.5	1.91	8.4	8.7	10.8	12.3	64.8
M5	20.0	178.0	69.0	1.86	10.4	14.3	16.4	14.6	49.8
M6	21.0	178.0	62.0	1.78	7.3	5.8	8.6	11.3	51.5
M7	21.0	180.6	66.5	1.84	7.6	6.2	10.8	12.0	78.3
M8	31.0	163.0	53.0	1.56	5.6	5.4	10.6	11.3	60.5
M9	26.0	184.0	74.0	1.96	8.6	9.8	6.6	11.1	51.6
M10	27.0	174.0	76.0	1.91	10.7	11.8	23.8	17.0	47.4
M11	28.0	165.0	61.0	1.68	10.5	9.6	23.3	16.8	48.4
M12	58.0	170.0	72.0	1.83	9.6	6.8	12.2	13.1	45.7
Mean (M)	29.2	173.8	68.8	1.83	9.3	9.6	14.1	13.6	54.4
SD	12.6	6.2	7.0	0.11	2.0	3.3	5.7	2.2	9.5
Mean pooled data)	26.8	171.0	67.5	1.79	10.9	10.7	12.8	13.7	52.6
SD	11.1	8.1	6.8	0.12	3.9	5.0	5.5	2.2	8.7

authority, and the subjects responded attesting to their suitability for physical activity on a Par-Q form (Physical Activity Readiness Questionnaire, British Columbia Ministry of Health 1978). The subjects were fully informed of the procedures and possible risks of the study and of their right to withdraw from the experiment at any time without prejudice. Written informed consent was obtained from all subjects before experimentation. The study was approved by the Human Ethics Committee at Laurentien University.

Physiological and anthropometric parameters

Maximal aerobic power ($\dot{V}O_{2max}$) was defined for all subjects, using a treadmill protocol (Quinton Q65 Treadmill series 90; Seattle, Wash., USA) that involved increases in speed and/or elevation. Expired gases were analyzed with a metabolic cart (Sensormedic model 2900-z; Anaheim, Calif., USA). The skinfold measurements were taken at three sites with a Harpenden Caliper (British Indicators, Burgess Hill, West Sussex, UK): on the triceps at the midpoint between the acromion and olecranon processes, the patella at the anterior mid point of tibia femur junction, and the abdomen, 2 cm distant to the right side of the umbilicus. Percent body fat was estimated from the skinfold thickness of two sites (abdomen and triceps), based on the formulas developed by Lohman (1981). In his review of "skinfolds and body density and its relation to body fatness", Lohman (1981) reported that the use of three or more skinfolds was not of greater advantage over the use of two skinfolds to predict body density and, ultimately, percent body fat.

Before water entry, a rectal probe (model no. 104-401; Yellow Springs, Ohio, USA) was inserted 15 cm beyond the anal sphincter to obtain an estimate of core temperature (T_{re}). The probe connector exited at the shirt collar and floated behind the subject on a small Styrofoam block. Subjects veered off-course during each lap of the swimming test, to an anchored raft so that the probe connector could be plugged into a calibrated hand-held temperature reader (YSI tele-thermometer Model 46 TU; Yellow Springs). Subjects treaded water for about 20 s while T_{re} was recorded.

Procedures

During the swimming test, the subjects were asked to swim as far as they could as if attempting to reach shore following an accidental immersion. They were given the freedom to use the stroke or strokes of their choice, but the subjects used the head above water crawl stroke 90% of the time. Side and breast were resting strokes. Exit from the water was mandatory if the T_{re} dropped below 35.0 °C. Swimmers were asked questions periodically to verify mental alertness. Each subject wore standard clothing believed to be typical for early spring or late fall outdoor activities. This included cotton gym shorts for men and lycra bathing suits for women plus these specific cotton items: a T-shirt, a long sleeved shirt, long pants, socks and low-cut athletic shoes. A nylon jacket was worn over the cotton shirt, and a personal floatation device was snugly secured over the torso (lifevest model MV 3116 "The Floaters"; Mustang Survival, Richmond, BC, Canada). The swim took place in a lake at the University beach on a 60-m course made up of two buoys that were placed 30 m apart. The tests were planned for a lake temperature of around 14 °C in either the spring or fall of the year. Ten subjects swam in the spring and seven in the fall. Air temperature averaged 16.4 °C; the wind was minimal in the protected bay and the waves were less than 0.2 m high. Subjects recovered from the cold swim in a warm environment until their T_{re} rose from the afterdrop nadir. A medical doctor and a lifeguard with a rescue board were always present during the swimming tests.

The following parameters were recorded during the swimming tests: the water temperature 0.5 m below the surface once every 20 min; T_{re} at the beginning, at every lap, at the end of the test, and continuously during recovery; total time in the water and distance covered during the swimming test by the subjects from the entry time into water to exit time (defined as the distance covered in m). The following values were defined or calculated based on the recorded parameters: the T_{re} at entry ($T_{re(entry)}$), the T_{re} at exit ($T_{re(exit)}$), the T_{re} drop (in °C) from entry to exit (i.e., $T_{re(entry)}-T_{re(exit)}$); the peak $T_{re(peak)}$ (in °C) and the time to $T_{re(peak)}$ (peak time) during the swimming test (in min); the T_{re} drop (in °C) from the $T_{re(peak)}$ to $T_{re(exit)}$ (i.e., $T_{re(peak)}-T_{re(exit)}$); the $T_{re(exit)}$ at exit time (in °C); the minimum T_{re} at the end of the afterdrop period ($T_{re(nadir)}$, in °C); the distance covered per °C drop in T_{re} (in $m \cdot °C^{-1}$); the swimming velocity (in $m \cdot min^{-1}$); the time from water exit to $T_{re(nadir)}$ (in min), and the body cooling rate (in $°C \cdot h^{-1}$). Two body-cooling rates were estimated: the overall cooling rate was calculated from $[(T_{re(entry)}-T_{re(exit)}/\text{time in water}]$, and the peak cooling rate was assessed from $[(T_{re(peak)}-T_{re(exit)})/(\text{time in water–peak time})]$.

Statistical analysis

The measured independent variables were analyzed on a correlation matrix assessed at the two-tailed probability level (Statview 4.5; Abacus Concepts, Berkeley, Calif., USA). Gender and season differences were tested using *t*-tests set at the $P < 0.05$ level with two-tailed probability. A stepwise multiple regression analysis was performed to determine which combination of independent variables was related to distance covered and what percentage each independent variable contributed to the variance in distance covered. Non-directional (two-tailed) null hypothesis tests were used for the following variables: percent body adiposity, triceps, patellar and abdomen skinfold thicknesses, $\dot{V}O_{2max}$, overall cooling rate, and peak cooling rates. Data are presented as the mean (SD).

Results

The physical and anthropometric characteristics of the subjects are presented in Table 1. Females and males differed at the $P < 0.05$ level for their height and body surface area only.

The average water temperature (T_w) during the swimming tests was 14.0 (2.1) °C, and no difference in T_w was observed between the spring and the fall swimming sessions. The distance covered and rectal temperature changes that occurred during and after each swim are presented in Tables 2 and 3, respectively. No significant differences attributable to gender were found for the swimming performance data or body temperature changes. Table 2 shows that on average the subjects swam 889 (387) m within 43.5 (20.8) min before being incapacitated or being unable to make effective progress (stalled or ineffective directional control). At the time of water exit, the average T_{re} was still above the 35 °C cutting threshold by 0.7 (1.1) °C. No subject was asked to exit the water because of a low core temperature. No significant relationship was observed between the swimming performance or body temperature changes and the T_w during the swimming tests.

Table 4 presents the correlation coefficients between a series of measured independent variables that are susceptible to the distance covered. All of the independent variables tested were pooled for both genders since no significant difference was observed between genders. The tests showed that triceps skinfold thickness was significantly correlated at the $P < 0.01$ level with the distance covered, while the patellar skinfold was significant at the $P < 0.05$ level. Abdominal skinfold, percent body fat and $\dot{V}O_{2max}$ were not significantly correlated with the distance covered. Both the overall and peak cooling rates showed a significant negative correlation with distance covered ($P < 0.01$). Cooling rates were also negatively correlated with time in the water ($r = -0.64$, $P < 0.01$). When the female data were removed from the regression analysis, the correlation between triceps skinfold thickness and distance covered remained significant. A multiple stepwise regression analysis indicated that the greatest contributor to variance ($r^2 = 0.49$) in the dependent variable (i.e., distance covered) was triceps skinfold thickness ($F = 14.18$; $P < 0.01$). The other dependent variables tested (patellar and abdomen skinfolds, percent body fat, $\dot{V}O_{2\max}$, and overall and peak cooling rates) were not found to contribute significantly to the variance in the distance covered.

Table 2 Performance data during the swimming tests in the cold water

Subject	Total distance covered (m)	Time in the water (min)	Swimming velocity ($m \cdot min^{-1}$)	Distance covered per 1 °C drop (m)
F1	960	44	21.8	317
F2	1260	64	19.6	1010
F3	1740	93.7	18.6	2615
F4	1020	52.8	19.3	1028
F5	720	34.1	21.1	306
Mean (F)	1140	57.7	20.1	1055
SD	387	22.9	1.3	940
M1	1260	65.1	19.4	444
M2	780	31.1	25.1	451
M3	1500	73.4	20.4	731
M4	600	24.9	24.1	147
M5	420	21.1	20.9	173
M6	1020	54.4	18.8	295
M7	600	28.9	20.8	163
M8	420	26.5	15.8	144
M9	660	33.2	19.9	171
M10	1080	40.0	27.0	1783
M11	480	20.5	23.4	571
M12	600	31.2	19.2	322
Mean (M)	785	37.5	21.2	450
SD	351	17.5	3.1	460
Mean (pooled data)	889	43.5	20.9	628
SD	387	20.8	2.7	669

Discussion

The results from the stepwise regression analysis show that triceps skinfold thickness is the best predictor of swimming distance covered in cold water, notwithstanding the expected significant negative correlation between cooling rate and swimming distance when analyzed individually. Percent body fat, aerobic fitness and abdominal skinfold thickness were not correlated with the distance in our subject population (Table 4). Dividing our subject population into two groups [subjects who covered less than the average swimming distance observed in our study (< 889 m) and subjects who covered more distance (> 889 m)], shows that the group that swam over 889 m had a significantly larger triceps skinfold thickness [13.4 (4.3) mm, $n = 8$] than the group that did not swim as far [8.6 (1.6) mm; $n = 9$]. It is worth noting that these results were found for a population of

Table 3 Body temperature changes during and after the swimming tests. Negative cooling rate values represent an increase (i.e., warming up) in rectal temperature (T_{re}). (*Temp* Temperature, $T_{re(entry)}$ core temperature at entry, $T_{re(peak)}$ peak core temperature, $T_{re(exit)}$ core temperature at exit, $T_{re(nadir)}$ core temperature at the end of the afterdrop period)

Subjects	$T_{re(entry)}$ (°C)	$T_{re(peak)}$ (°C)	$T_{re(exit)}$ (°C)	$T_{re(nadir)}$ (°C)	Overall cooling rate ($°C \cdot h^{-1}$)	Peak cooling rate ($°C \cdot h^{-1}$)	Peak time (min)	Temp drop $T_{re(peak)}$ to $T_{re(exit)}$ (°C)
F1	37.4	37.4	35.1	34.7	3.1	4.0	5.4	2.4
F2	37.5	37.8	36.8	36.2	0.6	1.0	5.4	1.0
F3	37.1	37.7	37.3	35.3	−0.1	0.4	31.0	0.4
F4	36.5	37.5	36.8	35.2	−0.3	1.0	10.5	0.7
F5	36.9	37.0	35.2	32.9	2.9	3.9	5.1	1.8
Mean (F)	37.1	37.5	36.2	34.9	1.2	2.0	11.5	1.2
SD	0.4	0.3	1.0	1.2	1.7	1.7	11.1	0.8
M1	37.5	37.5	35.2	34.7	2.1	2.3	4.2	2.3
M2	36.1	36.7	35.5	35.4	1.3	2.5	1.8	1.2
M3	36.4	37.0	35.3	35.1	0.9	1.6	8.0	1.7
M4	36.6	36.8	34.7	33.7	4.5	7.4	7.0	2.1
M5	37.0	37.0	35.3	33.7	5.0	5.4	2.2	1.7
M6	37.6	37.7	35.2	34.8	2.6	3.1	10.7	2.5
M7	37.0	37.0	35.0	33.6	4.2	4.8	3.6	2.0
M8	37.2	37.1	35.2	33.8	4.5	4.8	2.7	2.0
M9	37.2	37.5	34.8	34.2	4.4	5.2	2.0	2.7
M10	37.5	38.1	37.6	37.1	−0.2	1.4	17.0	0.5
M11	38.0	38.2	38.0	36.9	0.0	1.3	9.5	0.2
M12	37.5	37.6	36.4	35.9	2.0	2.5	2.5	1.2
Mean (M)	37.2	37.4	35.7	34.9	2.6	3.5	5.9	1.7
SD	0.4	0.5	1.1	1.2	1.9	1.9	4.7	0.8
Mean (pooled data)	37.1	37.4	35.8	34.9	2.2	3.1	7.6	1.6
SD	0.5	0.5	1.1	1.2	1.9	2.0	7.3	0.8

Table 4 Correlation coefficients (r) between distance covered and skinfold thickness, percentage (%) of body fat, maximum oxygen consumption ($\dot{V}O_{2max}$), and cooling rates

Variable	r
Skinfolds:	
Triceps	0.70**
Patellar	0.56*
Abdomen	0.04
% Body fat	0.43
$\dot{V}O_{2max}$	−0.17
Overall cooling rate	−0.63**
Peak cooling rate	−0.67**

* Correlation coefficient significant at $P < 0.05$
** Correlation coefficient significant at $P < 0.01$

healthy and fit individuals (average $\dot{V}O_{2max}$ of $52.6\ \text{m} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ in the present study as compared to the Canadian average of $41.5\ \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ for the same age group; Government of Canada Fitness and Amateur Sport 1986), and having a below average body fat content (average percent body fat of 13.8 in the present study as compared to the Canadian average of 19.5 for the same age group; Government of Canada Fitness and Amateur Sport 1986). It is possible that different results could have been found for a population more representative of the average Canadian population, where aerobic fitness could have been more or less of an issue.

The present results support the observation of Nadel et al. (1974), who reported that the limiting factor responsible for the termination of a swim in cold water is related to muscle fatigue of the arms. It is known that the arm muscles contribute the major propulsive force during swimming activity (Holmer and Astrand 1972) and that they are predisposed to early onset of muscle fatigue because of their partial anaerobic working conditions, particularly in untrained swimmers (Holmer 1972). Swimming in cold water may accelerate the onset of fatigue in the arm muscles, primarily due to muscle cooling. It has been observed that during cold-water immersion at rest, about 90% of the arm insulation is provided by the underperfused muscle tissue (Ducharme and Tikuisis 1991). During arm exercise, however, the perfusion of the muscles will increase several-fold, which will cause a significant decrease of muscle insulation, as reported by Nadel et al. (1974) and Veicsteinas (1987). It was suggested by Doubt (1991) that a reduction in muscle temperature below normal will reduce muscle perfusion for a given workload. This limited muscle perfusion will increase the anaerobic contribution to the work effort and will increase the rate of muscle fatigue (Pendergast 1988). Furthermore, cooled muscles have a reduced contractile force (Blomstrand et al. 1986; Petrofsky et al. 1981), which in itself can limit the muscle performance during cold-water swimming.

Any factor that could decrease the rate of muscle cooling during swimming activity in cold water could have an impact on swimming performance by delaying muscle fatigue and thus improving swimming distance. This is partially based on the observation that the majority of the decrement in arm performance seen during cold-water immersion is due to the local effects of cooling on arm tissue, and not to general hypothermia (Giesbrecht et al. 1995). The present study shows that skinfold thickness of the arm has an influence on the distance covered during swimming in cold water before incapacitation. It has been shown in several studies that subcutaneous fat is an effective barrier against heat loss (Golden et al. 1979; Hayward 1983; Pugh and Edholm 1955), and that this fat layer is minimally perfused even during exercise in cold water, thus keeping its effective thermal resistance high (Ferretti et al. 1989; Veicsteinas 1987). Having more subcutaneous fat around the arm will decrease heat loss from the working muscles, thus keeping the muscle perfusion and temperature higher, and therefore possibly delaying muscle fatigue.

When analyzed individually, patella skinfold thickness also correlated significantly with the distance covered. This might be explained by the significant correlation ($P < 0.01$) between patella and triceps skinfold thicknesses and by the more vigorous leg action that is performed while wearing personal floatation devices as compared with the alternate face-immersion crawl stroke technique. Since the legs could have contributed more to propulsion in the present study, similar observations regarding muscle cooling could be applied to the leg muscles.

In their study, Hayward and Keatinge (1981) estimated local tissue insulation and found that exercise in cold water caused the insulation measured at the thighs, calves, upper arms and forearms to decrease, but not for the sites measured on the trunk. Furthermore, Sloan and Keatinge (1973) showed that in children with a given trunk skinfold thickness, the boys had less limb fat and cooled more quickly than the girls who had more limb fat, while swimming in cold water. These observations suggest that the rate of cooling observed during exercise in water may be more related to the subcutaneous fat thickness on the limbs than to the subcutaneous fat on the trunk. Using a correlation matrix analysis, it was indeed found that abdominal skinfold thickness was not significantly correlated to the overall and peak rates of cooling ($r = -0.38$ and -0.36, respectively), in contrast with the triceps skinfold thickness, which was found to be significantly correlated to the rates of cooling ($P < 0.01$). This observation could explain why triceps skinfold thickness was the only significant parameter predicting swimming distance from the stepwise regression analysis, despite the significant correlation between swimming distance and cooling rates when analyzed individually.

The present study does not support the assumption used by Hayward et al. (1975) that hypothermia could be responsible for the incapacitation to swim in cold water while wearing a personal floatation device. Hayward et al. (1975) predicted that the average swimming distance before incapacitation would be

1,374 m, based on the body cooling rate to reach a core temperature of 33 °C, which was considered to be the lower limit for maintenance of "useful activity" such as swimming. Despite similar peak cooling rates between the two studies (present study: 3.64 $°C \cdot h^{-1}$; Hayward et al. 1975: 3.44 $°C \cdot h^{-1}$), the current subjects ended their swimming activity with an average core temperature of 35.8 °C and after an average swimming distance of 889 m, long before any incapacitation by general hypothermia had developed. Using the same predictive assumptions as Hayward et al. (1975), the current subjects should have covered a distance of 2,058 m before incapacitation by hypothermia, which is more than double the voluntary distance covered of 889 m.

In conclusion, for a healthy adult population accidentally immersed in cold water and wearing personal floatation devices, triceps skinfold thickness is a stronger predictor of the distance covered than body adiposity, $\dot{V}O_{2max}$, or the drop in T_{re}. The present conclusion may, however, be limited to swimming in cold water above 10 °C with a personal floating device. Factor(s) limiting the distance covered in colder water (i.e., approaching the freezing point), and/or when the victim does not wear a personal floating device, need further investigation.

Acknowledgements The authors wish to thank the subjects who took part in this project, and Mr. John McIlwain, technologist, Laurentien University, School of Human Movement, for his statistical support.

References

Blomstrand E, Kaijser L, Martinsson A, Bergh U, Ekblom B (1986) Temperature-induced changes in metabolic and hormonal responses to intensive dynamic exercise. Acta Physiol Scand 127: 477–484

Cannon P, Keatinge WR (1960) The metabolic rate and heat loss of fat and thin men in heat balance in cold and warm water. J Physiol (Lond) 154: 329–344

Carlson LD, Hsieh ACL, Fulington F, Elsner RW (1958) Immersion in cold water and body tissue insulation. J Aviat Med 29: 145–152

Doubt TJ (1991) Physiology of exercise in the cold. Sports Med 11: 367–381

Dubois D, Dubois EF (1916) A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17: 863–871

Ducharme MB, Tikuisis P (1991) In vivo thermal conductivity of the human forearm tissues. J Appl Physiol 70: 2682–2690

Dulac S, Quirion A, DeCarufel D, Leblanc J, Jobin M, Côté J, Brisson GR, Lavoie JM, Diamond P (1987) Metabolic and hormonal responses to long-distance swimming in cold water. Int J Sports Med 8: 352–356

Ferretti G, Veicsteinas A, Rennie DW (1989) Conductive and convective heat flows of exercising humans in cold water. J Appl Physiol 67: 2473–2480

Giesbrecht GG, Pu Wu M, White MD, Johnston CE, Bristow GK (1995) Isolated effects of peripheral arm and central body cooling on arm performance. Aviat Space Environ Med 66: 968–975

Golden FStC, Tipton MJ (1987) Human thermal responses during leg-only exercise in cold water. J Physiol (Lond) 391: 399–405

Golden FStC, Hampton IFG, Hervey GR, Knibbs AV (1979) Shivering intensity in humans during immersion in cold water. J Physiol (Lond) 290: 48p–49p

Government of Canada Fitness and Amateur Sport (1986) Canadian standardized test of fitness (CSTF) operation manual. Fitness and Amateur Sport Canada, Ottawa, ON, Canada

Hayward JS (1983) The physiology of immersion hypothermia. In: Pozos RS, Wittmers LE (eds) The nature and treatment of hypothermia. Croom Helm/University of Minnesota, London

Hayward MG, Keatinge WR (1981) Roles of subcutaneous fat and thermoregulatory reflexes in determining ability to stabilize body temperature in water. J Physiol (Lond) 320: 229–251

Hayward JS, Eckerson JD, Collis ML (1975) Effect of behavioral variables on cooling rate of man in cold water. J Appl Physiol 38: 1073–1077

Holmer I (1972) Oxygen uptake during swimming man. J Appl Physiol 33: 502–509

Holmer I, Astrand OO (1972) Swimming training and maximal oxygen uptake. J Appl Physiol 33: 510–513

Keatinge WR (1960) The effect of subcutaneous fat and of previous exposure to cold on the body temperature, peripheral blood flow and metabolic rate of men in cold water. J Physiol (Lond) 153: 166–178

Keatinge WR (1961) The effect of work and clothing on the maintenance of body temperature in water. Q J Exp Physiol 46: 69–82

Keatinge WR (1969) Survival in cold water. Blackwell, Oxford, p 131

Lohman TG (1981) Skinfold and body density and their relation to body fatness: a review. Hum Biol 53: 181–225

Nadel ER, Holmer I, Bergh U, Astrand P-O, Stolwijk JAJ (1974) Energy exchanges of swimming man. J Appl Physiol 36: 465–471

PAR-Q Validation Report (1978) British Columbia Ministry of Health

Pendergast DR (1988) The effect of body cooling on oxygen transport during exercise. Med Sci Sports Exerc Suppl 20: S171–S176

Petrofsky JS, Burse RL, Lind AR (1981) The effect of deep muscle temperature on the cardiovascular responses of man to static effort. Eur J Appl Physiol 47: 7–16

Pugh LGC, Edholm OG (1955) The physiology of channel swimmers. Lancet 2: 761–768

Royal Life Saving Society of Canada (1997) Hypothermia: the cold wet facts. Royal Life Saving Society of Canada, Ottawa, Ontario, Canada

Sagawa S, Shiraki K, Yousef MK, Konda N (1988) Water temperature and intensity of exercise in maintenance of thermal equilibrium. J Appl Physiol 65: 2413–2419

Sloan REG, Keatinge WR (1973) Cooling rates of young people swimming in cold water. J Appl Physiol 35: 371–375

The Canadian Red Cross Society (1983) Cold water survival (SW83003–200M-E M/M). The Canadian Red Cross Society, Ottawa, Ontario, Canada

The Canadian Red Cross Society (1995) Swimming and water safety. Mosby Lifeline, Toronto, p 303

Veicsteinas A (1987). Changes of muscle and fat insulation during exercise in water. In: Samueloff S, Yousef MK (eds) Adaptive physiology to stressful environments. CRC, Florida, pp 51–57