Immersion deaths and deterioration in swimming performance in cold water

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Summary

Background General hypothermia (deep body temperature <35°C) has been implicated in immersion-related deaths, but many deaths occur too quickly for it to be involved. We investigated changes in swimming capability in cold water to find out whether such changes could lead to swim failure and drowning.

Methods Ten volunteers undertook three self-paced breaststroke swims in a variable-speed swimming flume, in water at 25°C, 18°C, and 10°C, for a maximum of 90 min. During each swim, we measured oxygen consumption, rectal temperature, swim speed and angle, and stroke rate and length. Swim failure was defined as being unable to keep feet off the bottom of the flume.

Findings All ten swimmers completed 90 min swims at 25°C, eight completed swims at 18°C, and five at 10°C. In 10°C water, one swimmer reached swim failure after 61 min and four were withdrawn before 90 min with rectal temperatures of 35°C when they were close to swim failure. Swimming efficiency and length of stroke decreased more and rate of stroke and swim angle increased more in 10°C water than in warmer water. These variables seemed to characterise impending swim failure.

Interpretation Impaired performance and initial cardiorespiratory responses to immersion probably represent the major dangers to immersion victims. Consequently, treatment should be aimed at symptoms resulting from near-drowning rather than severe hypothermia.

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Introduction

In the past 25 years, between 400 and 1000 immersion-related deaths have occurred each year in the UK,[1–3] which represents a major cause of accidental death in children and adults. Many of those who die are judged to be competent swimmers.[1]

Hypothermia has been implicated in these deaths, but many seem to have occurred too quickly for hypothermia (deep body temperature <35°C)[4] to be involved. Alternatively, the uncontrollable hyperventilation seen on immersion[5] can lead to a lack of coordination between swim stroke and respiration, which increases the possibility of aspiration and inability to swim.[6] The deterioration in swimming performance, after the initial respiratory responses have adapted (about 2 min) but before onset of hypothermia, has not been investigated in detail. We aimed to characterise the changes that occur in swimming capability during this time, and to find out how the changes seen might contribute to swim failure, immersion death, and understanding of the status of immersion casualties.

Methods

Volunteers

The local ethics committee of the Karolinska Institute, Stockholm, approved the study protocol. Ten healthy young adult volunteers (nine men, one woman) participated after giving informed written consent. The swimmers were from the UK and Sweden, of just above average fitness (table 1), with no previous experience of cold-water swimming, and all were judged to be competent swimmers.

Each swimmer, wearing swim-wear, completed self-paced breaststroke swims in water at 25°C, 18°C, and 10°C. All participants swam in water at 25°C first; five undertook the 18°C swim second, followed by the 10°C swim, and the other five swam in 10°C water second then 18°C water. All swims were done in a variable-speed swimming flume with a depth of 1·5 m; the water speed was adjusted throughout the swims according to the requests of swimmers. We asked the volunteers to choose a pace that they could sustain for a long time. Throughout their swims the swimmers were unaware of the time. Swims were ended after 90 min or prematurely if: the swimmer asked to stop; rectal temperature fell to lower than 35°C; abnormalities were seen on electrocardiography; the independent medical officer or project officer ended the swim; or swim failure (inability to keep feet off the bottom of the flume) occurred. Once removed from the water, swimmers were rewarmed under supervision.

All swimmers did an additional swim in water at 25°C so that peak oxygen consumption could be measured.

Variables

We measured height, body mass, and skinfold thickness at biceps, triceps, forearm, chest, subscapular, suprailiac, thigh, and calf.

Rectal temperature was measured with a rectal thermistor, inserted 0·15 m beyond the anal sphincter, and was recorded on computer every 10 s throughout the swims.

Characteristic	Mean (range)
Age (years)	30 (23–39)
Height (m)	1·75 (1·65–1·89)
Weight (kg)	80 (58–90)
Skinfold thickness (mm)*	47·6 (23·5–82·3)
Limb skinfold thickness (mm)†	127 (64–203)
Body fat (%)	19·7 (10·6–26·8)
Peak oxygen consumption (mL kg^{-1} min^{-1})	48·7 (39·2–67·8)

*At biceps, triceps, suprailiac, and subscapular on right side of body.
†At biceps, triceps, inner and outer forearm, thigh, and calf on left and right side of body.

Table 1: **Physical characteristics of volunteers**

Oxygen consumption was calculated continuously by sampling of exhaled air collected in a 9 L mixing box and was recorded on computer. We measured concentrations of oxygen and carbon dioxide with a mass spectrometer (Airspec Ltd, Kent, UK), and expiratory volume by argon dilution in a mass-flow regulator (Brooks Instrument BV, Veenendaal, Netherlands).

Respiratory frequency, inspiratory volume, and tidal volume were measured continuously with a turbine ventilatory module (KL Engineering, Northridge, CA, USA) placed on the inspiratory side of the mouthpiece and recorded on computer.

We recorded heart rate continuously by three-lead electrocardiography (Sirecust, Siemens, Danvers, MA, USA).

We assessed swimming angle and stroke rate by analysis of underwater video recordings of the side-view of swimmers. Stroke length, defined as the length of each swimming stroke, was calculated from stroke rate and swim speed. Swimming efficiency, defined as metres swum per litre of oxygen consumed, was calculated from consumption of oxygen and swim speed. We measured the grip strength of the swimmers' hands before and after each swim with a hand-held dynamometer.

Statistical analysis

The data were analysed by a repeated-measures within-swimmer ANOVA,[7] with water temperature as the main factor. We used the Tukey method of contrasts to investigate any significant differences. Wilcoxon's signed-ranks test was used to assess the difference in swimming angle at the start and the end of the swims in 10°C water. Since only five swimmers completed 90 min swims in all water temperatures, we restricted comparisons of the responses for the full swimming time to them. We used Pearson's product moment correlation to look at the relation between the skinfold thicknesses of swimmers and their rate of change in swimming efficiency in water at 10°C. Statistical significance was taken to be at the 5% level (p<0·05).

Results

The physical characteristics of swimmers are given in table 1.

The inspiratory-volume, respiratory-frequency, and heart-rate responses in the first 3 min of swimming increased with decreasing water temperature (table 2). The swim speed was initially higher in the colder water than in 25°C water, but the ratio of expiratory volume to oxygen consumption was also increased in the colder water, which showed that hyperventilation occurred.

All swimmers swam for 90 min in water at 25°C. In 18°C water, eight of ten swimmers swam for 90 min. One of the remaining two swimmers was withdrawn at 27 min with a rectal temperature of 35·0°C, the other was withdrawn at 60 min with cold-induced shoulder pain. In 10°C water, five swimmers completed 90 min swims. Four swimmers were withdrawn after swim times between 22 min and 50 min, when they were close to swim failure, with a mean rectal temperature of 35·0°C; one swimmer was withdrawn at 61 min because of swim failure, at which point rectal temperature was 35·3°C.

	25ºC	18ºC	10ºC
Respiratory frequency (breaths/min)	18·2	25·1*	33·3†‡
Inspiratory volume (L/min)	26·7	43·8§	65·8†‡
Expiratory volume/oxygen consumption ratio	30·5	41·6§	53·8‡||
Heart rate (beats/min)	99·9	119·1*	145·3†‡

Data are arithmetic means for all ten volunteers.
*25ºC *vs* 18ºC p<0·01. †18ºC *vs* 10ºC p<0·01. ‡25ºC *vs* 10ºC p<0·01. §25ºC *vs* 18ºC p<0·05. ||18ºC *vs* 10ºC p<0·05.

Table 2: **Mean responses over first 3 min for swims at 25ºC, 18ºC, and 10ºC**

The mean rates of change of temperature were: in 25°C water, 0·03°C/h (range 0·60 to –0·65); in 18°C water, –0·75°C/h (0·50 to –4·09); and in 10°C water –2·57°C/h (–0·75 to –5·34). Rectal temperature was significantly lower at the end of the 10°C swim than in the two warmer water temperatures (p=0·01, table 3).

The mean oxygen consumption during the swims in each water temperature was 45%, 59%, and 65%, respectively, of peak oxygen consumption in 25°C water, and was not influenced by whether or not the swimmer could complete the 90 min swim.

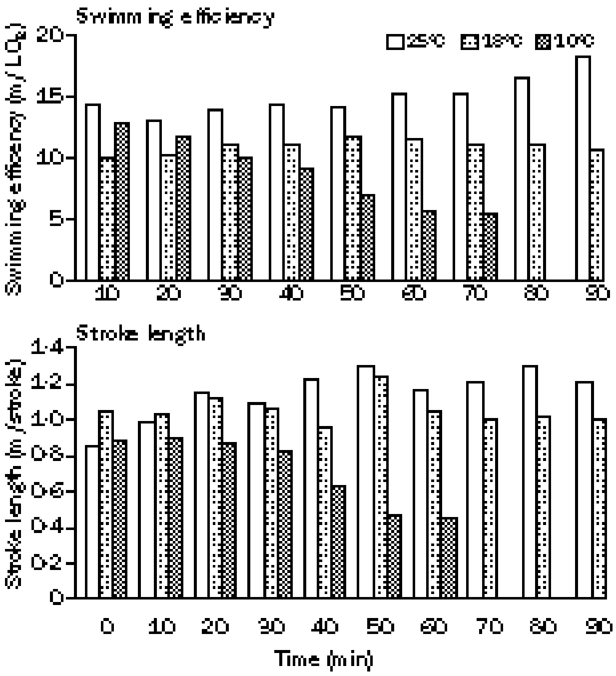
Swimming efficiency was similar in 25°C and 18°C water and remained constant throughout the swims. By contrast, in 10°C water, swimming efficiency declined over time (table 3). The rate of decline in the five swimmers who did not complete the 90 min swim at this temperature was ten times that of the other swimmers. The swimmer who reached swim failure had the lowest absolute swimming efficiency at the end of his swim (5·6 m/L oxygen, figure). The decrease in swimming performance, as defined by the change in swimming efficiency, was most closely correlated with sum of the skinfold sites of the upper limbs (triceps, outer forearm, and subscapula, R^2=0·68)

Stroke rate and length were similar in 25°C and 18°C and remained fairly constant throughout the swims for all swimmers. By contrast, during the 10°C swims, stroke length was decreased, whereas stroke rate increased with time (table 3). In the last 10 min of the swims in 25°C and 10°C water, the swimmers were swimming at about the same speed (0·49 m/s and 0·47 m/s, respectively). However, in 25°C water, the average stroke rate was 29·8 strokes/min, with a stroke length of 0·99 m/stroke. In 10°C water, stroke rate was increased to 34·2 stroke/min, and stroke length was decreased to 0·83 m/stroke. These

	25ºC		18ºC		10ºC	
	C	W	C	W	C	W
Average swim speed (m/s)	0·44	0·46	0·53*	0·55	0·50†	0·47
Average oxygen consumption (L/min)	1·68	1·87	2·20*	2·56	2·43‡	2·32
Swimming efficiency (m/L oxygen)						
At 10 min	15·9	16·2	15·5	15·2	14·2	15·1
At end	15·3	16·2	14·2	12·7	11·2	10·0
Stroke rate (min)						
At 10 min	29·2	28·5	28·0	28·2	31·0	32·4
At end	29·8	28·8	31·6	32·4	34·2†	36·0
Stroke length (m/stroke)						
At 10 min	0·85	0·98	1·10	1·18	1·07	0·95
At end	0·99	1·00	1·09	0·99	0·83	0·66
Rectal temperature (ºC)						
At 0 min	37·44	37·33	37·52	37·29	37·51	37·30
At end	38·06	36·77	37·73	35·87	35·80‡	35·04§

C=completed (n=5); W=withdrawn (one or more swims, n=5)
*25ºC *vs* 18ºC p<0·05. †25ºC *vs* 10ºC p<0·05. ‡25ºC *vs* 10ºC p<0·01. §18ºC *vs* 10ºC p<0·01.

Table 3: **Mean values for physiological and physical measures for three 90 min swims**



Swimming efficiency and stroke length at 25ºC, 18ºC, and 10ºC for swimmer who reached swim failure in 10ºC water

changes in characteristics of swim stroke were most pronounced in swimmers who were closest to swim failure; stroke length decreased by 50% during the last 30 min before the swimmer who reached swim failure in 10°C water stopped swimming at 60 min (figure). The changes in characteristics of swim stroke coincided with an increase in swimming angle from an average of 18·4° to the horizontal at the start, to 23·4° at the end of this swim. The increase in swim angle was greatest in swimmers who came closest to swim failure, with the swimmer who reached swim failure finishing with a swim angle of 35°.

After 15–30 min in 10°C water, swimmers' fingers were splayed and starting to flex. At the end of swims in 10°C water, swimmers reported that it became increasingly difficult to straighten their limbs and coordinate their swimming movements. The loss in coordination was attributed to increased shivering, which interfered with, and in some cases almost inhibited, swimming. As time progressed, the gliding phase of breaststroke was shortened and by the end of the swim was absent in most swimmers. Grip strength was not altered by swimming in water at 25°C. After swimming in water at 18°C and 10°C, grip strength was significantly decreased by 11% ($p=0·01$) and 26% ($p=0·01$), respectively.

Discussion

General hypothermia is believed to be the major danger associated with immersion in cold water. This belief is reflected in search and rescue policies, requirements for protective clothing, and treatment. By contrast, all the responses we reported occurred without swimmers becoming even moderately hypothermic. Golden and Hervey[8] outlined four stages of immersion in cold water associated with particular risk: immediate, short-term, long-term, and post-immersion (on and after removal from water). Most immersion deaths occur in the first two stages, whereas hypothermia is seen as a result of long-term immersion and is unlikely to be present in individuals who have been immersed for less than 30 min.

In previous studies, during swimming at less than maximum ability, oxygen consumption for a given speed increased with decreasing water temperature because of shivering,[9–11] which decreases swimming efficiency. In our study, this decline seemed to be linear with time, and a swimming efficiency of less than 5 m/L consumed oxygen was equated with swim failure. Therefore, swimming efficiency may be a good predictor of impending swim failure.

The decrease in swimming efficiency seen in the 10°C water was accompanied by a change in characteristics of swim stroke in which the volunteers swam with shorter, more rapid strokes in a more upright position. These changes lead to further decreases in swim speed and efficacy and the increase in swimming angle increases drag and sinking force.[9] Since stroke length and rate and swim angle are more easily observed than swimming efficiency, they may also help to identify individuals who are about to reach swim failure.

The correlation between thickness of fat over the arms and swimming efficiency in cold water supports previous findings, which suggest that the arms are especially susceptible to cooling when exercised in cold water.[12,13] Thus, arm cooling and consequent muscle fatigue, rather than general hypothermia, may be the primary mechanism that led to the decline in swimming ability seen in our study. This hypothesis is supported by the decline in grip strength we reported, and the relation between low muscle temperature, and impaired physical performance during exercise in cold wet conditions in the open air identified by Pugh.[14] Effective arm activity is needed even by people wearing lifejackets while immersed in choppy open water to keep the back of the head to the waves to prevent drowning from wave splash.

Previous studies have reported high proportions of fully clothed people reaching swim failure within the first few minutes of immersion in water at 5°C.[15–17] Such swim failures have been attributed to the initial respiratory response to immersion.[6] Although we saw similar respiratory responses, especially in 10°C water, they were not incapacitating, probably because swimmers were provided with a mouthpiece and were not encumbered by clothing.

Although hypothermia has been reported to be an important cause of swimming failure,[18] we found swim failure in cold water to be a progressive decrease in swimming efficiency in the absence of general hypothermia. Therefore, even if an individual survives the initial responses to cold-water immersion, drowning remains the major threat, since local muscle cooling impairs swimming performance and, consequently, the ability to keep the airway clear of the water. The implication for rescuers is that, with the exception of children rescued after long submersion in icy water,[19] the major challenge for treatment is likely to be symptoms resulting from near-drowning rather than from severe hypothermia.

Contributors

All the researchers were coinvestigators, assisted with data collection, and contributed to the writing of the paper. In addition, Michael Tipton was the principal investigator and codesigner of the study with Frank Golden. Michel Gennser assisted with data analyses and coordinated the project in Sweden. Clare Eglin assisted with data analysis.

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