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The Physiological Response to Immersion in Cold Water and Cooling Rates During Swimming in a Group of Children Aged 10–11 Years

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Swimming is a popular activity in the United Kingdom (UK); however, cold water immersion often found in open waters in the UK is not without increased risk. Drowning is among the leading cause of accidental death in 1–14-year-olds in most countries. We examined whether children and adults exhibit similar cold shock responses; rates of cooling while swimming; and subjective recognition of cooling. Nineteen children aged 10–11 years voluntarily undertook a 5 min static immersion in 15 °C (59 °F) water. Ten of them completed a swim of up to 40 min. Resting heart rate, respiratory frequency, and inspiratory volume increased in all participants on initial immersion. The mean ($\pm$ SD) cooling rate while swimming was 2.5 °C hr⁻¹ ($\pm$ 3.1°). No significant correlation was found between cooling rate and thermal sensation or comfort, implying a lack of subjective awareness in children. On comparing data from unacclimatized adults in 12 °C (53.6 °F) water, children showed a smaller cold shock response ($p \leq .05$), and no difference was found in cooling rates during swimming.

Keywords: drowning, cold water immersion, cold shock response, children

Swimming is the most popular sport in the United Kingdom (UK) with over 20 million people of all ages and abilities participating annually (Amateur Swimming Association, 2013). The marked increase in successful solo and relay-team crossings of the English Channel in the last decade reflects an increase in open water swimming (Channel Swimming & Piloting Federation, 2011). Open water swimming and particularly that involving cold open water is not without risk. Drowning represents the third leading cause of accidental death worldwide, accounting for an

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estimated 388,000 annual fatalities (World Health Organization, 2012). Children are recognized to be particularly at risk; in those aged 1–14 years, it represents the leading cause of accidental death in some countries, and those aged under 5 years have the highest drowning mortality rates worldwide (with the exception of Canada and New Zealand) (World Health Organization, 2012).

The human physiological response to acute cold exposure has been well documented, and substantial research has been conducted into adult thermal responses to initial and prolonged immersion in cold water (Golden & Tipton, 2002; Keatinge & Evans, 1961; Tipton, 1989). It is well recognized that the initial cold shock response seen in adults upon immersion includes uncontrollable respiratory gasping and increased cardiac workload that are particularly hazardous. It has been assumed that the cold shock response seen in adults also exists in children; however, this has not previously been measured in a pediatric cohort. In addition to the cold shock response, both localized and deep body hypothermia can increase the risk when swimming during short and prolonged exposure to cold water. Adjustments to these responses are critical to a person's chances of survival (Tipton, Golden, & Kelleher, 1994; Tipton, Eglin, Gennser, et al., 1999).

A number of studies have looked at cooling rates in lightly clothed or naked adults on immersion in cold water, conducted in varying water temperatures, in acclimatized and unacclimatized groups, and during differing levels of activity (Hayward, Eckerson, & Collis, 1975; Hingley, Morrissey, House, et al., 2010; Tipton et al., 1999). Cooling rates have been found to vary widely among individuals with certain factors impacting on their ability to maintain thermal balance including water temperature, body morphology, anthropometry, and whether one remains still or exercises during immersion (Hayward & Keatinge, 1981; Keatinge, Khartchenko, Lando, et al., 2001; Sloan & Keatinge, 1973; Tipton et al., 1999; Wallingford, Ducharme, & Pommier, 2000).

Children differ from adults physically, physiologically, and psychologically. They have larger surface area to mass ratios (SA: M), less subcutaneous fat, and are considered more susceptible to hypothermia (Klein & Kennedy, 2001; Stocks, Taylor, Tipton, et al., 2004). Little quantitative evidence exists to support these considerations. The studies conducted in children at rest and while exercising in cold dry environments imply that despite physiological disadvantages, their thermoregulatory response is as effective as those of adults, achieved largely due to greater relative metabolic heat production and greater reduction in limb skin temperature (Falk, 1998; Williams, 2007). These explanations have not been demonstrated in cases of cold, wet climates, either at rest or during exercise. A seminal paper published by Sloan and Keatinge (1973) observed the response to hypothermia in children swimming in cold water. They found that subcutaneous fat and SA: M were most strongly correlated to body temperature. Since then, experiments have been conducted with children cycling in a cold environment of 5 °C/41 °F (Smolander, Bar-Or, Korhonen, & Ilmarinen, 1992), but little additional quantitative data on children's cooling rates while swimming in cold water has been collected.

Children are considered poor subjective judges of the cold. It is recognized that somatosensory perception develops during childhood; however, the mechanisms underlying this process and whether there is a critical age at which this perception occurs are yet to be fully understood. A study that looked at quantitative sensory testing found that younger children were less sensitive to either cold or

warm thermal stimuli than older children and adolescents (Blankenburg, Boekens, Hechler, et al., 2010).

Given the paucity of information on the responses of children to immersion in cold water this study aimed to investigate (1) to what degree the cold shock response exists in children and (2) the cooling rates and subjective responses of children swimming in cold water. We hypothesized that children would demonstrate an equivalent cold shock response, a greater rate of fall in core temperature while swimming, and poorer thermal perception when compared with that reported in adults.

Method

Participants

Ethical approval for this study was granted by the University of Portsmouth Bio-Sciences Research Ethics Committee. Written informed assent and consent were obtained from each child and their parent/guardian respectively. During testing, each child was accompanied by a parent/guardian throughout.

Nineteen participants, 11 boys and 8 girls, aged 10–11 years, were recruited from applicants to the Bristol English Channel Swim Team (BEST)—an attempt by a group of children to break the world record and be the youngest relay team to swim the Channel. Participants were recruited for BEST through distribution of fliers and posters within a 30 mile radius of Bristol. All applicants to BEST received a presentation about this study by the Principal Investigator and were given a participant information sheet. It was made clear that the BEST attempt and this study were two separate entities and that any involvement in this study had no impact on their selection or exclusion from BEST.

Each potential participant completed a medical questionnaire, clinical examination, and 12-lead ECG. All participants had been assessed by a consultant pediatric cardiologist and were reviewed by an independent medical officer (IMO) on the study day. Any considered unfit to begin the training program for BEST or to be involved in the research were excluded from this study. All participants were proficient swimmers, fit at the time of the study, and no participant had been exposed to any regular cold water exposure or acclimatization regimen previously.

Procedures

Wearing swimming shorts/costume, participants had a restricted anthropometric profile taken and were asked to swallow an ingestible radio-pill thermometer measuring gastrointestinal core temperature (T_{GI}). Of the 19 participants, five were unable to swallow the thermometer pill and so did not partake in the swim part of this study; they were removed from the water 5 min after initial immersion and rewarmed. The remaining participants entered the flume room, air temperature (T_a) 20 °C/68 °F, humidity 50% and were seated on an immersion chair with a seat belt fastened around their waist. Participants were instrumented with a 3-lead ECG, chest strap heart rate monitor, nose clip, and mouthpiece to collect expired air. Each participant was then lowered into the water on the chair, temperature 15 °C/59 °F at 8 cm.sec⁻¹, until immersed to the clavicle. They spent up to 45 min in the water; this time was divided as follows:

Initial 5 min static immersion: anticipated to be long enough to obtain a cold shock response profile if it existed

40 min swim: the time thought necessary to obtain valid deep body temperature profiles

Participants remained seated while their cardiovascular and respiratory responses were monitored and recorded throughout, and metabolic rate was measured using a Douglas bag method during the first and fifth minute of immersion. The participants were then raised out of the water and ECG leads removed.

Participants were again lowered on the immersion chair into the water, temperature 15 °C/59 °F at 8 cm.sec⁻¹, where they unseated themselves and swam for a maximum of 40 min. During this time heart rate was recorded and T_{GI} monitored throughout. At approximately the eighth minute, and every ten minutes thereafter, participants were brought to the side of the flume to don the nose clip and mouthpiece and then asked to recommence swimming using breaststroke with head above water. Every tenth minute, expired air samples were collected for one minute, using the Douglas bag method. Participants were encouraged to swim at their own pace and to keep a constant speed as much as possible. Swimming hats were not worn, but goggles were worn by all. Subjective thermal sensation and comfort were recorded before immersion, after 5 min static immersion, and at the end of the swim. Each participant was then passively rewarmed in a bath of 39–40 °C/102.2–104 °F water.

Withdrawal Criteria

Before entering the water, it was re-emphasized to participants and their parent/guardian that they could end the immersion or swim and be assisted from the water at any point should they wish to stop. Throughout the study they were regularly asked if they were happy to continue. Participants were removed from the water if T_{GI} fell below 35 °C (95 °F), at their own request, or the request of the IMO, investigators, or parent/guardian.

Measures

Anthropometric profile. Participants' height, body mass, percentage body fat, arm span, skinfold thickness at eight different sites (i.e., biceps, triceps, subscapular, suprailiac crest, supraspinale, abdominal, front-thigh, medial-calf) and girth measurement at five different sites (i.e., medial calf, arm girth relaxed and flexed/tense, and waist and gluteal girth) were taken. These measures were taken, in duplicate, by an anthropometrist accredited by the International Society for the Advancement of Kinanthropometry.

Gastrointestinal temperature (T_{GI}). Ingestible radio-pill thermometers (Vital-Sense, Mini Mitter Inc, Bend, OR, USA) were used to record gastrointestinal temperature as a measure of deep body temperature, every minute during the cold water exposure.

ECG and heart rate. A 3-lead ECG (Lead II) was displayed continuously during the static 5 min immersion (Miniman 7137 plus, Kondtron Instruments, Charter-Kontron Ltd, Milton-Keynes, UK). During the swim-phase, heart rate was recorded

continuously using a heart-rate monitor chest strap (Team System, Polar Electro Oy, Kempele, Finland).

Respiratory and metabolic response. During the static immersion, ventilation rate, tidal volume, and inspiratory frequency were measured continuously using a flow turbine (KL Engineering, Sylmar, CA, USA) and recorded using data acquisition software (PowerLab, AD Instruments Ltd, Oxford, UK). During the first and fifth minute of static immersion and every tenth minute while swimming, participant’s metabolic rate was measured using a 100L Douglas bag connected by a length of breathing tubing to the exhalation port of a three way valve (Hans Rudolph Inc, Shawnee, KS, USA), connected to the mouthpiece of a swim snorkel. Subsequent fractional gas concentrations were analyzed using O₂ and CO₂ gas analyzers (Series 1400, Servomex Ltd, Cambridge, UK) and expired volume measured using a dry gas meter (Harvard, USA). Gas temperatures for V̇O₂ were measured using an electronic thermometer (Model 810-080, Electronic Temperature Measurement Ltd, Worthing, UK). Expired air samples were collected for one minute.

Thermal perception. Thermal sensation (TS) and thermal comfort (TC) were measured using validated (Davey, Reilly, Newton, et al., 2007) continuous visual analog scales (VAS) as shown in Figure 1. A sliding pointer was moved along the scale until the participant said “stop” at the point at which they valued their TS and TC. Each scale measured 20 cm in total and was divided equally. No numerical values were displayed, and the mark was removed once the measurement had been recorded, therefore no point of reference was visible for any subsequent measurement.

Calculations

Oxygen uptake (V̇O₂) was calculated, following conversion from ambient temperature pressure saturated (ATPS) to standard temperature pressure dry (STPD), using the Haldane transformation.

Percentage body fat (% BF) (for children) was calculated as follows with ΣSKF = sum of skinfolds calf + triceps (mm) (Slaughter, Lohman, Boileau, et al., 1988):

Boys: %BF = 0.735 (ΣSKF) + 1.0 (1)

Girls: %BF = 0.610 (ΣSKF) + 5.1 (2)

Figure 1 — Visual Analog Scales (VAS) measuring thermal sensation and thermal comfort.

Body surface area was calculated using the formula proposed by Gehan and George (1970), and body surface area to mass ratio (SA: M) was calculated as follows:

$$SA: M = BSA \text{ (m}^2\text{)}/\text{mass(kg)} \quad (3)$$

Statistical Analyses

Prism 5 (GraphPad Prism v6.01) was used for statistical analysis. D'Agostino and Pearson omnibus normality tests were calculated and where appropriate one-tailed *t* tests, two-tailed *t* tests, unpaired *t* tests, and two-way repeated measures analysis of variance tests were calculated. Where nonparametric tests were indicated by virtue of nonnormal or ordinal data, the Mann Whitney test was applied. Statistical significance used the standard 5% level ($\alpha < 0.05$).

Results

Participants

The mean ($\pm$ SD) anthropometric characteristics of participants in the initial response group and cooling rate group compared with age- and sex-matched children from UK Reference Data are shown in Table 1 (NHS, 2010).

Initial Static Immersion

Seventeen of the 19 participants, 10 boys and 7 girls, completed the 5 min static immersion. Two participants voluntarily withdrew in the first minute of immersion and were not included in the data analysis.

Table 1 Mean ($\pm$ SE) Height, Body Mass, and Body Mass Index of Children Who Took Part in the Initial Response Group ($n = 17$) and Cooling Rate Group ($n = 10$) Compared With Age- and Sex-Matched Children From UK Reference Data (NHS, 2009)

	Initial Response Group, Aged 10–11 Years		Cooling Rate Group, Aged 10–11 Years		UK Reference, Aged 11 Years	
	Boys*	Girls†	Boys*	Girls†	Boys	Girls
Height (cm)	151.1 (0.03)	150.9 (0.04)	152.2 (0.04)	147.3 (0.04)	148 (0.63)	147.2 (0.79)
Body mass (kg)	45.1 (2.51)	44.0 (5.20)	45.7 (3.83)	44.9 (8.35)	42.6 (0.90)	42.4 (1.16)
Body mass index (kg.m ⁻²)	19.7 (0.74)	19.0 (1.58)	19.6 (0.83)	20.2 (2.55)	19.3 (0.33)	19.4 (0.42)

Note. * Mean age = 10.9 years; † Mean age = 11 years.

Mean respiratory frequency, heart rate, and ventilation ($L \cdot min^{-1}$) taken at 10 s intervals from 30 s before immersion to the end of 5 min of static immersion, are shown in Figures 2, 3, and 4.

Figure 2 — Mean ($\pm$ SD) respiratory frequency during immersion in 15 °C/59 °F water ($n = 17$).

Figure 3 — Mean ($\pm$ SD) heart rate plots during immersion in 15 °C/59 °F water ($n = 17$).

Mean heart rate, respiratory frequency, and ventilation (L.min⁻¹) in minutes 1, 2, and 3 of immersion, compared with 30 s before immersion and resting baseline data, taken during participant’s medicals, are shown in Table 2.

Oxygen uptake measured during the first and fifth minute of immersion did not differ, with a mean (± SD) relative $\dot{V}O_2$ of 11.4 (± 3.0) mL.kg⁻¹.min⁻¹ and 11.4 (± 4.6) mL.kg⁻¹.min⁻¹ respectively. The latter compare with predicted resting $\dot{V}O_2$ of 5.9 (± 1.4) mL.kg⁻¹.min⁻¹ in boys and girls of the same age (Harrall et al., 2005).

Figure 4 — Mean (± SD) inspiratory volume plots during immersion in 15 °C/59 °F water (n = 17).

Table 2 Mean (SD) Heart Rate, Respiratory Frequency, and Ventilation Before and on Initial Immersion in 15 °C/59 °F Water (n = 17)

Time	Heart Rate (beats.min ⁻¹)	Respiratory (breaths.min ⁻¹)	Ventilation (L.min ⁻¹)
Resting	80 (8)	16 (2)	n/a
Pre-immersion (30 s)	96 (12)	22 (8)	14 (4)
Immersion min 1	109 (14)	36 (9)	32 (7)
Immersion min 2	99 (13)	32 (12)	26 (8)
Immersion min 3	98 (15)	30 (13)	23 (7)

Cooling Rates While Swimming

Ten participants, six boys and four girls, successfully swallowed the radio-pill thermometer and went on to swim following the initial 5 min static immersion. Three participants completed the maximum swim time of 40 min; one swim was terminated at 11 min due to a rapid fall in T_{GI} ; one participant was removed from the water after 24 min due to early signs of swim failure; and five participants voluntarily withdrew between 7–30 min. Seven of the 10 participants swam for 20 min or more. This subsection of participants had a mean ($\pm SD$) height of 1.5 (± 0.09) m, body fat of 23.9 (± 5.8) %, and SA: M of 0.03 (± 0.00).

Participants' heart rates were relatively stable throughout the swim, measuring a mean ($\pm SD$) of 146 (± 27) beats.min⁻¹ in the first minute, and 145 (± 18) beats.min⁻¹ over the total swim, compared with a resting HR of 80 (± 8) beats.min⁻¹ recorded during the medicals. Mean relative $\dot{V}O_2$ (mL.kg⁻¹.min⁻¹) levels are illustrated in Figure 5. These compare with a mean resting relative $\dot{V}O_2$ of 5.92 (± 1.41) mL.kg⁻¹.min⁻¹ in age- and sex-matched children (Harrell et al, 2005). Mean ($\pm SD$) T_{GI} at the start of the swim was 37.7 °C (± 0.26) following a 5 min static immersion in 15 °C/59 °F. The changes in T_{GI} over the course of the swim varied greatly between individuals, as illustrated in Figure 6.

Despite an increase in T_{GI} seen in two participants over the course of their swim, T_{GI} was seen to be falling in all participants by the end of their swim. The greatest decrease in T_{GI} was 1.5 °C/34.7 °F over a 10 min swim. Mean ($\pm SD$) deep body cooling rate was 2.5 °C.h⁻¹ (± 3.06), calculated from a linear section of each individual plot toward the end of each swim. The change in T_{GI} was most strongly associated with sum of skinfolds ($R^2 = .42$). The speed of the flume could range from 0–30 units, with a group average flume speed of 7.2 units (± 1.4), equating

Figure 5 — Mean ($\pm SD$) oxygen uptake ($\dot{V}O_2$ mL.kg⁻¹.min⁻¹) taken for one minute every 10 min of the swim period in water with a temperature 15 °C/59 °F.

Figure 6 — Individual plots of T_{GI} over the course of the swim in a water temperature of 15 °C/59 °F.

to a water velocity of 0.53 m.sec⁻¹. No significant correlation was found between rate of fall in deep body temperature toward the end of their swim and subjective awareness of thermal sensation and comfort.

Discussion

This study provides the first published evidence of the cold shock response in children, quantitative data on cooling rates of children swimming in 15 °C/59 °F water and evidence to suggest a lack of subjective awareness of deep body cooling in children while swimming. Given the risks associated with the cold shock response in adults, quantitative evidence of a similar response in children may partly explain a proportion of the large number of drowning incidences seen among children worldwide.

When compared with adults (a mixed sex group of unacclimatized adults ($n = 10$) who underwent a static immersion in water 12 °C/53.6 °F in the same laboratory as part of a different unpublished study (S. Hingley et al., personal communication, July 6, 2009) the children in the current study demonstrated lower heart rates ($p < .01$), respiratory frequencies ($p < 0.05$), and minute ventilation volumes ($p < .01$) during the first minute of immersion in 15 °C/59 °F water, despite similarly recorded and predicted (Dugdale, 2011) resting values between the two groups, with a larger percentage reduction in these responses in children during the first 3 min of immersion. While this may be due to methodological differences, it begs the question as to whether there is a variation in the magnitude of the cold shock response associated with age. Such variation has not been demonstrated in the diving response where no difference was found between adults and children

capable of breath holding for long enough to elicit a response (Ramey, Ramey, & Hayward, 1987). Cooling rates varied greatly between individuals, likely due to differences in anthropometric profiles, and in keeping with Sloan and Keatinge's findings (1973), change in deep body temperature was most strongly associated with sum of skinfolds ($R^2 = .42$).

The cooling rates of this group of children were compared with the same unacclimatized adult group, detailed above, swimming in 12 °C/53.6 °F for up to 40 min (S. Hingley et al., personal communication, July 6, 2009). Contrary to popular opinion that children are at greater risk of hypothermia on immersion, no difference was found in cooling rates between these groups. This could be due to a lower water temperature in the adult study; it also may be explained by the significantly greater percentage body fat ($p < .05$) and higher relative $\dot{V}O_2$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) ($p \leq .01$) seen in the children. These findings support studies performed with children exercising in cold dry environments where they were found to maintain their core temperatures as effectively as adults, possibly due to a greater relative metabolic heat production and lower skin limb temperatures (Williams, 2007).

Limitations

The limitations of this study are partly by virtue of it being opportunistic, thanks to the BEST project. This affected the sample size and water temperature considered ethically appropriate. We recognize that the cohort of participants were highly specific and arguably unrepresentative of most children aged 10–11 years. Although these participants' challenge-seeking behaviors may have been beyond that of their peers, their previous exposure to cold open water was highly varied and feasibly similar to that of a random population of British children. We also recognize the limitations of comparing studies (i.e., adult *versus* children) with differing methodologies, namely that of water temperature and core temperature measurements. Rectal thermometers, as used in the adult studies, were deemed inappropriate in children, given that a reliable and suitable alternative was available.

We conclude that children demonstrate a cold shock response, albeit possibly of lesser magnitude than that seen in adults. While swimming in cold water, children also appear to have similar deep body temperature cooling rates to those seen in adults. Given the significance attributed to the cold shock response and onset of hypothermia in cases of accidental immersion and drowning in adults, it is hoped that this study provides a better understanding of children's physiological responses to accidental and nonaccidental immersion and will aid risk assessments in projects involving pediatric cold water immersion.

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In September 2010, six 12-year-old children successfully completed the 21 mile swim from Shakespeare Beach, Dover, to Cap Gris Nez, France, to become the youngest relay team to swim the English Channel.

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