14 Open-Water Swimming

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A Relatively New, Challenging and Unique Sport Open-water swimming (OWS) is defined by its governing body, FINA (Fédération Internationale de Natation), as any competition that takes place in rivers, lakes, oceans or water channels. Major competitions are typically 5, 10 or 25 km, whereas Marathon swimming specifically defines any 10-km event in open-water conditions. FINA first hosted an OWS Marathon at its World Championships in Perth, Western Australia in 1991, and it has been included in the Olympic aquatics programme since Beijing, 2008. A Marathon World Cup is now also well established and overseen by technical and medical officials. An additional FINA Grand Prix series has also emerged, featuring races from 10 to 88 km at various international venues, while other swims typically include crossings of famous waterways. OWS is governed by FINA's OWS Rules and Regulations, and is swum front crawl. Specific By-Laws govern the risk management and safety of competitors in all FINA-sanctioned events. OWS is also represented over shorter distances (typically 0.75–3.8 km) in multisport events such as Triathlon and Ironman (see Chap. 15), with rules set largely by the International Triathlon Union (ITU).

The major differences with OWS relative to pool swimming are the variability of environmental factors (e.g. water temperature; T_w) and the distance (1500 m being the longest pool event). Longer distance and hence longer duration of swimming

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introduces the concept of feeding stations (pontoons) from which competitors may receive food and drink from support staff as they swim past (especially for 10-km events). Elite competition, held at a variety of international venues, requires extensive travel with attendant circadian dysrhythmia, climatic variation and other challenges of the local aquatic venue. Great variance may occur in T_w, dry bulb air temperature (T_{db}), humidity, solar radiation, water currents, water type and quality, wind, chop and swells. Warm T_w is mostly accompanied by high T_{db} (e.g. 35–40 °C; dry tropics) or moderate T_{db} with high humidity (e.g. >2 kPa; wet tropics or season). Such environments may seriously challenge the thermoregulatory capacity of swimmers with high rates of metabolic heat production held for durations of 1–2 h in 5- and 10-km events, respectively. Immersion (hydrostatic pressure), the prone posture and the upper-body-dominated nature of exercise add further complexity to the physical and physiological effects of OWS.

Thermodynamics of OWS Metabolic rate can be increased up to 20 times (to as much as 84 kJ min^{-1}) during endurance exercise. Due to the relatively poor efficiency of oxidative metabolism, more than 75% of the energy is lost as heat even in the most efficient modes of locomotion. Swimming has a low efficiency of mechanical work (~5–10%, or ~8–10% at the speeds involved in elite OWS; i.e. ~1.4 m s^{-1}; [1]), and no net storage of kinetic or potential energy. The metabolic rate of swimming at ~1.4 m s^{-1} has been reported to be 3.25 L min^{-1} (~1000 W; [1]) up to 5 L min^{-1} (~1750 W; [2]). Fortunately for swimmers, however, the upper limbs and trunk muscles produce much of this heat and perhaps upward of half is conducted and convected directly to skin overlaying the active muscles [3].

Of particular interest for OWS are the differences in thermoregulation and heat exchange that arise from exercising in water. Evaporation, the body's most powerful heat loss mechanism in air, is nullified for continuously immersed skin. Evaporation can occur particularly from an upper limb during its recovery phase but the surface area of one upper limb is small (~10%) and the time exposed to air is limited (<50%). However, water has a much higher heat capacity than air (4.18 kJ kg^{-1} $°C^{-1}$ vs. 1.30 kJ $(m^3)^{-1}$ $°C^{-1}$, respectively), and a 25-fold greater conductivity (0.600 vs. 0.025 W/(m K)) [4, 5], thus facilitating many-fold faster conductive and convective transfer. Nevertheless, with the major impediment to evaporation, a largely unanswered question is whether individuals who exercise in warm water are also susceptible to larger increases in body temperature. We have preliminary data from ~90 maximal effort performance swims in T_w of 30–33 °C (at similar T_{db}), which showed that such increases are no larger than for running in warm conditions outdoors (unpublished data and [6]).

OWS in warm water normally involves considerable radiant heat load, especially given the prone posture of exercise. This aspect of OWS thermodynamics has been overlooked in almost all laboratory-based studies, yet the findings from such studies are implicitly or explicitly applied to outdoor settings. Irradiance (light energy) from the midday sun on a clear day in tropical locations can reach 1 kW m^{-2}. Nielsen et al. [7] have shown that exercising outdoors under clear sunny skies (solar radiation intensities of 300–700 W m^{-2}) can impose an additional heat load of ~100 W. In terrestrial exercise this additional load appears to incur increased sweating of ~150–180 g h^{-1}, along with an elevated heart rate by 8 b min^{-1} and $\dot{V}O_2$ by 0.15 L min^{-1} [7]. Other research has determined that the T_{db} equivalent for solar radiation experienced in a desert environment in summer is an additional ~7–10 °C [8]. We have not found a measureable increase in rectal temperature (T_{re}), heart rate or sweat rate when adding radiant heat load (~400–800 W m^{-2}) in a small pilot study of 20- and 120-min swim performance trials in ambient heat stress (32 °C T_w and T_{db}). Thus, despite the potential for radiant heat load to add to the heat burden of OWS, the few available (laboratory-based) data do not yet support it having a notable impact.

Rate of heat gain/loss when exercising nearly naked in water is linearly dependent on surface area and the skin temperature (T_{sk})—T_w gradient, and non-linearly (diminishingly) on the velocity of skin relative to water. Change in thermal energy and thus mean body temperature depends further on passive and active factors. Passive factors are body mass, mass:area ratio, tissue specific heat and the distribution and extent of subcutaneous fat. Active factors are rate of heat production and blood flow to skin and superficial muscle, which is governed mostly by T_c. Active and passive factors interact in numerous ways, for example, when immersed in cool and cold water the reduction in T_c and increase in $\dot{V}O_2$ are proportional to both the subcutaneous fat thickness and the T_w [9–12]. Within a given individual, the rate of forced convective heat transfer therefore depends largely on the difference between T_w and T_c and on the activity [4].

Heat transfer is maximised for swimming for multiple reasons, one of which is that almost the entire skin surface is perpendicular to the water flow (i.e. in contrast to running in water or on land, for example). Swimming also uses muscles throughout the body. Combined upper- and lower-body exercise, and upper-body exercise alone, cause a lower rise in T_c than for lower-body exercise alone, within cool and temperate T_w (i.e. within 20 and 26 but not 33 °C water) [13]. These larger effects for exercise that utilises the arms are likely due to: (1) the smaller muscle mass, which can lead to relatively greater blood flow than the legs; (2) the relative closeness of this arm-muscle blood supply to the skin (coupled with a smaller subcutaneous fat layer compared to the legs) reducing the conductive distance leading to higher convective heat transfer and (3) the greater surface area:mass ratio causing a greater conductive and convective heat loss at the skin–water interface [13]. Therefore, the primary use of arms in swimming, especially over longer distances, may lead to greater heat losses in water. This also indicates that the results obtained from immersion research using cycling and running exercise (especially if the running does not include much arm movement) would be erroneously applied to upper-body-dominated exercise like swimming, due to these differences in heat loss and other issues such as the head and face being largely immersed when swimming. Greater heat loss may be beneficial in warmer water but possibly detrimental in cool and cold water.

In addition to autonomic and metabolic thermoeffector responses, behavioural mechanisms are critically important in helping maintain thermal homeostasis.

In fact, behavioural thermoregulation is more sensitive [14] than autonomic thermoregulation and is of utmost importance for safe and effective performance of endurance exercise (see Chap. 1). In warm water, the loss of evaporative cooling potentially increases one's reliance on behaviour for effective thermoregulation (especially via pacing), although many relevant behavioural responses—such as adjusting posture, donning clothing (wetsuit) or moving to a warmer environment—are constrained or unavailable in many OWS settings. The basic drive for behavioural thermoregulation is thermal displeasure or discomfort. Thermal discomfort appears more dependent on T_{sk} as a thermal input than autonomic thermoregulation does, so the importance of T_{sk} (and thus T_w) should not be underestimated [14]. Yet, data are lacking as to whether swimmers can sense their thermal strain and respond appropriately. This cannot be assumed. The control of thermal comfort during exercise differs from that at rest [15, 16]. Most naturally occurring bodies of warm water will be <33 °C, which clamps the entire skin at a uniform temperature and at a level that would—in air—be associated with thermal comfort (~33 °C) or cool-related discomfort (<30 °C) [17]. Thus, thermo-afferent drive from the skin could be counteractive and thus counterproductive to that from the core when considering that high-intensity exercise will impact T_c in the face of a T_{sk} that is clamped at 'inappropriately' low levels from a sensory perspective. This leads to the question of whether swimmers are able to perceive their thermal strain, or whether the perception and reality are uncoupled. Two studies provide preliminary data relevant to this question. We found that swimmers were in fact able to accurately detect their heat strain (as measured rectally, in controlled T_w and T_{db} conditions), at least as strongly as during terrestrial exercise, despite T_{sk} being clamped during swims in T_w of 30, 32 and 33 °C [6, 18]. Similarly, McKenzie [19] had eight males cycle for ~45 min at ~60% $\dot{V}O_2$ max in 29.7 and 31.5 °C water, and heat-related discomfort was rated 8/10 in the 31.5 °C water despite T_{re} plateauing at only 38.06 °C. Therefore, swimmers are not necessarily at increased risk of insidious hyperthermia.

14.1 Influence of Heat on Performance and Health

Few studies have examined performance per se, or performance- or health-related physiological effects of intense or prolonged exercise in water (especially warm water), and even fewer used swimming. Knowledge pertaining to OWS competition is further limited because most studies using swimming exercise have used different strokes, relatively low and controlled exercise intensities (≤50% $\dot{V}O_2$ max) and short exercise durations (≤30 min). Also, these studies have mostly been conducted in a swimming pool, thereby restricting the ability to collect physiological data while also impairing ecological validity (e.g. fixed T_w and turns at each end). Effects of radiant heat load in warm T_w have not been examined other than as mentioned above. These points are important if the results are to be transferred to OWS, especially for longer swims (>20 min or 1.5 km).

Only five studies, to our knowledge, have examined effects of warm T_w over distances and intensities relevant to OWS. Robinson and Somers [20] undertook the first of these and also used elite swimmers. Six male Olympic-level swimmers swam as far as possible in 60 min in each of three T_w, averaging 33.5, 29.0 and 21.0 °C. The authors also included a comparison to a single runner on a treadmill (at approximately the same metabolic rate; 585 W m^{-2}) for 60 min in two T_{db}, averaging 25.0 and 9.3 °C. The T_{re} of the two fastest swimmers increased to 38.4 °C after 60 min in the 33.5 °C water (metabolic rate 580–605 W m^{-2}). This was a similar peak T_{re} to that seen in the runner after 60 min (38.6 °C) exercising in the cool air (9.3 °C), but the runner appears to have started with a T_{re} ~0.5 °C lower, therefore his rise was even more than the swimmers. Further, the T_{re} of the runner in 25.0 °C air ended much higher (39.7 °C) than in the fastest swimmers in 33.5 °C water (i.e. 38.4 °C). In the cool water (21.0 °C), the slightly slower swimmers (metabolic rate of 390–465 W m^{-2}) showed a small drop in T_{re}, from 37.5 to 37.1 °C. However, while also struggling in the cool conditions, the two fastest swimmers (metabolic rate of 560–595 W m^{-2}) showed a small increase in T_{re}, from 37.3 to 37.9 °C. Thus, it appears that after 60 min of intense exercise at a similar metabolic rate, the T_{re} of a runner in temperate air (25 °C) can rise to a potentially concerning level of 39.7 °C, while a swimmer in warm water (33.5 °C) appears to remain a modest T_{re} of 38.4 °C. This finding cannot be considered to apply to all swimmers due to likely differences in swimming efficiency and body composition that may affect heat balance.

Holmér and Berg [10] had five males (incl. two swimmers) complete incremental swimming tests to exhaustion lasting 5–8 min after a 20-min preload of swimming at 50% $\dot{V}O_2$ max in each of 18, 26 and 34 °C T_w, in a swimming flume. Each participant undertook an identical running protocol in 20–22 °C air on a treadmill. The authors found no significant difference in performance between T_w (detail not reported). Other relevant findings included (1) highly variable oesophageal temperature (T_{oes}) in cool water but homogeneous T_{oes} in warm water, (2) vastus lateralis temperature averaged ~1 °C above T_{oes} and (3) both of these were higher after running than swimming, regardless of T_w.

Macaluso et al. [21] had competitive Masters swimmers complete a 5-km race simulation in three T_w: 23, 27 and 32 °C. This OWS simulation was completed in an indoor 25-m pool, and the average split times (94–95 s 100 m^{-1}) indicate that the participants were at least moderately trained. Performance was impaired by both cool and warm water; mean times were 5.3% slower in 23 °C and 3.7% slower in 32 °C than in 27 °C. Yet, the T_{re} (from mercury thermometers before and after each swim) showed minimal change in 23 °C water and mean rises of 0.9 °C in 27 °C water and 1.1 °C in 32 °C water. The peak T_{re} recorded after the 5-km swims in 27 and 32 °C water (which took 75–80 min) was only ~38 °C, and thus supports the earlier findings [20] in showing only modest heat strain effects of swimming in overtly warm T_w. Thus, performance was optimised—*on average*—when swimming in normal pool temperatures, and impairments in cooler or warmer water were (again, on average) not attributable to swimmers reaching the limits of tolerable T_c.

Two studies examining the effect of cold-water ingestion in international-level OWS during pool training (T_w: ~30 °C) and competition (T_w: 28–29 °C) showed T_c increases of <1.0 °C during swims with neutral-water ingestion [22, 23]. Swim pace was similar, although no maximal performance trials were completed to examine the effects of fluid temperature.

Unpublished data from our laboratory indicate performance swim distance was 4–7% less in 32 °C compared to 27 °C across 20-, 60- and 120-min distance trials in well-trained swimmers. Effects were clear for 20 and 60 min only. The magnitude of impairment was also more homogeneous than the performance effects of swimming in the coolest water used for non-wetsuit swimming in ITU events, i.e. 20 °C, wherein some swimmers were faster and some slower than in 27 °C. These performance effects are logical because 32 °C is heat stressful for all swimmers and thus incurs multiple forms of physiological and psychophysical strain that could contribute to fatigue, whereas cool water will be a net cold stress to some swimmers (especially lean or slow) [10, 24], but thermally optimal for others (especially a combination of large, adipose and fit, for reasons described above and observed previously [25]).

We also had eight trained swimmers undertake self-paced performance swims in 33 °C before and after 6 days of heat acclimation (1 h of interval and continuous swimming) in a swimming flume at this same T_w and T_{db} [6]. Swims included a 10-min warm-up, a 20-min distance trial and 30 min at an intensity aimed at maximising training load and heat strain. Thermoregulatory responses during warm-water swimming were compared against those of terrestrial exercise (cycle ergometry) under conditions intended to incur equivalent T_{sk} (~33 °C; T_{db} 29 °C, 60% RH, 3 m/s air velocity; v_a). Swimmers' heat strain at completion of the 20-min distance trial was modest, i.e. peak T_{re} was on average 38.3 °C (range: 37.5–38.7). Notably, this did not exceed the peak T_{re} of terrestrial exercise (38.4 °C; range: 37.7–39.0), was comparable with the peak obtained during the daily 60-min heat acclimation swims (~38.0 °C) and was minimally higher than the peak recorded from an overlapping cohort doing 20-min distance trials in temperate (27 °C) water (38.0 °C; range: 37.2–38.8).

Safety monitoring of athletes' T_c (gastrointestinal pill) has been undertaken in some international OWS competitions held in Asia (T_w 25.0–32.0 °C). As shown in Fig. 14.1, T_c from five such races is typically higher than in flume-based equivalent T_w, and while peak T_c is ~39 °C, on average, T_c up to 40.0 °C was evident. The higher T_c seems unlikely to be a methodological issue of the site of T_c measurement [26], and thus highlights the importance of gaining further such race data during OWS competition. It is equally important to contextualise these against the at-least-as-high T_c that occur during terrestrial endurance competition of similar durations in these geographic regions and to understand the importance of intact behavioural thermoregulation (discussed below).

The Physiology of OWS Brief discussion of the physiology of OWS training and competition is warranted here because of its importance to performance, health and potential countermeasures to heat stress. A far more extensive and contemporary review of the physiology of immersion and swimming is available elsewhere [27]. Table 14.1 is a summary of the causes of strain and potential countermeasures. It is critical for the reader to appreciate that the multiple impacts of OWS in warm water

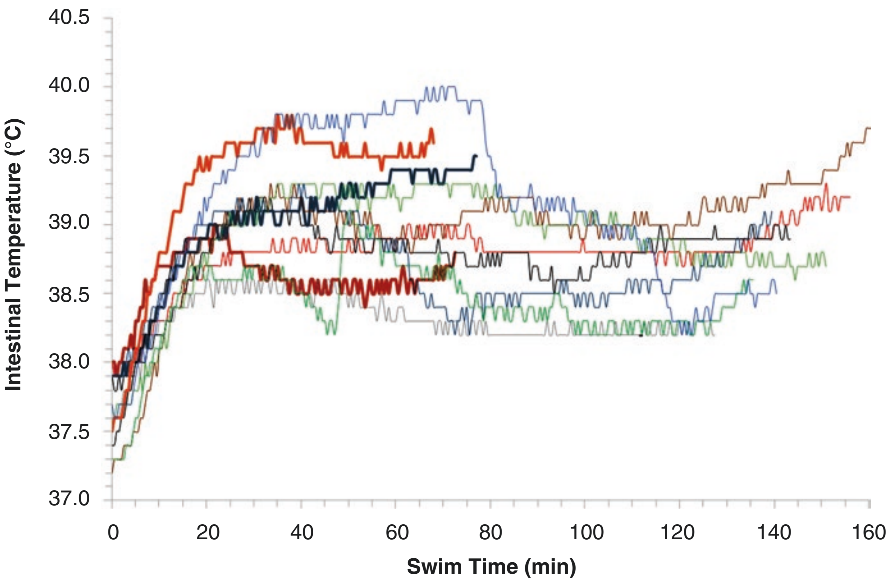

Fig. 14.1 Gastrointestinal pill thermometer-recorded temperatures from five swimmers during OWS competitions in Asian ocean and lake swims of 5 km (thick lines) and 10 km (thin lines). T_w ranged from 25 to 32 °C with similar T_{db}. Data reproduced with the permission of the Singapore Sport Institute. Any omission or error remains with the authors

(shown in Table 14.1) will have interactive effects that could acutely impair health or performance [28].

Cardiovascular and Metabolic Another consequence of predominantly arm-based exercise is that cardiorespiratory, autonomic and metabolic strain of exercise is greater than would be incurred from equivalent leg-based exercise [29–31]. This has numerous implications for health, performance and potential countermeasures. For example, the higher rate pressure product will increase the risk of myocardial infarction in susceptible swimmers, particularly in cool water. Conversely, rates of local and whole-body glycogenolysis are higher ([32]; and presumably more so in warmer T_w [33]), which would make OWS advantageous as a form of exercise for facilitating glucose removal from the blood, but disadvantageous for endurance swimming performance. Hypoglycaemia can develop despite regular intake of carbohydrate (~0.7 g/kg/h) during arm-based exercise (e.g. kayaking) within other ultra-endurance settings, and seems to be specific to the arm exercise [34], so warrants consideration as a potential problem especially during longer OWS events.

Inflammatory Considerations OWS racing in warm water will increase competition for blood flow by the skin and muscles, further reducing gut blood flow for extended durations, a response that can contribute to exercise-induced endotoxaemia in terrestrial settings ([35]; Chap. 5). Indeed, some of the increased T_c during

Table 14.1 Causes of strain relevant to open-water swimming and potential countermeasures

Physical or physiological effect	Predisposing factors (**Bold = relatively specific to OWS**)			Potential countermeasures			
	Person	Exercise	Environment	Conditioning and tapering	On the day (pre-race)	During race	Effective?
Cold strain (especially ↓ T_c)	↓ mass, ↓ mass:area, ↓ adiposity, slow, fatigue	Whole-body but arm dominant, immersed, prone	↑ **Specific heat**, ↓ T_w	Fitness, adiposity, CHO	Passive warming? CHO	Mildly hot rehydration	Minimal
Heat strain (especially ↑ T_c)	↑ mass:area, ↑ adiposity		**Negligible evaporation**	Intense heat acclimation?	Precool, minimise warm-up, hydration	Pacing, hydration, no cap	Minimal
↑ then ↓ blood volume	Unfit	Prone, sweating	Immersed, ↓ T_w, often sea water	Upright exercise in heat?	Sodium and water loading	Hydration	Minimal
↓ Glycogen, hypoglycaemia?	Unfit, diet	Arm dominant	↓ or ↑ T_w	Training and dietary	CHO	CHO	Yes

Some effects are largely unavoidable and thus minimally conducive to amelioration via countermeasures

CHO carbohydrate, T_c core temperature, T_w water temperature prolonged exercise in hot ambient conditions appears to be due to inflammatory mediators [36], but the extent to which this occurs in endurance-trained swimmers is unknown. It is possible that sustained, intense and hence energy-depleting exercise that relies mostly on upper-limb and -trunk muscles may also lead to exercise-induced muscle inflammation despite the absence of eccentric contraction and ground reaction forces. Importantly, these may be two key pathways (heat-induced endotoxaemia and heat-induced tissue damage) that can contribute to the development of heat stroke, both of which appear to be associated with systemic inflammation ([37, 38]; discussed in Chap. 5). Thus, exercise may increase local inflammation and compromise heat tolerance by increasing the pro-inflammatory cytokine response through endotoxaemia. Swimmers with high training loads may be at increased risk of heat stroke due to a combination of factors such as immunosuppression, musculoskeletal inflammation, subclinical infections (including from ingestion of water while swimming) and gastrointestinal disturbances contributing to increased pro-inflammatory and decreased anti-LPS (lipopolysaccharide) activity during heat stress and exercise [37]. Such effects seem worthy of studying, even if via observational studies within elite and recreational swimmers.

Blood Volume Dehydration (i.e. net loss of body water) is common with endurance exercise and, while not apparent in a study of elite swimmers training in a pool [39], may be exacerbated for OWS in warm water, for a few reasons. Reasons include the (1) prolonged duration in warm water, (2) limited opportunities to rehydrate during races and (3) unique neuroendocrine and hydrostatic effects that combine to drive a greater diuresis than in terrestrial activity. Specifically, an initial increase in blood volume can occur as the external hydrostatic pressure may reverse the normal trans-capillary pressure gradient (Starling forces), facilitating movement of interstitial fluid, particularly in the legs, into the intravascular space [40, 41]. However, the hydrostatic squeeze and a prone posture both act to increase venous return and the resultant increase in mean arterial pressure and central blood volume and pressure will ultimately favour diuresis (after ~30–60 min) by way of increased secretion of atrial natriuretic peptide and suppression of antidiuretic hormone [41–43]. Modest and cool T_{sk} will exacerbate this effect by limiting venous pooling and further increasing central blood volume. Speculatively, swimmers may benefit from the initial immersion and posture-related increases in blood volume, and this may even allow increased skin blood flow [44], which in warm water would assist heat loss. However, the combined effect of renal- and sweat-induced dehydration from more prolonged immersion may increase the competition for blood flow, thus reducing the capacity to store and remove heat and circulate oxygen and substrates [45]. This is complicated by exercising in water, which may have an opposite effect on plasma volume (i.e. decrease) and neuroendocrine responses [46–49].

Sweating Sweat rates during terrestrial endurance events in temperate and warm conditions can vary between individuals but are typically ~0.5–2.5 L h^{-1} in the OWS-comparable sport of Marathon running [50]. These sweat rates are similar to those reported during 5-km performance swims in 27 and 32 °C T_w [21] and also our unpublished observations from 60- and 120-min swims in similar T_w (range: ~0.1–2.2 L h^{-1}), despite hidromeiosis presumably acting to constrain sweating [51]. Even so, these rates are unhelpful to swimmers because they contribute nothing to the (very small) evaporation that will occur from exposed skin, and exacerbate renal losses. Presumably, most elite swimmers would already be aware of their body mass changes in training and racing, thus these magnitudes may not be surprising. However, since there is a strong likelihood many swimmers ingest water (during the stroke, and more than they are aware of), these similar rates of mass loss compared to terrestrial athletes might underestimate sweat loss. This has implications for hydration and feeding strategies of 10-km swimmers and highlights a possibly problematic situation for swimmers in sea water events where the swallowing of salty sea water may exacerbate dehydration (transiently) through intestinal absorption of extracellular fluid. This is an area where further research would certainly be warranted.

The unique thermodynamics of OWS would appear to produce very a challenging environment for at least three settings. One is elite swimmers competing in 5- and 10-km events in cool (~20 °C) water, by virtue of swimmers' low adiposity, high area:mass ratio and high velocity. Multiple laboratory-based studies demonstrate the inability of such swimmers to maintain T_c in cool water regardless of their velocity, so in the absence of a wetsuit or any other effective and realistic countermeasure (Table 14.1), their safety depends on race duration, intact behavioural thermoregulation and an adequate opportunity to exit the water. Another group is small and slow swimmers in prolonged mass participation events in cool water, by virtue of low metabolic rate, low thermal mass and high area:mass ratio and often a limited opportunity to remove themselves from the setting. Their risk is evident in field studies showing high casualty rates (e.g. [24]), especially compared with specialist long-distance events (e.g. channel swims), which are undertaken by experienced, fit and morphologically suited swimmers. For both of the above-mentioned settings, a wetsuit is of obvious potential value, but also provides buoyancy and lessens drag and was therefore illegal in FINA-sanctioned events and in ITU events above category-specific T_w. Another concern is whether the performance advantage afforded by the buoyancy makes its use ubiquitous and hence exposes cold-tolerant swimmers to heat injury. These issues are addressed below under countermeasures.

The third thermally challenging setting is elite swimmers in warm water, by virtue of their high metabolic rate. This potential is highlighted by the death of an elite and experienced, American swimmer, Fran Crippen, during a FINA 10-km World Cup event in Fujairah, UAE in 2010. Official reports indicate that T_w at this event was 29 °C, but anecdotal athlete reports suggest it was more likely 31–33 °C [52]. The ambient conditions were reported as T_{db} 35 °C, and while no humidity was officially recorded, meteorological records show the daily humidity to have ranged from 45 to 75% (i.e. ~3 kPa). Being late morning, radiant heat load will also have been present. The consequences of that tragedy are further addressed in the final section below.

Health and performance effects of OWS in warm water must be kept in perspective relative to those of cool water. Hypothermia appears to be relatively prevalent in cool water, and the prevalence of mortality also appears to be far higher in cool [53] than warm water, but of course so is the exposure, so exposure-normalised risk would be valuable to establish. Competitive swimming in cool water carries additional and unique risk factors, especially to cardiac safety. The cold shock response and cold-induced incapacitation are well-recognised risks, but 'autonomic conflict' (dual sympathetic and parasympathetic activation; [54]) may constitute a special hazard warranting attention (see: [53, 55]). Notably, the above-mentioned OWS simulations undertaken at the University of Otago showed more problems with cool (20 °C) water than 32 °C water in regard to athletes' tolerance.

Given that both cool and warm/hot water exert so many physiological effects, it is unsurprising (but also somewhat ironic) that both passive and active cool and warm water immersion are also of rapidly growing interest for their potential to stimulate health-related adaptations [56–59], including aerobic fitness adaptations [60].

14.2 Countermeasures to Optimise Performance and Health

Acute Thermoregulation Behavioural and autonomic thermoeffector responses are both vital in helping maintain thermal homeostasis, and are vital prerequisites to optimising performance and health. Behavioural thermoregulation is the more sensitive and more powerful of these, as detailed in Chap. 1 and discussed earlier in this chapter. Thermoregulatory behaviour during heat-stressful competition is most easily achieved by reducing pace (i.e. heat production), whereas in cold-stressful competition it would seem prudent not to enter the event in the first place *if* the swimmer knows themselves to be cold intolerant. Increasing (or decreasing) adiposity and thus one's passive thermoregulatory capacity (body mass, mass:area ratio and especially insulation) over the months preceding cold (or heat) stressful OWS competition is theoretically possible but may not be practicable, not least because subcutaneous fat on the arms is most important in both circumstances but is minimally affected.

Adaptive Thermoregulation Heat acclimation, as reviewed thoroughly in Chap. 8, is a common strategy used in terrestrial sports to improve performance and tolerance in hot environments. Heat acclimation modifies several elements of active thermoregulation that collectively lessen heat content and increase the capacity for its storage. The adaptations most relevant for OWS include reduced resting T_c, increased blood volume, and increased skin blood flow, whereas any attendant increase in sweating power would be counterproductive (i.e. hasten dehydration without any evaporative benefit). The reduction in resting T_c and thus exercising T_c develops rapidly (mostly within seven exposures), as does hypervolaemia [61, 62], whereas peripheral aspects of the increased skin blood flow develop more slowly [63].

A commonality to most heat acclimation and acclimatisation protocols used to date is that they are terrestrial, whereas OWS is obviously aquatic. Resting in hot water or swimming in warm water may be more specific for swimmers, especially if undertaking heat acclimatisation. However, the main adaptations that arise from repeated bouts of exercise in air may be limited especially for swimming in water. For example, the increased conductivity of water and primarily arm-based exercise may reduce thermal strain, while the prone posture and hydrostatic pressure will attenuate the acute reductions in central venous pressure and renal blood flow. Accordingly, we [6] found that short-term (1 h/day for 6–7 days) heat acclimation using swimming in warm (33 °C) water did not confer measurable heat adaptations for trained swimmers, nor did it improve performance in warm or temperate T_w, or warm terrestrial exercise. There is one report of heat acclimatisation leading to improved performance (by 10 s, or ~4%) in temperate water 30 days after the acclimatisation [64] but this requires verification. It remains unknown whether resting in hot water and/or exercise in hot air would provide physiological, psychophysical or functional benefits for swimmers, but such research would be valuable. Matching time of day of heat stress bouts to the impending competition has been considered important for gaining the thermal advantage of a lower T_c [65] although recent research using post-exercise hot water immersion indicates this is possibly unnecessary [66]. It would also seem prudent to exercise upright (to target cardiovascular rather than sudomotor adaptations), incorporate some upper-limb exercise and provide intensity rather than volume of heat stress in each session.

Thermal Protection As mentioned above, one problem facing the organisations overseeing OWS (i.e. FINA, ITU and IOC) is whether wearing a wetsuit helps protect against hypothermia in susceptible swimmers without imposing undue heat strain in tolerant swimmers. We therefore undertook, and report here, a small study of the effect of wetsuit usage in 22 °C T_w (21.4 °C T_{db}), i.e. the ITU threshold at and above which wetsuits were not permitted to be worn. Swimmers undertook 1500-m performance trials with and without a wetsuit, in crossover fashion on separate days. Participants were eight well-trained surf swimmers and triathletes (4 males, 4 females); body fat averaged 14% (SD 5; range: 6–22%) as determined using 8-electrode bioimpedance analysis. Body mass averaged 67.3 kg (9.9; range 49.1–77.5), and body mass index (BMI) averaged 22.3 kg m^{-2} (1.8; range 18.7–25.0). Without a wetsuit, oesophageal temperature (T_{oes}) fell in two of the eight swimmers—reaching 35.3 °C in one (Fig. 14.2, top panels)—without any notable cold discomfort (Fig. 14.2, middle panels), whereas the wetsuit prevented a decline in T_{oes} in both swimmers. When wearing the wetsuit, T_{oes} rose 0.6 ± 0.6 °C (mean ± 95% CI) more than when not wearing it (0.8 vs 0.2 °C; P = 0.03; ES = 0.94). Adiposity predicted one third (32%) of the variability in T_{oes} response when not wearing a wetsuit, but none (1%) when wearing a wetsuit. The wetsuit effect on T_{oes} was largest in those who were coolest without it ($r = 0.77$; Fig. 14.2, bottom panel), and had negligible effect (<0.3 °C) for the two swimmers whose T_{oes} rose >1.0 °C without it. Perhaps most importantly, thermal discomfort was closely coupled with rising T_{oes}

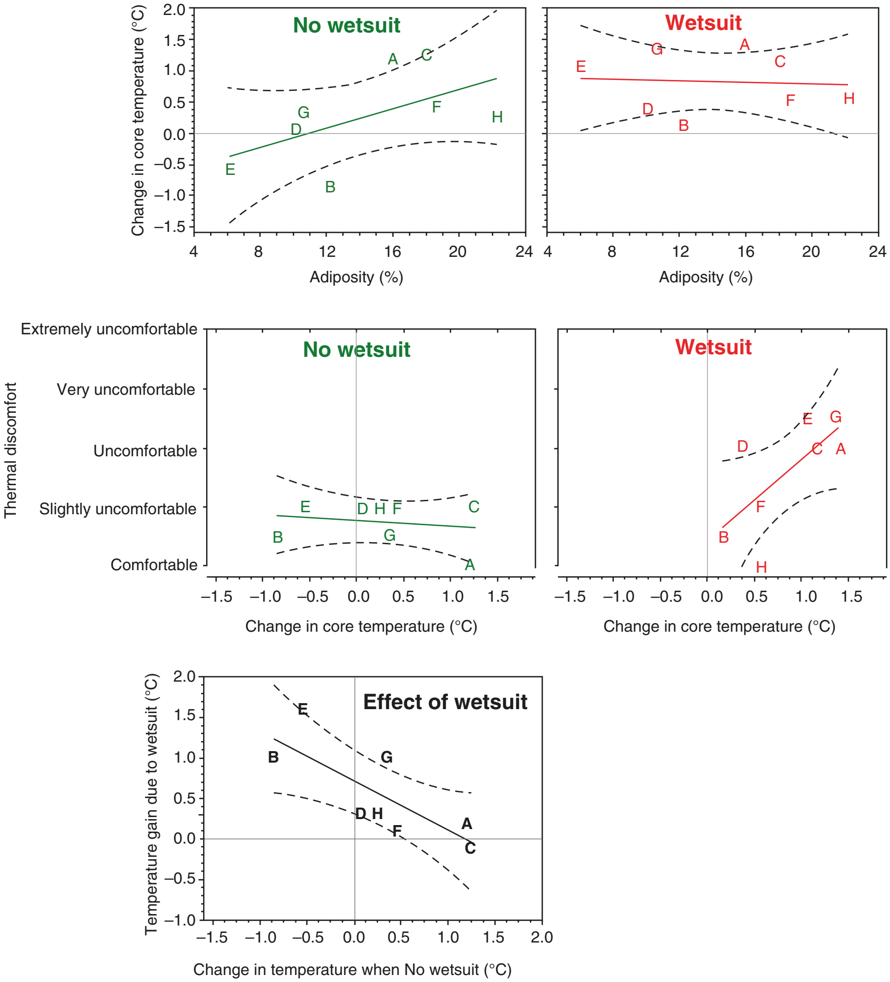

Fig. 14.2 Oesophageal temperature (T_{oes}; top panels) and thermal discomfort (middle panels) in response to swimming 1500 m with or without a wetsuit in 22 °C water. The top panels show T_{oes} responses in relation to adiposity, while the middle ones show thermal discomfort in relation to T_{oes}. The bottom panel shows the effect of wearing a wetsuit, relative to the response in the no wetsuit swim. These data show that a wetsuit prevented core cooling in cold susceptible swimmers, without adding notably to the rise in T_{oes} in other swimmers of this cohort, and any swimmer whose T_{oes} rose while wearing the wetsuit also became uncomfortably hot

with a wetsuit, but not when swimming without it (Fig. 14.2, middle panels). These data preliminarily indicate that wetsuit usage can provide thermal protection in cold-intolerant swimmers without imposing excessive heat stress or insidious heating of the core in others, whereas core cooling was evident without a wetsuit and failed to elicit discomfort.

The use of a swim cap may also influence the thermal status of swimmers in warm and cool water. One study showed that wearing a silicon cap during warm-up and an 800-m time trial led to 0.3 °C higher $T_{c,}$ compared with no cap, and was associated with ~2% faster performance despite similar physiological and subjective measures in ~33 °C water [67].

Thermal Manipulation Swimmers' heat content can be manipulated up or down during the hour before competition using an active warm-up or a precooling strategy, respectively. These are often used in combination, but both require scrutiny. The rise in T_c incurred by a 20-min warm-up will easily wipe out all of the calorimetric (thermal reserve) benefit gained from a 7- to 10-day heat acclimation. Warm-ups are also typically far longer than is physiologically necessary even for severe-intensity dynamic exercise performed at $\dot{V}O_2$ max [68]. Performance gains are modest for such exercise so may be either non-existent or counterproductive for the prolonged, concentric-contraction and body-weight-supported nature of OWS. Therefore, an obvious countermeasure that warrants an open mind and careful investigation by sport scientists and swimmers is limiting the warm-up (e.g. to 3–4 min of upper-body exercise) or potentially removing it before competitions in warm water. This would aid heat storage capacity while also minimising loss of substrates (water and energy) and time, along with psychological dependence.

Pre-race cooling strategies (as discussed in Chap. 7) may help mitigate some of the heat stress encountered by OWS in warm water, but seem likely to provide only modest physiological and performance benefit for 5-km races and negligible benefit for 10-km events. Specifically, the overwhelming dominance of convective heat transfer in OWS will reduce or reverse the normal heat transfer gradients between skin and water, and thereby further reduce the already-modest benefits of precooling that exist in ecologically valid terrestrial exercise settings. Ingesting an ice slurry before competition seems more thermodynamically appropriate for OWS.

OWS is conspicuous among endurance sports in affording athletes no meaningful opportunity for supplemental cooling during competition, other than by reducing their pace. Ingestion of cool fluids has been shown to have little effect [69], although there is some evidence it may be thermally beneficial during endurance swimming in warm water [22, 23]. Ingesting an ice slurry *during* a race seems unwise for at least two reasons, however. First, its rate of ingestion is too slow due to the intense cold, whereas the time available for ingesting fluid and energy is so heavily constrained. Second, the gut has recently been shown to be thermosensitive and thus participates actively in thermoregulatory control. This will potentially reduce athletes' thermal safety reserve for heat injury and might explain findings of athletes achieving higher performance and peak T_c during heat-stressful exercise after consuming an ice slurry within laboratory-based experiments.

Energy and Hydration Beginning a race with high muscle and liver glycogen content seems essential because of the prolonged, mostly arm-based exercise and limited opportunity for ingestion from the pontoons while racing. Optimal rates of intake of up to >90 g carbohydrate per hour are realistic for elite terrestrial athletes ingesting a composite of simple sugars [70], but we are unaware whether this applies also to OWS. Gastric emptying and intestinal absorption might be enhanced by the mechanical action, posture or hydrostatic effects of swimming, but could alternatively be impaired if sympathetic activation is higher than for running or cycling. Swimmers may also swallow water frequently (unpublished observations from our studies), which could impair gut function if they were ingesting sea water or non-potable water. Considerations for hydration are similar to those for energy replenishment, except that swimmers' ability to remain euhydrated will be constrained for reasons described above.

14.3 Heat Policy and Implementation

Following the tragic events in a FINA-sanctioned event in October 2010, there was an urgent call for greater control and scrutiny of the open-water competitive environment. Until then, the well-intended rules governing OWS were less informed by science and more by experience and anecdotal evidence gleaned from swimmers, coaches and officials. In early 2011, FINA joined with the IOC and ITU to invite expressions of interest to undertake specific investigations surrounding the safety of different T_w for OWS, especially warmer water. Research from The University of Otago was reported to these organisations in January 2013 outlining the findings from ~200 swims from a cohort of 24 experienced and elite swimmers. Participants completed 20-, 60- and 120-min distance-trial swims in a flume (to simulate 1.5-, 5- and 10-km OWS) in T_w of 20, 27, 30 and 32 °C with matching T_{db}. Swims in 32 °C T_w also included simulated radiant load (400–800 W m^2). Several physiological and psychophysical variables were measured, including those summarised above. The outcome for FINA and ITU has been the implementation of specific rules that now stipulate the maximum upper T_w of 31 and 32 °C, respectively, for OWS events. Additionally, all ITU OWS distances are reduced to 750 m in T_w over 31 °C [71, 72]. For FINA and ITU, respectively, the rules demand that the venue T_w is taken 2 and 1 h prior to the start of the event at an agreed mid-course site and at a depth of 40 and 60 cm. Thereafter, FINA regulates that T_w is monitored by race officials hourly, with the authority to halt the event if subsequent readings are outside the FINA-approved range for water temperature (16–31 °C).

A more recent development has been the revision of FINA Rules governing the use of wetsuits. From 1 January 2017 a new By-Law (BL 8.5) declared that wetsuits of an appropriate design are optional in T_w of 18–20 °C and compulsory below 18 °C. ITU maintains its wetsuit policies, that vary slightly between elite and age group athletes, but make their use mandatory below 16 °C and forbidden above 22 or 25 °C for events over 1500 m.

Local bodies can enforce their own variations of these rules for non-FINA or ITU sanctioned events. For example, after 2010, USA Swimming set an upper T_w limit for cancellation of local events of 29.45 °C or the sum of T_{db} and T_w exceeding 63 °C. These criteria remain in the current 2018 rule handbook. Also, USA Triathlon allow wetsuits use for $T_w < 25.6$ °C.

As noted above, thermal perceptions appear to remain intact for swimmers in warm water, and feeling hot is important. Therefore, while these rules are evidence-based, they cannot be considered definitive. An onus remains on all athletes to heed their internal cues and for coaches to be vigilant in monitoring their athletes for uncharacteristic signs and demeanour. This is especially important in the face of competitive behaviour and illness and is no different to what is expected and acted upon by terrestrial athletes. A marked difference for open-water swimmers, however, is that their environment is much less forgiving if they get into trouble.

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