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Review Article

Cold water immersion: kill or cure?

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New Findings
- **What is the topic of this review?**
  This is the first review to look across the broad field of 'cold water immersion' and to determine the threats and benefits associated with it as both a hazard and a treatment.
- **What advances does it highlight?**
  The level of evidence supporting each of the areas reviewed is assessed.

Like other environmental constituents, such as pressure, heat and oxygen, cold water can be either good or bad, threat or treatment, depending on circumstance. Given the current increase in the popularly of open cold water swimming, it is timely to review the various human responses to cold water immersion (CWI) and consider the strength of the claims made for the effects of CWI. As a consequence, in this review we look at the history of CWI and examine CWI as a precursor to drowning, cardiac arrest and hypothermia. We also assess its role in prolonged survival underwater, extending exercise time in the heat and treating hyperthermic casualties. More recent uses, such as in the prevention of inflammation and treatment of inflammation-related conditions, are also considered. It is concluded that the evidence base for the different claims made for CWI are varied, and although in most instances there seems to be a credible rationale for the benefits or otherwise of CWI, in some instances the supporting data remain at the level of anecdotal speculation. Clear directions and requirements for future research are indicated by this review.

Introduction: history

For centuries, cold water has been regarded as both 'hero' and 'villain', as having both beneficial and detrimental effects. In 450 BC, Herodotus, describing the ill-fated seaborne expedition of the Persian General Mardonius, wrote, '. . . those who could not swim perished from that cause, others from the cold'. In December 1790, Dr James Currie, a physician, stood with a crowd unable to help as the crew of a stranded American sailing ship fell into the 5°C sea and drowned. This experience led Currie to undertake the first recorded experiments on the effects of cold water immersion (CWI) on humans.

Claims for the health benefits of cool and CWI, spa or sea, also date back centuries. According to Hippocrates, water therapy allayed lassitude, and Thomas Jefferson used a cold foot bath every morning for six decades to 'maintain his good health'. Largely anecdotal evidence extols the virtues of CWI or cold water swimming as a means of improving well-being and health (Digby, 1587, cited by Parr, 2011). These health benefits are believed to be a consequence of the physiological responses and biochemical milieu that occur from exposure to cold water (Huttunen *et al.* 2004; Kukkonen-Harjula & Kauppinen, 2006). Physiological changes occur acutely during CWI, with repeated bouts of CWI adaptive responses develop that may also impact upon indices of health.

In the middle ages, people did not learn to swim because they would then not be able to cross the river Styx when condemned to enter hell. In 1538, Wynmann wrote the first swimming book in an attempt to introduce a 'human stroke' and thereby reduce the number of drownings. As early as 1750, published work recommended sea swimming (and sea water drinking!) for the treatment of a range of diseases (Russell, 1755; Buchan, 1769), with winter considered the best time to engage in the activity. Sea bathing reached a peak in popularity in the late 18th century around the time of the development of the 'swim suit' and 'bathing machine' (Fig. 1). Whole communities, seaside resorts, were founded on the perceived health benefits of sea swimming. The hazard associated with this health benefit led to the introduction of beach lifeguarding (Tipton & Wooler, 2016). The modern age of open water swimming, as opposed to bathing, probably began on 3 May 1810, when Lord Byron swam several miles across the Dardanelles (Hellespont) from Europe to Asia.

Recently, there has been a significant growth in the number of people engaging in open, cold water swimming, in terms of both competitions (ice swimming, marathon swimming, winter swimming and triathlon) and general 'wild swimming'. With increased participation have come renewed and enthusiastic claims for the physiological and psychological health benefits associated with CWI. It therefore seems timely to review the evidence for the hazards and benefits associated with the stress of CWI.

Cold water: hazards

In 2012, an estimated 372,000 people (42 per hour) died from immersion, assumed to be drowning. Immersion is the third leading cause of unintentional injury-related death, accounting for 7% of all such deaths (World Health Oganisation, 2014). These figures are underestimations owing to poor reporting in many Third World countries that have a high number of deaths. The data also do not include life-long morbidity caused by immersion-related injuries, estimated to be a much bigger numerical problem.

There is no strict definition of 'cold water'. Given that some of the hazardous responses to cold water appear to peak on immersion somewhere between 15 and 10°C, it is reasonable to say that cold water is water <15°C (Tipton *et al.* 1991). However, the thermoneutral water temperature for a resting naked individual is ∼35°C, so it is possible for individuals to become very cold, with time, on immersion in water below this temperature. The corresponding temperature for those exercising (including shivering) is ∼25°C (Tipton & Golden, 1998).

Historically, the threat associated with CWI was regarded in terms of hypothermia or a reduction in deep body temperature below 35°C. This belief was established as a result of the Titanic disaster and supported by data obtained during maritime conflicts of World War II. However, more recently, a significant body of statistical, anecdotal and experimental evidence has pointed towards

Figure 1. Bathing machine, Germany 1893

other causes of death on immersion. For example, in 1977 a Home Office Report revealed that ∼55% of the annual open water deaths in the UK occurred within 3 m of a safe refuge (42% within 2 m), and two-thirds of those who died were regarded as 'good swimmers'. This evidence suggests more rapid incapacitation than can occur with whole-body cooling and consequent hypothermia.

The following four stages of immersion have been associated with particular risks (Golden & Hervey, 1981; Golden *et al.* 1991); the duration of these stages and the magnitude of the responses evoked within them vary significantly, depending on several factors, not least of which is water temperature:

- Initial immersion (first 3 min), skin cooling;
- Short-term immersion (3 min plus), superficial neuromuscular cooling;
- Long-term immersion (30 min plus), deep tissue cooling (hypothermia); and
- Circum-rescue collapse: immediately before, during or soon after rescue.

As a result of laboratory-based research, the initial responses to immersion, or 'cold shock', were identified as particularly hazardous (Tipton, 1989), accounting for the majority of immersion deaths (Tipton *et al.* 2014). These deaths have most often been ascribed to drowning, with the physiological responses of a gasp and uncontrollable hyperventilation, initiated by the dynamic response of the cutaneous cold receptors, resulting in the aspiration of the small volume of water necessary to initiate the drowning process (Bierens *et al.* 2016). Relatively little is known about the minimal rates of change of cold receptor temperature necessary to cause cold shock. The response has been reported to begin in water as warm as 25°C but is easy to suppress consciously at that temperature. In laboratory conditions, the respiratory frequency response (an indication of respiratory drive) peaks on naked immersion in a water temperature between 15 and 10°C, and is no greater on immersion in water at 5°C (Tipton *et al.* 1991). The corresponding average rates of change of chest skin temperature over the first 20 s of these immersions was 0.42 (water temperature 15°C), 0.56 (water temperature 10°C) and $0.68°C \: s^{-1}$ (water temperature 5°C). This suggests that an average rate of change in chest skin temperature between 0.42 and $0.56°C \: s^{-1}$ on the first 20 s of immersion is sufficient to evoke a maximal respiratory cold shock response.

More recently, it has been suggested (Shattock & Tipton, 2012) that a larger number of deaths than once thought may be attributable to arrhythmias initiated on immersion by the coincidental activation of the sympathetic and parasympathetic division of the autonomic nervous system by stimulation of cutaneous cold receptors around the body [sympathetic activation (cold shock)] and in

the oronasal region on submersion or with wave splash [vagal stimulation (diving response)]. This 'autonomic conflict' is a very effective way of producing dysrhythmias and arrhythmias even in otherwise young and healthy individuals, particularly, but not necessarily, if a prolonged breath hold is involved in the immersion (Tipton *et al.* 1994). It seems that predisposing factors, such as long QT syndrome, ischaemic heart disease or myocardial hypertrophy, are necessary for fatal arrhythmias to evolve (Shattock & Tipton, 2012); many of these factors, including drug-induced long QT syndrome, are acquired. Non-fatal arrhythmias could still indirectly lead to death if they cause incapacitation and thereby drowning (Tipton, 2013). The hazardous responses associated with the cold shock response are presented in Fig. 2.

The problems encountered in short-term immersions are primarily related to physical incapacitation caused by neuromuscular cooling (Castellani & Tipton, 2015). The arms are particularly susceptible because of their high surface area to mass ratio. Low muscle temperatures affect chemical and physical processes at the cellular level. This includes metabolic rate, enzymatic activity, calcium and acetylcholine release and diffusion rate, as well as the series elastic components of connective tissues (Vincent & Tipton, 1988). Maximal dynamic strength, power output, jumping and sprinting performance are related to muscle temperature, with reductions ranging from 4 to 6% per degree Celsius reduction in muscle temperature down to 30°C (Bergh & Ekblom, 1979). At nerve temperatures below ∼20°C, nerve conduction is slowed and action potential amplitude is decreased (Douglas & Malcolm, 1955). Nerve block may occur after exposure to a local temperature of between 5 and 15°C for 1–15 min. This can lead to dysfunction that is equivalent to peripheral paralysis and can, again, result in drowning owing to the inability to keep the airway clear of the water (Clarke *et al.* 1958; Basbaum, 1973; Golden & Tipton, 2002; Fig. 3).

Even in ice-cold water, the possibility of hypothermia does not arise for at least 30 min in adults. Hypothermia affects cellular metabolism, blood flow and neural function. In severe hypothermia, the patient will be deeply unconscious. The progressive signs and symptoms (approximate deep body temperature) are shivering (36°C), confusion, disorientation, introversion (35°C), amnesia (34°C), cardiac arrhythmias (33°C), clouding of consciousness (33–30°C), loss of consciousness (30°C), ventricular fibrillation (28°C) and death (25°C) (Bierens *et al.* 2016). There is great variability between deep body temperature and the signs and symptoms of hypothermia. For example, although the deep body temperature associated with death is often quoted as 25°C, the lowest temperature recorded to date after accidental exposure to cold (air) and with full recovery was 12.7°C in a 28-month-old child (Associated Press, 2014). The coldest adult survivor of CWI followed by submersion

had a body temperature of 13.7°C (Gilbert *et al.* 2000). There is also a large amount of variation in the rate at which people cool on immersion in cold water, owing to a combination of thermal factors (including water temperature and water movement, internal and external insulation) and non-thermal factors (including body size and composition, blood glucose, motion illness, racial and sex differences; Haight & Keatinge, 1973; Gale *et al.* 1981; White *et al.* 1992; Mekjavic *et al.* 2001; Golden & Tipton, 2002).

The most significant practical consequence of hypothermia in water is loss of consciousness; this prevents individuals from undertaking physical activity to maintain a clear airway and avoid drowning. Thus, once again, drowning is often the end-point (Fig. 3).

About 17% of those who die as a result of immersion die immediately before, during or after rescue (Golden *et al.* 1991). The deaths immediately before rescue are intriguing and probably related to behavioural changes at this time or the relief and psychophysiological alterations associated with imminent rescue, including a reduction in circulating stress hormone concentration and an increase in vagal tone. Death during rescue is most commonly associated with a collapse in arterial pressure when lifted vertical from the water and kept in that position for some time (Golden *et al.* 1991).

Finally, in this section it is worth mentioning that because sea water freezes at −1.9°C and human tissue at −0.55°C it is possible to get frostbite in the sea, although this is a rare occurrence. Much more common, but less well known and understood, is non-freezing cold injury. This can be caused by short immersions in very cold water or longer duration immersions in cool water. In reality, the details of the pathogenesis and pathology of non-freezing cold injury are not fully understood, but the consequences (cold sensitivity, hyperhidrosis and intractable pain) can be debilitating and permanent (Golden *et al.* 2013; Heil *et al.* 2016). Those advocating very cold water immersion, for example postexercise, are often unaware of this risk.
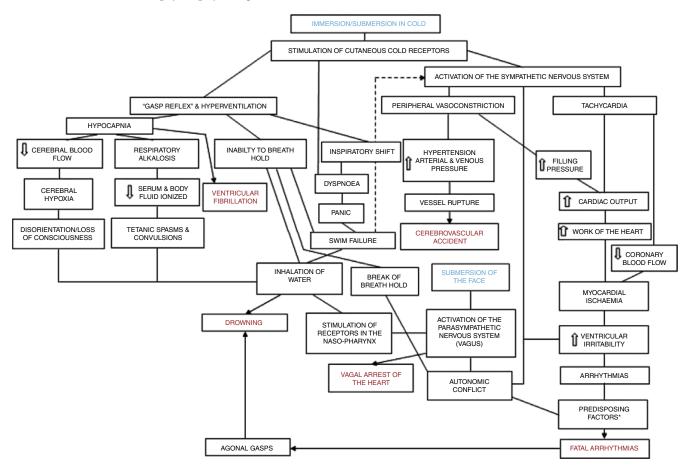

Figure 2. A contemporary view of the initial responses to immersion and submersion in cold water ('cold shock')
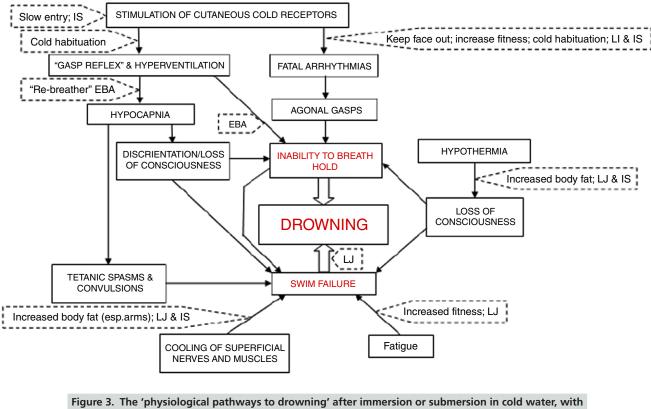Based on: Tipton (1989); Datta & Tipton (2006); Tipton *et al.* (2010); Shattock & Tipton (2012). *Predisposing factors include channelopathies, atherosclerosis, long QT syndrome, myocardial hypertrophy and ischaemic heart disease. Reproduced with permission, from Tipton (2016*a*).

Cold water: benefits

Prolonged survival under water. Generally, drowning results in cardiopulmonary arrest within 2 min (Fainer *et al.* 1951). Quan *et al.* (2014) reported on the outcome of 1094 open water drownings; most (78%) had bad outcomes (74% death, 4% severe neurological sequelae), and of the good outcomes, 88% were submerged for <6 min. This percentage falls rapidly (i.e. 7.4% of good outcomes when submerged for 6–10 min), with the risk of death or severe neurological impairment after hospital discharge given as 'nearly 100%' when the duration of submersion exceeds 25–27 min (Szpilman *et al.* 2012).

However, if the water is cold this time can be extended, with the current 'record' being 66 min of submersion with near-complete recovery (Bolte *et al.* 1988). In such cases, the temperature of the water appears protective, with records of submerged survival with minimal long-term sequelae only having been reported in water <6°C (Tipton & Golden, 2011). The Q_{10} temperature coefficient, a measure of the rate of change of a biological or chemical system as a consequence of increasing or decreasing the temperature by 10°C, differs for different body systems; metabolic and rhythmic processes are particularly depressed by hypothermia (Q_{10} of ~3), and contractile

processes have a Q_{10} of ~2. As hypothermia progresses, metabolic and rhythmic processes are depressed more than the rates of diffusion of different metabolites (MacLean & Emslie-Smith, 1977). The hypoxic survival time of the brain is extended by hypothermia, with cerebral activity, and therefore oxygen demand, falling close to minimal levels at a brain temperature of 22°C (Adams & Victor, 1977).

The proposed mechanism of prolonged underwater survival involves the 2 min of drowning-related flushing of cold water in and out of the lung cooling the heart and carotid artery blood supply to the brain, thereby selectively cooling the brain, with consequent cerebral hypothermia protecting the brain from hypoxia (Golden *et al.* 1997; Tipton & Golden, 2011). Evidence for such a mechanism can be found in the animal work of Conn *et al.* (1995), who reported a 7.5–8.5°C reduction in carotid artery temperature after 2 min of submersion, with much slower cooling (0.8°C) during head-out cooling. The cooling rate also slows significantly after cardiorespiratory arrest (Conn *et al.* 1995), further supporting the involvement of respiratory heat exchange in the initial fast rates of cooling of carotid artery temperature. Although slower, continued cooling via surface cooling does add important additional protection; this helps to explain why those who cool the

Figure 3. The 'physiological pathways to drowning' after immersion or submersion in cold water, with possible interventions for partial mitigation (dashed)
Abbreviations: EBA, emergency breathing aid; IS, immersion suit; and LJ, lifejacket. Reproduced with permission, from Tipton (2016*b*).

most by this route owing to surface area-to-mass ratio advantages (i.e. the young and the small) tend to comprise the small number of individuals who have survived prolonged immersion with minimal consequences. Given that the brain is preferentially cooled, other sites for measuring deep body temperature have little prognostic value in such situations (Tipton & Golden, 2011).

Therefore, in contrast to the problems caused by cold shock outlined in the previous section, in this scenario (small individual submerged in water <6°C) the hyperventilation associated with cold shock during drowning may be beneficial rather than detrimental; this highlights the importance of circumstance for drawing such conclusions. Interestingly, the same protective mechanism that can occur naturally during drowning in very cold water has been considered as an intervention to reduce ischaemic brain damage after cardiac arrest or stroke. The challenge is to find a method that can cool the brain rapidly enough to be of value (Hoa *et al.* 2008; Rewell *et al.* 2017).

Deliberate cooling.

Cooling for hyperthermia and heat illness. Cooling strategies are used by athletes to cool themselves between bouts of exercise. Such interventions are also used to treat those with heat illness ranging from heat exhaustion to potentially fatal heat stroke.

Various techniques, including ice-vests, air and water-perfused vests, have been developed to cool individuals between and following bouts of exercise. Of these, hand immersion in cold water and whole-body fanning with or without artificial sweating (water spraying) have been shown to be preferential when a viable peripheral circulation remains (Barwood *et al.* 2009). This is because these techniques use the physiology of the body to deliver heat to the skin via the circulation rather than trying to overwhelm it and remove heat via conduction. The latter approach runs the risk of evoking the body's heat-loss defence mechanisms, including vasoconstriction, thereby resulting in slower cooling. The same mechanisms explain why whole-body immersion in temperate water (26°C) is as effective at removing heat from a resting body as immersion in cold water (14°C) when there is a viable circulation (Tipton, 2006; Taylor *et al.* 2008; Casa *et al.* 2010). However, in the absence of a viable circulation, such as in heat stroke, heat loss by conduction remains the only available route, and therefore, in such circumstances, heat loss is inversely related to water temperature (Proulx *et al.* 2003; Zang *et al.* 2015).

Precooling for performance. It has long been known that prolonged exercise performance is diminished in hot environments compared with cooler conditions (Galloway

& Maughan, 1997; Tatterson *et al.* 2000). The mechanisms thought to underpin the ergolytic effect of heat are complex and varied but are, broadly speaking, attributable to the direct and indirect consequences of hyperthermia on body temperatures (e.g. brain) and regional (e.g. muscle/skin) blood flows (Febbraio, 2000; Nielsen & Nybo, 2003; Nybo, 2008; Cheuvront *et al.* 2010). Any intervention that creates a heat sink by reducing the initial body heat content (precooling) should enable the storage of a greater amount of heat before reaching a given level of hyperthermia. Thus, precooling might potentially be ergogenic during exercise in a hot environment. Equally, precooling may be debilitating if sufficient to impair neuromuscular function (see "Cold Water Hazards"). Its effect will therefore depend on the nature of the cooling stimulus (muscle cooling *versus* deep body cooling) and the event (power output *versus* endurance) to be undertaken as well as environmental conditions.

Perhaps the first study examining the effect of precooling on tolerance to hot conditions was conducted by Veghte & Webb (1961), who used different durations of CWI (16°C), as well as air cooling, to demonstrate that the resting tolerance time in a high ambient temperature (71°C) was inversely related to the initial body temperature. The first precooling studies examining exercise performance typically used pre-exercise cold air exposure, rather than CWI, and investigated performance in relatively temperate environmental conditions (18–24°C). Nevertheless, these studies demonstrated that reducing initial body heat content resulted in reduced thermophysiological strain and improved exercise performance (Schmidt & Brück, 1981; Hessemer *et al.* 1984; Olschewski & Brück, 1988; Lee & Haymes, 1995), although the combination of suboptimal convective cooling and relatively high metabolic rates in these studies would probably have induced a potentially limiting thermal burden, even in these relatively benign ambient conditions (Ely *et al.* 2007). However, because the thermal conductivity of water is 24 times that of air, and the energy required to heat a given volume of water by 1°C is 3500 times that of air, the cooling power of cold water in terms of human deep body temperature is approximately three times that of cold air at the same temperature (Smith & Hanna, 1975). Consequently, a given rate of heat loss can be achieved at a higher temperature, and with a narrower skin–environment temperature gradient in water, than in air (Marino, 2002). Indeed, there is evidence from meta-analysis that CWI is more effective than all other types of precooling interventions (Jones *et al.* 2012)

Perhaps the seminal study examining the effectiveness of pre-exercise CWI on exercise performance in the heat is that of Booth *et al.* (1997). Using a counterbalanced design, they got eight trained participants [average maximal oxygen uptake ($\dot{V}_{O_2 max}$) = 63.1 ml kg^{-1} min^{-1}] to undertake a 30 min run in hot, humid conditions (32°C,

60% relative humidity) on two occasions, i.e. with or without (control) prior CWI. The CWI consisted of 60 min of immersion in water which, to minimize discomfort, was progressively cooled from ∼29 to ∼23°C. This reduced the pre-exercise rectal temperature (T_{re}), mean skin temperature ($\overline{T}_{sk}$) and heart rate by ∼0.7°C, 5.9°C and 13%, respectively. The reduced T_{re}, $\overline{T}_{sk}$ and heart rate persisted for 20, 25 and 10 min, respectively during the exercise bout and enabled the participants to run significantly further than in the control condition (average 304 m). A similarly influential study was undertaken by González-Alonso et al. (1999), in which participants undergoing 30 min of CWI at 17°C had an initial average oesophageal temperature (T_{oes}) of 35.9°C and were subsequently able to cycle for 63 min at 60% $\dot{V}_{O_2 max}$ in a hot environment (40°C, 19% relative humidity), whereas immersion in 36°C water resulted in an initial T_{oes} of 37.4°C and an average time to exhaustion of 46 min. After warm water immersion (40°C), a starting T_{oes} of 38.2°C and time to exhaustion of 28 min were recorded. Numerous subsequent studies have confirmed the efficacy of precooling by CWI (e.g. Duffield et al. 2010; Siegel et al. 2012; Skein et al. 2012).

However, it should be noted that, in accordance with Newton's cooling law (Newton, 1700) and the heat transfer equation (Fourier, 1807), in a hot environment precooling increases the rate of heat transfer between the human body and the environment as a consequence of an increased thermal gradient (Taylor et al. 2014). The onset of sweating is also delayed during exercise after precooling (Wilson et al. 2002), which will diminish evaporative heat loss. As a result, a precooled individual will gain heat more rapidly than a hotter individual until convergence at a common temperature (Booth et al. 2004). Thus, although precooling by CWI represents an effective strategy for enhancing endurance exercise performance in a hot environment, its efficacy may be limited to exercise durations shorter than the time taken for body temperature to converge with that in non-precooled conditions.

Postexercise CWI for recovery. The use of CWI after intense exercise is prevalent among sports people and primarily stems from the belief that CWI facilitates aspects of recovery and regeneration, thereby conferring a potential training and performance advantage (Versey et al. 2013; Leeder et al. 2015). The potential negative aspects of postexercise immersion in ice-cold water, such as non-freezing cold injury (see "Cold Water Hazards"), often do not seem to be considered.

The physiological mechanisms by which postexercise CWI influences recovery are not entirely clear (White & Wells, 2013), but are most probably related to effects of removal of body heat, reduced tissue temperature and hydrostatic pressure effects, rather than to the cold shock response (Fig. 4). For example, decreased tissue temperature may reduce acetylcholine production and lower nerve conduction velocity (Abramson et al. 1966) and the firing rate of the muscle spindles (Ottoson, 1965). These alterations could decrease muscle spasm and exert an analgesic effect (Meeusen & Lievens, 1986; Wilcock et al. 2006). Alternatively, hydrostatic pressure might reduce oedema and inflammation by increasing the pressure gradient between the interstitial and intravascular
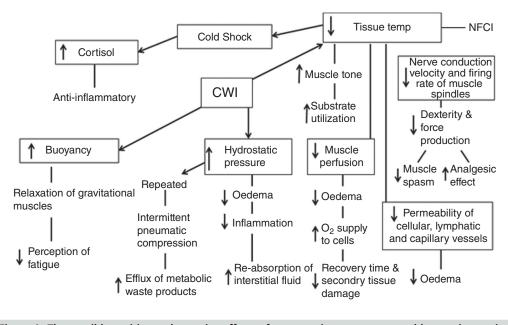

Figure 4. The possible positive and negative effects of postexercise responses to cold water immersion
Abbreviations: CWI, cold water immersion; and NFCI, non-freezing cold injury.

space, promoting the re-absorption of interstitial fluid in a manner similar to compression stockings (Partsch *et al.* 2004). Cold and hydrostatic pressure could also act synergistically; decreased muscle temperature may reduce oedema by reducing muscle perfusion (cold-induced vasoconstriction) and fluid diffusion into the interstitial space (Yanagisawa & Fukubayashi, 2010; Gregson *et al.* 2011), as well as through reduced permeability of the cellular, lymphatic and capillary vessels (Coté *et al.* 1988). This might complement any hydrostatic pressure effects on interstitial–intravascular fluid movement.

Regardless of the underlying mechanism, reduced oedema is hypothesized to preserve the oxygen supply to cells better; this supply may otherwise become compromised by local swelling and the associated capillary constriction (Wilcock *et al.* 2006), although the extent to which this is offset by the decreased perfusion is unclear. Additionally, a decreased tissue temperature should, as noted above, reduce the metabolic rate and oxygen requirement of the cooled tissue (Drinkwater, 2008). Together, these effects could lessen exercise-induced inflammation by decreasing hypoxic cell death or damage and, by reducing the infiltration of leucocytes and monocytes, minimize secondary tissue damage (Swenson *et al.* 1996; Wilcock *et al.* 2006). Similar claims have been made for hyperbaric oxygen therapy (Kindwall, 1995).

Given these potential benefits, it is unsurprising that the use of CWI for facilitating recovery has received considerable attention within the literature. Indeed, a wide variety of protocols have been investigated, with variations in terms of the exercise 'insult', the timing of immersion after exercise, the temperature, duration and depth of immersion and the outcome measure reported. Thus, given the potential mechanisms of action it is perhaps not unexpected that there is variation in the reported efficacy of CWI within the literature (White & Wells, 2013), with some studies supporting the efficacy of CWI for recovery (e.g. Bailey *et al.* 2007; Vaile *et al.* 2008; Ingram *et al.* 2009) and others showing no benefit (e.g. Goodall & Howatson, 2008; Corbett *et al.* 2012; Leeder *et al.* 2015). Nevertheless, meta-analyses (Leeder *et al.* 2012; Machado *et al.* 2016) and a Cochrane systematic review (Bleakley *et al.* 2012) of the relevant studies have concluded that CWI is effective at reducing perceived postexercise muscle soreness, with some meta-analytic evidence also supporting the effectiveness of CWI in reducing blood creatine kinase concentrations and improving the recovery of muscle power (Leeder *et al.* 2012). However, this assertion should be tempered by the fact that, given the nature of the intervention, it is difficult to administer a true placebo in these studies. In one study that did include a placebo treatment, the effect of CWI was found to be no bigger than the placebo effect (Broatch *et al.* 2014).

It seems reasonable that the control conditions for such studies should be the widely used active recovery rather than nothing (rest). Indeed, recent research has reported that infiltration of inflammatory cells, mRNA expression of pro-inflammatory cytokines and neurotrophins, and the subcellular translocation of heat shock proteins did not differ significantly between CWI and active recovery groups after a single bout of resistance exercise. This suggests that CWI is no more effective than active recovery for reducing inflammation or cellular stress in this single-bout exercise model (Peake *et al.* 2017).

Finally, if CWI reduces the inflammatory response to exercise-induced trauma, and this response is important for beneficial adaptations to repeated exercise bouts, i.e. training, then CWI may in fact be counter-productive (Schoenfeld, 2012). Indeed, recent evidence indicates that CWI during a 12 week training programme attenuated long-term gains in muscle mass and strength and blunted the activation of key proteins and satellite cells in skeletal muscle up to 2 days after resistance exercise (Roberts *et al.* 2015). However, CWI may enhance other aspects of the adaptive response to exercise. Ihsan *et al.* (2014) have shown that a 15 min leg immersion in 10°C water after a single exercise bout consisting of 30 min submaximal running followed by intermittent running to exhaustion enhances the gene expression of peroxisome proliferator-activated receptor γ coactivator-1α (PGC-1α), a key regulator of mitochondrial biogenesis, and vascular and metabolic adaptations to exercise. Allan *et al.* (2017) have presented similar evidence for increased PGC-1α expression with leg CWI, but also demonstrated increased PGC-1α in the non-immersed leg (relative to control conditions), suggesting that this is a systemic response to CWI, possibly as a consequence of β-adrenergic activation of AMP-activated protein kinase (AMPK).

Importantly, these effects do not appear to be confined to a single bout of exercise and CWI, with Ihsan *et al.* (2015) demonstrating that some (e.g. p38 mitogen-activated protein kinase, AMPK and mitochondrial proteins complex I, complex III and β-HAD), although not all, indices of mitochondrial biogenesis were increased when individuals underwent postexercise CWI after three sessions per week of endurance training for 4 weeks. However, the physiological significance of these findings remains unclear, with Yamane *et al.* (2006) reporting attenuated improvements in $\dot{V}_{O_2 max}$ when CWI was used after training in a 4 week endurance training programme consisting of three or four training sessions per week; it has been suggested that CWI may dissociate the relationship between mitochondrial content and exercise performance, and the increase in mitochondrial content could be offset by increased uncoupled mitochondrial respiration (Ihsan *et al.* 2015). More work is required to elucidate these potentially conflicting responses and to establish the

cold stimulus/dose (intensity, duration and number of exposures) required to produce them.

Inflammation. Keeping with the topic of inflammation, there is an expanding body of evidence linking inflammation with health and disease. It has been shown that centenarians and supercentenarians have lower levels of inflammation than community-living very old (85- to 99-year-old) people (Arai *et al.* 2015). This study also showed that although centenarians and their offspring were able to maintain long telomeres, telomere length was not a predictor of successful ageing, whereas a low inflammation score was. Inflammation has also been associated with conditions including atrial fibrillation (Boos *et al.* 2006; Dernellis & Panaretou, 2004), atherosclerosis (Hansson, 2005), inflammatory bowel disease (Kaser *et al.* 2010), type 2 diabetes (Donath & Shoelson 2011), Alzheimer's disease (Wyss-Coray, 2006) and depression (Miller & Raison, 2016).

Modification of the inflammatory response has been associated with improved outcomes in both atrial fibrillation (Dernellis & Panaretou, 2004) and depression (Müller *et al.* 2006). Cold water habituation has also been shown to improve insulin sensitivity (Hanssen *et al.* 2015). Certainly, habitual exercise is recognized as a therapeutic intervention for type 2 diabetes (Boulé *et al.* 2001; Sigal *et al.* 2006).

As noted, historical documents and anecdotal evidence extol the virtues of CWI or cold water swimming as a means of improving well-being and health (Digby, 1587, cited by Parr, 2011). These health benefits are believed to be a consequence of the physiological responses to CWI and, particularly, alterations in these responses with cold water adaptation (Huttunen *et al.* 2004; Kukkonen-Harjula & Kauppinen, 2006). However, although controlled trials investigating the therapeutic use of CWI are lacking, there is a theoretical, physiological basis suggesting that this is an area worthy of investigation (Shevchuk, 2008; Harper, 2012).

The aim of any therapeutic intervention should be to reduce the magnitude of pro-inflammatory triggers, and cold water adaptation, developed through repeated immersions, may offer such a model. The hypothesis is that cross-adaptation exists between CWI and other forms of physiological stress, such as surgery or inflammatory-based conditions. By reducing the magnitude of the stress response, some of the negative consequences of this may be reduced or avoided. Anecdotal evidence also exists of therapeutic benefit from cold water adaptation for conditions associated with chronically elevated levels of inflammation (Harper, 2012; Starr, 2013; Waters, 2016).

The stress and inflammatory responses of adapted cold water swimmers were found to be lower than those of unadapted volunteers. For example, resting plasma noradrenaline concentrations were either similar or declined in adapted swimmers (Hirvonen *et al.* 2002; Leppäluoto *et al.* 2008). Catecholamine concentrations were elevated from baseline by two- to threefold during CWI in those who were cold habituated (Leppäluoto *et al.* 2008), but these increases were less than those observed in unadapted individuals (Goldstein & Frank, 2001; Leppäluoto *et al.* 2008). Additionally, repeated CWI reduced plasma ACTH and cortisol responses to CWI (Huttunen *et al.* 2000; Leppäluoto *et al.* 2008). Although the cytokine responses to repeated CWI showed no change in resting tumour necrosis factor-α, interleukin (IL)-6 and IL-1β in volunteers, provocation by lipopolysaccharide stimulation resulted in reduced IL-6 after repeated CWI (Dugué & Leppänen, 2000). However, the cytokine response must be treated with caution, because the inflammatory response is complicated, and low values are measured before cold water adaptation. It remains to be determined what effect cold water adaptation has on cytokine responses in patients with raised levels of inflammatory markers.

After CWI and cold-pressor tests, increased concentrations of dopamine (Šrámek *et al.* 2000), serotonin (Hirvonen *et al.* 2002) and β-endorphins (Suzuki *et al.* 2007) have been reported; these changes are associated with improved mood or the 'post-swim high' (Steinberg & Sykes, 1985). However, in contrast to the sympathoadrenal response, the concentrations of these chemicals have not been reported to change after cold water adaptation (Hirvonen *et al.* 2002). Pro-inflammatory cytokine release inhibits serotonin production and can promote behavioural change, including initiation of depressive symptoms, such as sadness, fatigue and social withdrawal (Slavic & Irwin, 2014). For example, the release of the pro-inflammatory cytokine indoleamine 2,3-dioxygenase (IDO) degrades tryptophan, a precursor to serotonin, and competes with the serotonin metabolic pathway. As a consequence, serotonin availability is reduced (Müller & Schwarz, 2007), a change that is thought to contribute to the development of symptoms of depression (Almond, 2013). This mechanism has also been found in rats displaying depression-like symptoms; swim training of the rats inhibited activation of IDO and reduced the depression-like symptoms (Liu *et al.* 2013). Consequently, it has been suggested that adaptation to CWI could reduce pro-inflammatory responses in humans, enhancing serotonin secretion and reducing symptoms of inflammatory-based depressive disorders (Fig. 5). It is not clear whether this pathway is specific for depressive disorders or if it could potentially ameliorate other inflammatory-based conditions.

Teleologically, it makes sense for there to be, at least in part, a common or shared physiological pathway in the response to stress. However, even having

established a theoretical basis for the effect of cold water adaptation on the inflammatory response, it is still necessary to demonstrate that adaptation in one system is reflected in another. Repeated exposure to a stressor evokes specific adaptive responses (Adolph, 1956), but there is also a component of general adaptation, often involving the autonomic nervous system, that is common to several stressors (Selye, 1950; Lunt *et al.* 2010).

Such 'cross-adaptation' was shown by Lunt *et al.* (2010) when they demonstrated that habituation of the sympathetic nervous response to short-term CWI (six 5 min immersions in 12°C stirred water) also improved the response to moderate exercise in hypoxic conditions (fraction of inspired O_2 0.12). Repeated CWI has been reported to increase the concentration of antioxidants in winter swimmers (Siems *et al.* 1999). Specific cold shock proteins have been identified in mammalian cells (Fujita, 1999), and cold exposure increases the expression of heat shock proteins (Holland *et al.* 1993; Lindquist *et al.* 2014). Thus, cold adaptation could enhance tolerance to other forms of stress by upregulating cell-protective mechanisms. This suggests that at the cellular level there may be a generalized response to different forms of stress, and it is these general responses which may allow, once habituated, a reduction in the response to a new stressor, if that new stressor shares the same general responses. Thus, through cross-adaptation or cross-tolerance, it may be possible to find common adaptive responses that occur with repeated CWI (Fig. 5) and that also reduce biochemical markers causing or contributing to ill health. The combination of the neurotransmitter and anti-inflammatory responses to repeated CWI may be the cross-adaptive link.

Although cross-adaptation is probably the key to the therapeutic effectiveness of cold water adaptation, there are other mechanisms that may be used to enhance the effect. Cold water adaptation studies typically use a set, static immersion protocol; it is more likely that in real life, cold water swimming will be the preferred technique. This would then be expected to provide the additional health benefits that are derived from exercise (Liu *et al.* 2013; MacAuley *et al.* 2015). In addition, open water swimming is thought to offer a range of other potentially beneficial 'interventions', including 'green therapy' (Gilbert, 2016) and 'blue therapy' (Nutsford *et al.* 2016) as well as the communal aspects and a sense of achievement (Waters, 2016). Green therapy and blue therapy involve access to and use of outdoor, green and blue spaces; green spaces are open land that is primarily vegetation, and blue spaces are bodies of water, such as lakes, rivers or the sea. Of particular note is the powerful parasympathetic stimulation derived from immersing the face in cold water (de Burgh Daly & Angell-James, 1979). Studies using electrical stimulation of the vagus nerve have been shown to have significant anti-inflammatory effects (Bonaz *et al.* 2016). Vagus nerve stimulation was approved by the US Food and Drug Administration for the treatment of drug-resistant epilepsy and depression in 1997 and 2005, respectively. Since then, 80,000 patients with epilepsy and 4000 with depression have had implanted bipolar pulse generators connected to electrodes wrapped around the left vagus nerve in the neck, with encouraging results (Englot *et al.* 2011; Bonaz *et al* 2016). Cold immersion of the face might represent a safer and cheaper means of stimulating the vagus.

At present, research does not unequivocally support the use of cold water adaptation (indoors or outdoors,
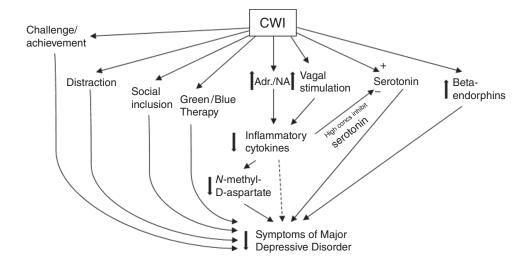

Figure 5. The hypothesized association between cold water immersion, inflammation and depressive disorders
Abbreviations: Adr./NA, adrenaline/noradrenaline; and CWI, cold water immersion.

Table 1. Static cold water immersion (CWI) studies

Study	Participants	Protocol	Results	Illness?
Janský et al. (1996)	10 unacclimatized men	Initial immersion: 60 min at 14°C, Blood samples before and after CWI	Total leucocyte numbers: increased, Individual types of leucocyte: no change, Serum IgG: increased, Serum IgA and IgM: no change	No
		Repeated immersions: as above, three times per week for 6 weeks. Blood samples before and after each CWI	Total leucocyte numbers: unchanged from single CWI. Pre- and postimmersion monocytes: increased. CD25 T lymphocyte numbers: increased. Pre- and post-immersion T and B lymphocytes: trend for increase. Serum IgA, IgG and IgM: unchanged from single CWI.	
Brazaitis et al. (2014)	40 unacclimatized men, divided into fast coolers (rectal temperature reached 35.5°C) and slow coolers (reached 120 min total CWI)	Intermittent CWI (20 min at 14°C followed by 10 min sitting in laboratory) until sooner of rectal temperature 35.5°C or 120 min total CWI. Blood samples before and after CWI	Fast coolers (n = 20): no changes Slow coolers (n = 20): total leucocytes increased; percentage of neutrophils increased; percentage of lymphocytes and monocytes decreased	No

static or swimming) for therapeutic purposes. There is a theoretical basis as well as non-specific anecdotal evidence, both contemporary (Starr, 2013; Waters, 2016) and historical (Russell, 1760), which suggests that cold water adaptation should be investigated as a non-pharmaceutical treatment for a range of conditions associated with chronic inflammation.

Immune function. Cold water swimmers claim to suffer fewer and milder infections as a result of the practice (Brenke, 1990). A boost to immunity from cold water is biologically plausible; CWI causes the release of stress hormones (Johnson et al. 1977; Kauppinen et al. 1989), and Dhabhar (2014) argues that short-term stress readies the immune system to deal with injury or infection. Research into the effects of CWI on immune function has produced mixed results, possibly because participants and protocols varied from unacclimatized individuals taking a brief dip in ice-cold water (Dugué & Leppänen, 2000), to longer static CWI (Janský et al. 1996), to experienced long-distance swimmers training for 8 h (Kormanovski et al. 2010). In addition, different leucocytes and immunoglobulins (Igs) have been measured. Furthermore, changes in immune system markers may not translate into altered in vivo defence (Castellani et al. 2002), and very few studies asked participants to report real illness. A general weakness of research in this area is that many studies have small numbers of participants, and differences between male and female participants are often not reported. However, participant recruitment is difficult, because cold water swimming is a minority activity, and non-swimmers are often reluctant to undergo CWI.

If CWI does benefit immune function, then there should be improvements in both immune system markers and real health over the course of an acclimatization programme, and habitual cold water swimmers could have the most robust systems. However, there may be differences in the responses to static CWI and cold water swimming, because exercise and cold both cause physiological stress, and their combined effect might exceed the individual effect of each (LaVoy et al. 2011).

The responses of the immune system to static CWI were investigated by Janský et al. (1996). Participants underwent an initial single immersion, followed by repeated CWI three times a week for 6 weeks, and the results are summarized in Table 1. It can be seen that adaptation altered both resting leucocyte numbers and their response to static CWI, with both innate and adaptive cells being affected. Nonetheless, these changes were small and of uncertain significance, and repeated CWI did not alter the Ig response (Janský et al. 1996).

Brazaitis et al. (2014) immersed men intermittently, as shown in Table 1, and found that there were differences

between fast coolers and slow coolers, with only the latter showing leucocytosis. Responses to static CWI appear to be strongly influenced by the protocol and the participants. The difference in leucocytosis between fast coolers and slow coolers may have resulted from slow coolers having been immersed for a total of 120 min as against a mean of 96 min for fast coolers, or from the two groups' differing responses to CWI. The use of alternating CWI and rewarming might also have complicated the physiological response. It seems also that the extent of the leucocytosis might correspond to the magnitude of the stress. Janský *et al.* (1996) found no increase in neutrophils after 60 min in water at 14°C, whereas Brazaitis *et al.* (2014) reported an increase of 55% after a total of 120 min in 14°C water with periodic rewarming.

The clinical significance of these findings is uncertain. Short-term leucocytosis arises from leucocytes leaving organs such as the spleen in response to the increase in catecholamines and cortisol, to be ready to deal with a threat (Dhabhar, 2014). Leucocytes are transferred in the blood to sites of potential infection, so arguably the most important part of this short-term response is a subsequent reduction in blood leucocytes as they move into tissues, such as the skin (Dhabhar, 2014). This has not been investigated in the context of CWI, but Yeager *et al.* (2016) found that monocytes and neutrophils did indeed migrate into sterile blister fluid in response to a dose of cortisol corresponding to that released during acute stress. The 29% increase in resting monocyte levels over 6 weeks of CWI reported by Janský *et al.* (1996) could indicate greater numbers in the body and a boosted immune system, but could also result from persisting presence in the blood rather than in sites of infection. Neither Janský *et al.* (1996) nor Brazaitis *et al.* (2014) considered real illness, and both had only male participants.

Almost all the studies investigating the immune response to dynamic CWI have had participants who were experienced cold water swimmers; however, there were wide variations in the swimming undertaken and the markers considered, and it is not possible to separate out the effects of exercise. Three studies asked swimmers to report colds or flu [upper respiratory tract infection (URTI)]. Upper respiratory tract infection is a useful measure of *in vivo* immune function, being a very common infection that challenges both innate and adaptive elements (Hannigan *et al.* 2009). The results of all these studies are summarized in Table 2.

Dugué & Leppänen (2000) found that habitual cold water swimmers had higher resting levels of some leucocytes than non-cold-habituated people. They also investigated the responses of both groups to brief dips in ice-cold water but, as this was after a sauna, it is not possible to separate the effects of the two thermal stresses. This was the only study to consider men and women separately, and there were differences between the sexes. However,

the low participant numbers make it difficult to establish the significance of these results.

Kormanovski *et al.* (2010) monitored 15 experienced long-distance swimmers for 6 months. Seven of the group completed three continuous long distance swims (LDS), one of 6 h (in month 1) and two of 8 h (in months 3 and 6), whereas the other swimmers rested (controls). All followed the same nutrition protocol. There were differences between the LDS group and the control group in leucocyte and Ig responses, over both the total study period and the LDS periods. The heavy training load may have slightly depressed basal levels of leucocytes in the LDS group, but a training bout caused appreciable increases; granulocyte numbers rose almost fourfold during the 8 h.

The LDS group had significant decreases in resting levels of serum Igs and salivary IgA (sIgA) over the training period, whereas control swimmers did not. During all three LDS periods, sIgA decreased markedly but remained unchanged in control swimmers, whereas serum Igs showed no clear pattern in either group. As the authors point out, Ig levels are subject to considerable diurnal variation and can be considerably higher in the morning.

The sIgA result accords with decreases seen in dry-land athletes with a heavy training load (Mortatti *et al.* 2012), so may have been attributable to exercise rather than the cold. The usefulness of Igs as markers of *in vivo* immune function is not established. Some studies have found a correlation between sIgA and URTI incidence (Gleeson *et al.* 2012), but others have not (Tiollier *et al.* 2005). None of the swimmers in this study reported an URTI during the 6 months of training or the 3 months afterwards, thus no relationship was found between immune markers and real illness.

Lombardi *et al.* (2011) investigated unacclimatized participants completing a 150 m race in cold water, and found a significant increase in total leucocytes compared with the previous day. There was no control group, and although it is not possible to simulate CWI, it would have been useful to take blood samples from non-immersed control subjects, because the stress of having blood taken could, in itself, affect immune markers (Dhabhar, 2014).

In the last two of these studies (Lombardi *et al.* 2011; Dhabhar, 2014) there seems again to be a link between the magnitude of the stress and the leucocyte response. The long-distance swimmers in the study by Kormanovski *et al.* (2010) had no significant change in agranulocytes (most of which are neutrophils) after 1 h, but after 2 h the numbers had increased by ∼50%, with a fourfold increase after 8 h. The unacclimatized swimmers in the study by Lombardi *et al.* (2011) showed the fastest response, with neutrophil numbers up 38% after a 150 m race. However, this was compared with the previous day, so some of the increase might have been attributable to race-day stress. All three studies report higher leucocyte numbers in cold water

Table 2. Cold water swimming studies

Study	Participants	Protocol	Results	Illness?
Brenke (1990)	85 ice swimmers	Swam regularly for ≤5 min, water temperature −1 to 4°C. Retrospective questionnaire	40% reported suffering fewer, less severe and shorter infections than previously	Yes
	Eight patients at a remote rural practice, who began ice swimming	Swam for 5–6 year period. Reported consultations for flu-like illnesses	Consultations decreased from 0.88 per year before starting ice swimming to 0.5 per year at end of study period	
Dugué & Leppänen (2000)	Habitual cold water swimmers (five women, seven men). Control subjects, unacclimatized (six women, two men)	Resting blood samples	Swimmers *versus* control subjects. Female swimmers: higher leucocyte and neutrophil numbers. Male swimmers: no difference in the above. All swimmers: 50% higher monocyte numbers	No
Kormanovski *et al.* (2010)	15 experienced long-distance swimmers (eight men, seven women), divided into LDS group (four men, three women) and controls (four men, four women)	Carried out 6 months training, ≤160 km per month. LDS group completed continuous swims of 6 h (month 1) and 8 h (months 3 and 6), water temperature 18–21°C, while control subjects rested. All followed the same nutritional protocol. Blood and saliva samples before, during and after LDS period. Blood analysis and medical examination every 2–3 weeks during study period	LDS group *versus* control subjects over 6 months. LDS group: trends for decreased resting granulocytes and agranulocytes ($P = 0.099$ and 0.059, respectively); decreased resting serum IgG and IgM and sIgA. Control subjects: no changes. LDS group *versus* control subjects during the three LDS periods. LDS group: granulocyte numbers increased; agranulocyte numbers rose then fell slightly; sIgA decreased; serum Igs showed no change during first LDS, but fluctuated during second and third LDS. Control subjects: no change in sIgA; increased serum IgA, decreased serum IgM in last 2 h of 8 h rest. No swimmer had an URTI in the 6 month study period or the 3 months immediately afterwards	Yes
Lombardi *et al.* (2011)	Unacclimatized individuals (13 men, two women)	150 m race in water at 6°C. Blood samples day before and straight after race	After race *versus* day before: total leucocytes increased (especially neutrophils, monocytes and lymphocytes)	No

(Continued)

Table 2. Continued

Study	Participants	Protocol	Results	Illness?
Huang *et al.* (2011)	Swimmers: 14 middle-aged men. Control subjects: 11 sedentary middle-aged men	Swimmers swam five times per week (mean 55 min at moderate intensity), water temperature 13–19°C. Resting blood samples	Swimmers *versus* control subjects. Swimmers' mononuclear cells inhibited growth of leukaemia cells 4 times more effectively than those of controls	No
Teległów *et al.* (2014)	10 male winter swimmers	Swam regularly for 5 min, water temperature ≤7.5°C from November to March. Post-swim blood samples	Serum IgA, IgG and IgM: no change over study period	No
Collier *et al.* (2015)	21 habitual cold water swimmers and their cohabiting non-swimming partners. 23 habitual pool swimmers and their cohabiting non-swimming partners	Weekly report of common cold symptoms for 13 weeks from December to March	Cold swimmers had fewer colds than their partners. No differences between cold swimmers and pool swimmers	Yes

Abbreviations: LDS, long-distance swim; sIgA, salivary IgA; and URTI, upper respiratory tract infection.

swimmers, but again it is not known whether these reflect greater numbers in the body or redistribution between different sites. The swimmers in the study of Kormanovski *et al.* (2010) were highly trained, and those of Lombardi *et al.* (2011) were unacclimatized and racing.

Other studies have focused on recreational habitual cold water swimmers. Huang *et al.* (2011) compared middle-aged cold water swimmers with a sedentary group, and found that mononuclear cells from swimmers inhibited growth of leukaemia cells four times more effectively than those from control subjects. However, the control group comprised sedentary adults rather than men undertaking a similar amount of dry-land activity, so did not control for effects of exercise, and the swimmers were much fitter than the control subjects ($\dot{V}_{O_2\,max}$ 46.9 *versus* 28.3 ml kg^{-1} min^{-1}). Teględów *et al.* (2014) investigated 10 male winter swimmers and found no significant changes over the winter in their post-swim serum IgA, IgG or IgM. As blood samples were taken only after swimming, it is not possible to establish whether their response to immersion changed. There was also no control group of non-swimmers, making it impossible to distinguish between the effects of cold water and those of exercise.

Of all the above studies, only that of Kormanovski *et al.* (2010) reported real illness in those exposed to cold water. In spite of alterations in immune markers, none of the swimmers suffered an URTI. However, this was a small group of highly trained individuals and so may not be representative of recreational cold water swimmers.

Two further studies investigated URTI incidence in habitual cold water swimmers. Brenke (1990) surveyed 85 regular ice swimmers, of whom 40% stated that they suffered fewer, less severe and shorter infections than previously. In addition, he followed eight patients at a remote rural practice and found a significant reduction in consultations for flu-like illnesses. Collier *et al.* (2015) compared URTI incidence and severity in cold water swimmers with that in their cohabiting, but non-swimming, partners and with pool swimmers, and found that cold swimmers had fewer colds than their partners, but there were no differences between cold and pool swimmers.

All three studies that investigated URTI relied on participant self-report of illness. This has two possible drawbacks: first, it is difficult to remember having had colds in the past as Brenke (1990) asked participants to do; and second, many cold water swimmers are deeply convinced that the practice is beneficial and so may under-report infections, whether consciously or otherwise. The swimmers in the study of Kormanovski *et al.* (2010) were monitored by a medic during their 6 months of training, but were asked to report URTIs in the 3 months that followed. Collier *et al.* (2015) reduced the likelihood of recall error by asking participants to report URTIs each week, but the possibility of biased responses remains.

In spite of the repeated claims for the benefits of cold water swimming, it is also possible that it may be detrimental in large doses. Collier *et al.* (2015) noted trends for positive correlations between cold water exposure and URTI incidence and severity, as shown in Table 2. If short-term stress is like an exercise

that enhances the effectiveness of the immune system, then prolonged stress could lead to fatigue and a reduced response. Dhabhar (2014) defines short-term stress as lasting minutes to hours, and chronic stress as being repeated for hours each day for weeks or months. Frequent cold water swimming with prolonged shivering afterwards might fall into the latter category. Loria *et al.* (2014) found that regular winter swimmers had abnormal daily cortisol variations, and Dhabhar (2014) comments that prolonged stress can lead to dysregulation of the diurnal cortisol cycle and to a suppressed immune response. Eccles & Wilkinson (2015) argue that both breathing cold air and chilling the body surface increase the likelihood of URTI, partly because of vasoconstriction in the nose. Exercise intensity may also be relevant: Wang & Huang (2005) found that exercise at 80% $\dot{V}_{O_2 max}$ led to lymphocyte apoptosis. Oxygen consumption is greater in cold water, and $\dot{V}_{O_2 max}$ is decreased (Tipton & Bradford, 2014), thus relative exercise intensity is increased. Physiological stress could also be affected by swim duration, air and water temperatures, body composition and extent of acclimatization. These factors could act together to push the impact of cold water swimming on immune function from 'benefit' to 'detriment'.

It is concluded that there is some evidence that the short stress of CWI may prime the immune system to deal with a threat, and thus be beneficial. Whether this effect is augmented by swimming has not been established and may depend on the frequency, intensity and duration of the exercise, among other factors. The disturbed diurnal cortisol rhythm seen by Loria *et al.* (2014) suggests that an excess of cold exposure may lead to continued physiological stress, and this could lead to immunosuppression. Thus, the 'optimal dose' of cold has yet to be determined, and is likely to differ between individuals. The definitive studies in this complex area await completion.

- Cold Shock – Drowning ****
- Cold Shock – Cardiac arrest***
- Autonomic Conflict – Cardiac Arrest**
- Cold-induced neuromuscular incapacitation – Drowning ***
- Hypothermia ****
- Circum-Rescue Collapse ***
- Cold injury ***
- Blunted anabolic signalling & long-term gains in muscle mass & strength***

- Prolonged underwater survival (occurrence ****, mechanism**)
- Deliberate cooling for oxygen conservation and treatment of hyperthermia****
- Pre-cooling for improved performance in the heat***
- Improved recovery post-exercise **/*** (depending on exercise model/control)
- Treatment of inflammation-related conditions*
- Upregulation of immune function **

Level of evidence (Based on SIGN50 criteria)
- *   Anecdotal
- **   Case control or cohort studies with a high risk of confounding or bias and a significant risk that the relationship is not casual
- ***   Case control or cohort studies with a low risk of confounding or bias and a moderate probability that the relationship is causal
- ****   High quality systematic reviews of case control or cohort studies

Figure 6. Cold water immersion: kill or cure
The responses in each category, with a level of evidence assessment.

Summary and conclusion

The areas reviewed are presented in Fig. 6. We have assessed the evidence base for the claims made for CWI in each area using a modified version of the Scottish Intercollegiate Guidelines Network (SIGN) criteria (Scottish Intercollegiate Guidelines Network, 2011).

Other areas continue to evolve and are worthy of further study; included amongst these are the potential metabolic and thermogenic benefits associated with cold exposure and the activation of brown adipose tissue (Blondin *et al.* 2014). The role that CWI and acclimatization to CWI may have in this area remains to be investigated in humans. The closest investigators have come thus far is use of a water-perfused cooling suit to demonstrate that brown adipose tissue acts as a non-shivering thermogenesis effector (Ouellet *et al.* 2012).

It is concluded that CWI is a significant cause of death internationally, and the physiological precursors to these deaths have been identified and investigated, although not fully described in all instances. The beneficial effects of CWI in terms of surviving prolonged immersion, cooling hyperthermic casualties, pre-CWI for enhanced performance in the heat, postexercise CWI for recovery, and CWI adaptation as a treatment for inflammation-related conditions or to boost the immune system all remain to be elucidated fully. Each of these areas has feasible rationales and hypotheses, but the areas are complex and the impact of CWI can vary from beneficial to detrimental depending on the subtle interplay of factors such as the following: duration and intensity of cold water exposure; duration of post-CWI event; degree of hyperthermia; control condition adopted; potential benefit of inflammation; and nature of the exercise to be performed. In short, for CWI, the evidence base for 'kill' is currently somewhat more developed than that for 'cure'.

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Additional information

Competing interests

None declared.

Author contributions

M.J.T. conceived the review, wrote the CWI hazards and prolonged underwater survival sections and took overall editorial control; N.C. wrote the section on immune function; H.M. and M.H. co-wrote the section on inflammation; J.C. wrote the section on precooling and postexercise CWI; and all authors contributed to the figures and reviewed and revised the manuscript. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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