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EXCERPTS ON HUMAN COLD SURVIVAL*

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ABSTRACT

To understand fully the mechanisms of homeostasis in humans, especially during exercise and environmental challenges, one must also probe their physiological and psychological limits commensurate with survival. All elements of the Earth, air, fire and water quadruple are involved, especially during environmental cold exposure. The major body heat defense mechanisms against cold are reduction in peripheral (skin) blood flow via vasoconstriction, and increased metabolic heat production via muscular exercise and shivering; both can be enhanced by good nutrition and increased body fat content to facilitate avoidance of hypothermia, frostbite, and frozen tissue. Included in this brief review are data on incidence of hypothermia cases in Antarctica, Alaska, and during athletic events; as well as excerpts from human survival scenarios in cold water (Dachau experiments), in cold air on the ground (Etienne's trek, Napoleon's retreat), in cold air on cold water (Shackleton's ordeal), and in cold air at high altitude (airplane wheel-well passengers). These excerpts testify to the inherent redundancy of the homeostatic mechanisms that facilitate human survival in cold environments.

Key words: cold survival, heat defense mechanisms, hypothermia, frostbite, immersion

Introduction

Exposure to excessively cold ambient temperatures, thereby facilitating induction of body hypothermia, can be both a blessing and a curse: a blessing when used by surgeons to lower bodily functions and metabolism during operations; and a curse when the result is injury or death. Deep body (core) temperature (rectal, esophageal, ear-canal) is normally regulated at 37 ± 1˚C in humans, and its nominal survival range in clothed resting people is from about 27˚C (in cold water) to 42˚C (in hot air); that is a decrease of about 10˚C (net heat loss of 700 kcal), but an increase of only 5˚C with a net heat gain of 350 kcal (10). Thus, resting humans have a greater internal thermal survival range with exposure to cold than to heat. The lower level data came from Nazi Dachau water immersion experiments (2,10), whereas many non-acclimated humans resting in a hot-humid environment (42˚C, 90% rh) can tolerate core temperatures of 42˚C. But some can be close to their limit of consciousness and

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onset of heat stroke with rectal temperatures of only 38.5˚C (25, 27). However, at the end of Marathon races the range of core temperatures of some runners was 40.2˚C to 41.1˚C with no lasting ill effects (23). Thus, it is clear that noting only core temperature without knowledge of other mitigating circumstances is insufficient datum to determine a person's physiological state.

The purpose for this review is first to delineate the more important physiological responses, adjustments, and defense mechanisms of humans to acute and chronic exposure to environmental cold; and secondly to describe and discuss some interesting episodes of cold survival throughout history to study limits of human cold acclimatization and survival.

Physiology of cold exposure

Body core temperature – measured in the esophagus (Tes) or rectum (Tre) – is one of the most important and well-regulated variables in the human organism. At ambient temperatures below 28-30˚C, the so–called lower critical temperature for a naked individual, heat defense mechanisms must be activated to maintain a state of normothermia. These mechanisms include reduction of heat loss by vasomotor control (peripheral vasoconstriction), and increase in metabolic heat production by exercise or shivering.

Heat loss mechanisms

During cold exposure the cutaneous (shell) blood flow; especially in uncovered skin areas such as feet, hands, nose, and ears, is reduced significantly which attenuates heat loss. Vasoconstriction is due to prompt activation of the sympathetic nervous system which releases noradrenaline. The action of noradrenaline varies with ambient temperature: the contractile response of vascular smooth muscle at 30˚C is approximately 5-fold greater than at 41˚C, and it becomes attenuated at 15˚C. At 10˚C the effect of noradrenaline is negligible and local vessels vasodilate which markedly enhances heat loss from the warmer body to the cooler environment. The skin vessels of the human hand constrict so effectively in response to cold that the ratio of the maximal – to – minimal blood flow can be 60 to 1, while the same ratio in the body shell is about 6 to 1 (30).

When the body core is warm and only the peripheral parts are exposed to cold, intermittent episodes of vasodilation appear in the periphery. Cyclic waves of cold – induced vasodilation; i.e., a hunting response first described in 1930 by Lewis, are attributed to attenuated responsiveness of vascular smooth muscles to noradrenaline most probably due to the local tissue hypoxia and hypercapnia. Cyclic changes of skin blood flow in the extremities are advantageous because they serve two seemingly conflicting needs; limiting heat loss and preventing frostbite (19).

At low ambient temperature, heat loss from the head may account for half of resting heat production (15) because human facial circulation does not undergo significant reflex vasoconstriction to cold (28). However, because of its proximity to the thermal core areas in the head, facial temperature stabilizes well above freezing even under conditions of severe cold, which explains the relatively rare incidence of facial frostbite.

Effective control of skin blood flow is also achieved by arteriovenous anastomoses which are short, richly innervated vessels with muscular walls that join arteries to veins. When they are open, blood short – circuits the usual route through the capillaries thereby increasing blood flow and local temperature.

Mechanisms of heat production

Shivering and increased muscle tone are the most important sources of heat production in cold-exposed adult humans. Muscu-

lar tremor can appear after only 2 min of cold exposure, and it becomes generalized after about 25 min depending on environmental and/or core temperatures. Generalized shivering involves almost all muscles in the body and can increase metabolism up to five times over the basal rate (14).

The onset and intensity of shivering at a given ambient temperature, as well as the critical mean skin temperature for this metabolic response in men exposed to cold, depends on several factors; e.g., body size and insulation, level of physical fitness, and the level of habitual activity (16). Shivering is induced by temperature changes in both the body core and periphery. It appears, however, that changes in hypothalamic temperature are about 10 times more effective for inducing heat production than for lowering peripheral temperature (14). Input from cold sensors; e.g., in the skin and spinal cord, are integrated in the preoptic – anterior area of the hypothalamus. Then, impulses are transmitted from the caudal motor area through the mid – and hind – brain, and then to the ventrolateral columns of the spinal cord to the muscles. It should be emphasized that although shivering is involuntary, higher parts of the brain (e.g., the cerebral cortex) also play a role in the control of shivering mainly by inhibiting its magnitude (14).

Energy for shivering is generated from adenosine triphosphate (ATP), similar to that used for voluntary muscle contraction. The content of ATP is limited to about 3 mmoles/kg of muscle, so this immediate energy source must be quickly regenerated from ADP, which becomes a crucial factor for determining the intensity of oxidative phosphorylation in muscle mitochondria. Since mechanical work is not done during shivering, virtually all the energy released by those muscle contractions appears as heat. Carbohydrates and lipids are important fuels for shivering. During the initial stages of cold exposure energy for shivering is obtained mainly from muscle glycogen stores and intramuscular triacylglycerols. With prolonged cold exposure the glucose produced from liver glycogen, and free fatty acids originating from adipose tissue lipolysis, become more important as energy substrates. However, glucose is needed mainly for brain function, and free fatty acids cannot be utilized as a single source by contracting muscles. Thus, the duration and severity of the cold stress, as well as the nutritional state of the person, seem to determine the efficiency of shivering during exposure to low ambient temperature. It is surprising that there are only limited published data on this important problem (16).

Shivering is not an economical process for thermoregulation because constant muscle movements increase blood flow and conductive heat transfer to the skin which also enhance heat loss. As a result, the amount of heat generated by shivering which can be utilized to compensate for heat loss to a cold environment does not exceed 11% (14).

When the two major physiological heat defense mechanisms described above become insufficient for maintaining heat balance, normothermia cannot be maintained which results in decreased body core temperature and hypothermia with all its consequences.

Hyphothermia

The occurrence of hypothermia can be broadly ascribed to the net result of inadequate thermal insulation to attenuate the rate of heat loss sufficiently, and/or failure to sustain adequate metabolic heat production (6). With adequate provisions hypothermia can be prevented; but misfortune, miscalculation, misplaced confidence, logistic failure, and individual pathophysiological susceptibility either separately or in com-

bination, may contribute to the cause. There seems to be more interest in the treatment of hypothermia than in its etiology; there is greater concern regarding accidental hypothermia, due primarily to inadequate thermal insulation, than incidental hypothermia due primarily to a functional disorder of the body (6).

A retrospective study of medical records was performed to determine the type, severity, epidemiology, etiology, and treatment of cold injuries of British Antarctic Survey residents between 1986–1995 (7). While this continent is the coldest (-89˚C recorded on 21 July 1983 at the Vostok station in mid – East Antarctica at about 3420 m elevation), there were only 61 new consultations for cold injury (58 frostbite, one trench foot, two hypothermia) among 43 individuals over this 10-yr period that constituted only 2.5% of all new consultations; an incidence of 66 per 1000 people per year. The most common location of superficial frostbite was on the face and ears which occurred in 47% of the cases at ambient temperatures of –0.3˚C to –42.5˚C (mean = -21.2˚C ± SD 11.1˚C). Hypothermia constituted only 3% of the cases. New cases of cold injury were related inversely with ambient temperature, with the greatest incidences in winter. Time to freezing of mammalian tissue is reduced by 2 min for each degree Celsius drop in ambient temperature (20). Repeated cold injury was common; i.e., 30% of new consultations occurred in those with a history of frostbite, many at the same skin site. But neither decreasing temperature nor increasing wind chill were related to the severity of the frostbite.

In Alaska, between 1991 and 1995, there were 327 people hospitalized for cold-related injuries where, unlike Antarctica, hypothermia accounted for 46% of admissions followed closely by foot frostbite with 42% (8).

While hypothermia has occurred rather frequently in mountain hikers (21), cavers (3), and Channel swimmers (24), it is being diagnosed more frequently in distance runners. Ledingham et al. (17) were probably the first to report a case in a Glasgow Marathon runner who collapsed with a rectal temperature of 34.3˚C at an ambient temperature of 12˚C and wind – velocity of 16 to 40 km•hr^{-1}. Later, Maughan (18) reported that 18 of 59 runners who completed the Aberdeen Marathon in 1982 (ambient temperature of 12˚C, wind – velocity of 26 km•hr^{-1}) had rectal temperatures less than 38˚C, and four less than 37˚C.

Cold-Immersion Exposures

Four temporal periods of cold immersion serve as a means to analyze and interpret the pathophysiology: (a) the initial response (0 – 3min), (b) short – term response (3 – 15 min), (c) longer – term response (>30 min), and (d) post – immersion responce (13). While the possibility of injurious hypothermia does not usually occur within 3 to 15 min of immersion, the immersed individual must first survive the initial minutes of exposure, especially in ice water (31). The importance of cold – induced hypothermia in immersion deaths has often been overlooked in the past (12,15) in spite of the fact that cold exposure has been acknowledged as a cause of death separate from drowning. One striking example was with the sinking of the Titanic in April, 1912 in the North Atlantic. The official reason for the deaths of 1,489 victims immersed in ice water in every case was drowning, even though enough life belts were available to keep them afloat. Evidence for cold – induced hypothermia was overwhelming but apparently overlooked.

The lowest recorded body (rectal) temperature in any human survivor is 13.7˚C (11). A 29 year old female, while skiing in Norway, fell into a waterfall gully and was

wedged between rocks and overhanging river ice that periodically flooded with ice water for almost 80 min. Witnesses, who could not extract her, reported that she struggled for the first 40 min below the ice before her body movement ceased. It was another 39 min before rescuers arrived when the victim was freed and declared clinically dead. Basic cardiopulmonary resuscitation was initiated immediately. Upon arrival at a hospital physicians used a femoral cardiopulmonary bypass to rewarm her blood, and her heart began beating following 15 minutes of bypass. Interestingly, her Tre remained at 14.2˚C while Tes had increased to 31.5˚C at that time. At 170 min the patient's Tre had increased to 36.0˚C and the bypass was disconnected at 179 min. She was close to full recovery five months later. Apart from the general rescue response and rewarming techniques, it would appear that whole-body cooling which precedes circulatory arrest improves recovery ability.

Dachau experiments

These cold air and water immersion experiments on unwilling humans were coordinated by professor G.A. Weltz, M.D. from the Institüt für Luftfahrtmedizin in Munich. They were conducted at the Dachau concentration camp (in Block no. 5) from February 1942 to May 1944 by S. Rascher, M.D. and associates under the direction of Henrich Himmler, Reichsführer S.S., previously a school teacher who thought of himself as a scientist in that he took an active role in planning some tests (2).

The purpose for these experiments was to devise effective resuscitation procedures for hypothermic pilots and others who had been immersed in cold water. One series exposed nude men to air temperatures of -6˚C for as long as 14 hours to freeze peripheral tissues and reduce Tre to 25˚C. Another series immersed men in water at 2˚ to 12˚C either nude or dressed in standard flying clothing and equipment. About 103 men were used, some more than once, with only one known survivor; Dr. Leo Michalowski, a Polish Catholic priest (2).

The initial response to this very cold immersion was increased heart rate to 120-140 beats/min with defensive arm movements, followed within 15 min by increased respiratory frequency to 24 breaths/min and muscular rigidity with the arms pressed tightly to the chest (10). After 15 min the heart rate returned to normal and was maintained there until Tre reached 34˚C when bradycardia developed at 50 beats/min. With further lowering of core temperature the heart beat became irregular (atrial fibrillation) and there was sudden general muscular relaxation which indicated impending death from, presumably, heart failure. In only two instances did respiration fail simultaneously with cessation of heart action. In all other cases slow or gasping respiration persisted for up to 20 min after the heart stopped.

With the drop in core temperature the most striking blood constituent responses were 10 to 20% increases in hemoglobin, two-fold increases in viscosity, greatly increased leukocyte counts, persistent elevation of blood glucose by 80 to 100% with none in the urine, and significantly increased spinal fluid pressure by 50 to 60 mmH_2O. Three significant factors emerged to explain death from immersion – induced heart failure: increased blood viscosity causes overload on the heart; marked peripheral vasoconstriction causes fluid overloading of the more central vasculature; and the cooled heart muscle becomes hypodynamic leading to atrial fibrillation. Cooling may also damage the heart directly.

Some pertinent conclusions (2): (a). In 2˚ to 12˚C water the Tre drops slowly to 35˚C and thereafter decreases more quickly; some deaths occur at a Tre below 30˚C, but death is certain with Tre of 26˚ to 27˚C.

(b). After removal from cold water the patients' after – drop of core temperature (for 15 min or longer) may hasten death. (c). Intensive rewarming never injures a severely chilled person and the best therapeutic procedure is rapid and intensive heating by immersion in a hot bath (40° to 50°C) because it may relieve the overload on the heart. (d). Survival time in cold water can be doubled by use of special protective clothing. (e). Intake of alcohol before or during cold immersion accelerates the decrease in core temperature, while 100 to 200g of dextrose taken before chilling slows the decrease in core temperature. (f). Rate of cooling is largely independent of body composition, but more subcutaneous fat delays rate of cooling but also delays rate of rewarming.

Cold-Air Exposures

Altitude

Between 1947 and 1993 there have been 10 documented cases of young people 13 to 30 years old (probably all males) who stowed away in wheel – wells of the main landing gear of commercial airliners (33). When the landing gear retract, metal covers close these openings thus securing the stowaways during flight in the unpressurized wheel – wells. Five of those passengers either froze or fell to their deaths on take – off or landing. But miraculously, the other five (13, 17, 17, 30, 35 years old) survived in spite of being lightly clothed; one was covered in frost and all suffered from frostbite. The adverse environmental conditions were extreme altitude and cold: 8841 m (- 43°C) to 11,890 m (- 63°C), hypoxia with reduced partial pressures of oxygen (pO_2) that would not support consciousness, and decompression sickness above 6,099 m. The frost – covered 13 year – old survived the 11,890 m flight from Bogota to Miami with a pO_2 of 141 mmHg.

On Thursday 3 August 2000 at 8 p.m. a 180 cm tall 81 kg man, about 30 years old, was pulled from a wheel-well of an Air France jumbo jet at Los Angeles International Airport after an 8-hr 6452 km flight at 11,400 m altitude (-50°C) from Papeete, French Polynesia. His clothes were shredded but he was covered with gear-oil and grease. His body core temperature was 26°C (79°F) when he arrived at the UCLA Medical Center where he was treated for hypothermia and dehydration. He was euthermic and in "good condition" 24 hr later and was to be released within two days (34). The insulative effect of the oil and grease, similar to that used by swimmers in cold water (24), probably saved his life.

As the plane gained altitude the stowaway would experience slow – onset hypoxia and progressive cold. It has been suggested that survival in such conditions was due to establishment of a poikilothermic state whereby the severe hypoxia inactivated nerve cells in the preoptic – anterior hypothalamus so that thermoregulation is inactivated. Such a state is similar to hibernation in that oxygen (metabolic) requirements for the body are reduced considerably (33).

Antarctica

Two men walked 2300 km unassisted across Antarctica in 96 days during the Southern Hemisphere summer of 1992 –1993 while towing their supplies and equipment on sledges (29). Their caloric intake came from freeze – dried food providing 21.3 MJ/day or 5088 kcal/day (8% protein, 36% carbohydrate, 56% fat). Despite high-energy consumption, their energy expenditure was greater resulting in weight loss of both men in excess of 20 kg. With considerable variability in their metabolic responses to the combined stresses of cold, exercise, and undernutrition, both maintained elevated and relatively stable levels of protein synthesis with the protein intake of only 8% of the daily caloric intake.

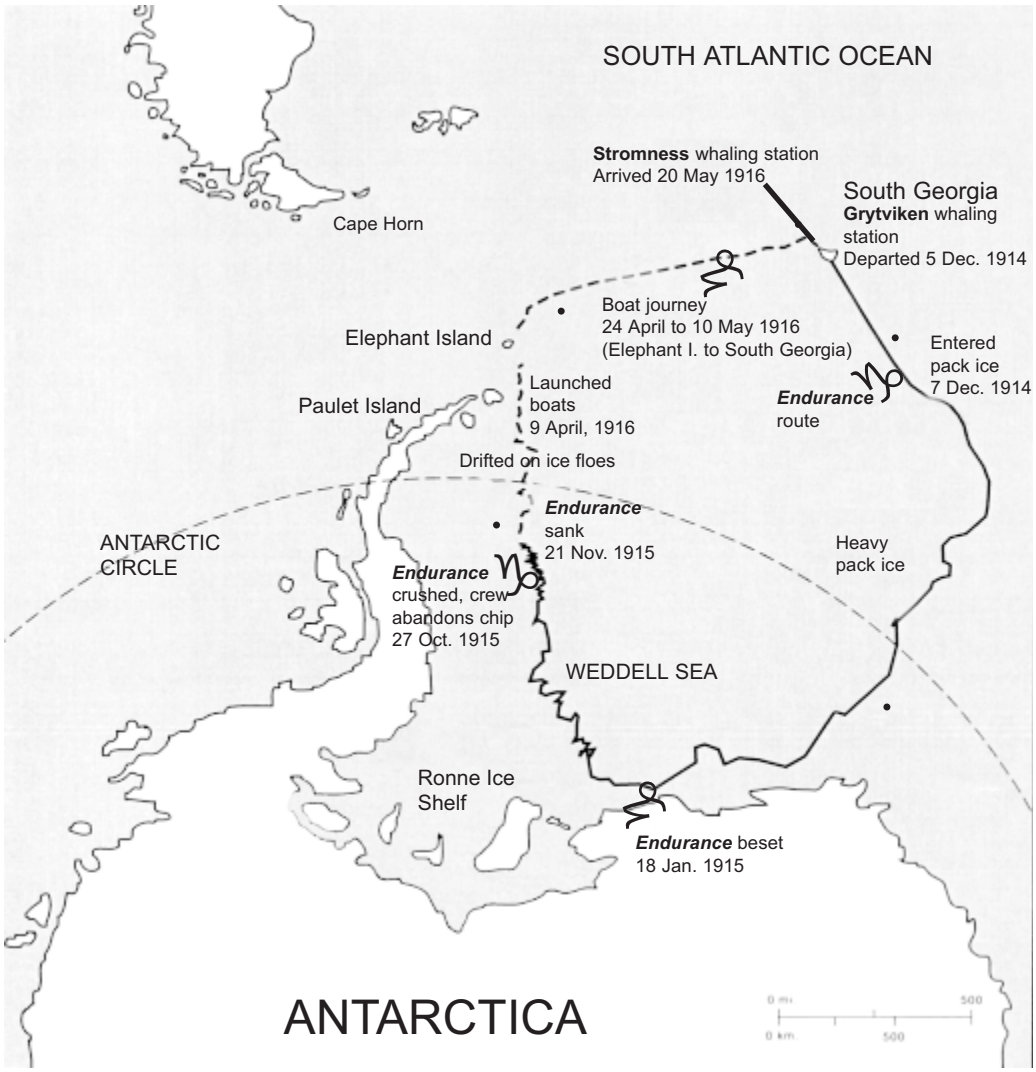

Fig. 1. *Map of Shackleton's voyages beginning at Grytviken whaling station on 5 December 1914 to the Weddell Sea, hence to Elephant Island and then back to Stromness whaling station on 20 May 1916. (Adapted from Alexander)*

Most people are familiar with the earlier exceptional polar journeys of Scott, Shackleton, and Amundsen from 1901 to 1912 (22). During the Southern Hemisphere summer of 1902 – 1903, British Navy captain Robert Falcon Scott, British merchant seamen Lt. Ernest Shackleton, and physician Dr. Edward Wilson covered 1333 km in 93 days using 19 dogs and reached a latitude of 82˚17'S. in their quest to reach the South Pole. Early termination of the trek was due not only to lack of ability to ski or to drive the dogs, but also to incompetence for not rationing their food which resulted in physical weakness, exhaustion, and some scurvy in Scott and Shackleton because of malnutrition. Shackleton returned spitting – up blood while being carried on a sledge. He was selected for the trip because of his physical strength. In the Antarctic summer of 1908 – 1909 Shackleton, Frank Wild, Dr. Eric Marshall, and Lt. Jameson Adams embarked on the ship *Nimrod* for an expedition to the South Pole using sledges pul-

led by four Siberian ponies, the last of which they ate. They reached their previous latitude of 82°17'S. in half the time of Scott et al.'s 1902 – 1903 expedition. But, as before, inadequate food and supplies, snow blindness, and frostbite forced them to return after reaching 88°23'S. latitude where Shackleton himself had man – hauled a sledge to within 123 km of the Pole. It was the farthest south anyone had reached at that time. Later, Roald Amundsen, an experienced Norwegian explorer accustomed to skiing and exposure to cold, and four others with 52 well – conditioned and trained dogs that could cover 24 to 32 km/day, set out on the first successful overland expedition and reached the South Pole on 14 December 1911 because supply depots were established along their route. Their round – trip distance of 2584 km was traversed in 99 days and they made 48 km/day returning in ambient temperatures of -5°C to -30°C. Because of the multiple food caches this party returned in good health. Thirty – five days later on 18 January 1912 the British expedition led by Scott and three others also reached the South Pole. Because they also used ponies, motor sledges that did not work, and dogs that no one knew how to drive, they became weak and also discouraged because Amundsen's party had arrived first. Scott and his comrades perished in 1912 on their return trip a mere 18 km south of a supply depot. Scott wrote that "We shall die like gentlemen. These rough notes and our dead bodies must tell the tale" (1).

Less well – known are the particulars of Shackleton's expeditions, all of which failed in their initial objectives; for instance he never reached the South Pole. After the 1908 – 1909 *Nimrod* expedition he abandoned plans to reach the Pole assuming Scott or Amundsen would get there first. Instead he considered undertaking the first crossing of the Antarctic continent. After hearing of Amundsen's success in reaching the Pole, Shackleton began planning his trans – Antarctic journey. From nearly 5000 applicants he selected 56 men. The overall plan was to sail two ships to the continent in October 1914: the *Endurance* from Buenos Aires to the Weddell Sea via South Georgia island, the most southerly outpost of the British Empire; and the *Aurora* from Hobart, Tasmania to the Ross Sea on the other (South Pacific) side of the continent. Shackleton and five men were to march from the Weddell Sea to the Pole and then continue on to meet the six men from the Ross base who were to have prepared supply caches along the route back to Ross. A few days after the outbreak of World War I the *Endurance* sailed from Plymouth, England on 8 August 1914 to begin one of the most epic journeys of human survival in the cold. The *Endurance* departed the Grytviken whaling station on South Georgia on 5 December 1914 and entered the pack ice on 7 December 1914 (Fig. 1). On 18 January 1915 the *Endurance* was frozen solid into the pack ice and carried northward for 10 months in the Weddell Sea until it was crushed and abandoned by the crew on 27 October 1915 when the real survival epic began (1). The 28 men camped on ice floes for five months while they drifted north into "warmer" water as the ice under them melted and cracked. Then they took to their three life-boats: the *James Caird*, the *Stancomb Wills*, and the *Dudley Docker* (named after the three principal donors to the expedition) on 9 April 1916 and sailed north toward Elephant Island. At times the winds reached gale force and the boat crews became exhausted from rowing because of their all – meat diet of dogs, seals, and penguins. There was continuous danger of the boats being crushed by the pack ice. Now their ordeal intensified as constant rain and snow squalls soaked the seasick and dehydrated men whose clothes froze upon them,

while being further tormented by swollen and bloody lips from the salt spray. Frank Wild, Shackelton's second – in – command, thought that at least half of the crew was moderately insane by acting helpless and hopeless. After seven days in the boats, and enduring the last 90 hours with little or no sleep, the three boats landed on Elephant Island at the beginning of the Antarctic winter. Shackleton's landing orders had to be relayed by Wild or Hurley because his own throat and tongue were so swollen that he could only whisper. Upon landing many of the men exhibited signs and symptoms of alcoholic – like aberrations such as walking about aimlessly, rolling around on the stone-covered beach, and one man wielded an axe to kill 10 seals. Many men were actually incapacitated, some with severe frostbite. A blizzard, which raged for five days after landing, ripped the tents to shreds. So, with nonexistent shelter and sodden sleeping bags, the men simply lay on the snow under the boats and collapsed tents while their body heat melted not only the snow but the frozen, reeking guano of the penguin rookery upon which they lay. It was perhaps no coincidence that Shackleton chose 20 April to organize a further expedition to South Georgia with five additional men in the *James Caird*. This 6.8 m open boat would have to cross some 1288 km of open sea in the winter with 129 km/hr winds and the notorious Cape Horn Rollers (18 m waves) with the crew navigating with only a sextant and chronometer under usually brooding skies. During the blizzard some canvas was thawed foot by foot and a cover was sewn together for the two – masted boat. Ballast was 1,500 pounds of small stones plus 500 pounds of boulders, and freeboard was only 66 cm. They stowed six sleeping bags and clothes, 36 gallons of melted ice, 112 pounds of ice, matches and cooking equipment, and some food: 300 sledging rations, 200 food rations, 600 biscuits, 1 case of sugar, and some milk and salt. Shackleton took his double – barreled shotgun and 50 cartridges, two axes, binoculars, candles, sea anchor, fishing line, compass, barometer, and navigation charts. The food supplies were calculated to last four weeks. Wild was left in charge of the crew remaining on Elephant Island. The boat crew wore woolen underwear under cloth trousers, heavy woolen sweaters, woolen socks, mittens, and a hood – like knitted cap. Over these they had Burberry (woolen) overalls and a parka. On the fifth day (28 April) the water – soaked crew had traveled 383 km from Elephant Island through gales and towering swells. On day 8 every inch of soaked wood, canvas, and line of the *Caird* had frozen solid in ice 38 cm thick – and she was sinking. Three bouts of chipping with knife and ax and the discard of two 18 kg frozen sleeping bags restored moderate seaworthiness. On May 2 (day 9) Shackleton (26) wrote that "We held the boat up to the gale during that day, enduring as best we could discomforts that amounted to pain." "The men were soaked to the bone and frostbitten. They were badly chafed by wet clothes that had not been removed for seven months, and afflicted with saltwater boils. Their wet feet and legs were a sickly white color and swollen. Their hands were black – with grime, blubber, burns from the primus (stove) and frostbite. The least movement was excruciating" (1). Shackleton gave his men hot food every four hours during the day and scalding powdered milk every four hours during the night. On May 8 (day 15), after surviving 10 gales and being without fresh water for 48 hours, the crew spotted Cape Demidov on South Georgia 16 km away. But they had to endure another horrendous gale showering the men with rain, snow, sleet, and hail that turned into a full hurricane, which they fought for nine hours. On their fifth attempt to land the *James Caird* ran in on a

swell and touched the beach at King Haakon Bay. A small stream provided fresh water for the parched crew. Later, they had heard that a 500 – ton steamer had foundered with loss of all hands in that same hurricane. After another harrowing sea voyage around and a 36-hr overland journey on South Georgia, Shackleton, Crean, and Worsley arrived at the Stromness Bay whaling station on 20 May 1916. Their bearded faces were blackened with blubber smoke; their matted salt – clotted hair hung to their shoulders, and their filthy clothes were in shreds. The hot baths and clean clothes were their first in two years. Four months later, after three failed attempts, Shackleton finally rescued his 22 remaining crewmembers on Elephant Island in the Yelcho, a Chilean steel tug. With loss of only a few fingers and toes from frostbite and gangrene, all 28 men returned alive on 3 September 1916, nearly two years later. "But in memories we were rich. We had pierced the veneer of outside things. We had suffered, starved, and triumphed, rovelled down yet grasped at glory, grown bigger in the big mass of the whole. We had seen God in his splendours, heard the text that Nature renders. We had reached the naked soul of man" (26).

Shackleton died of a massive heart attack in January 1922 at 47 years of age on South Georgia, where he is buried. His leadership qualities were elusive: "When occasion demanded he would attend personally to the smallest details... Sometimes it would appear to the thoughtless that his care amounted almost to fussiness, and it was only afterwards that we understood the supreme importance of his ceaseless watchfulness. Behind every calculated word and gesture lay the single - minded determination to do what was best for his men. At the core of Shackleton's gift for leadership in crisis was an adamantine conviction that quite ordinary individuals were capable of heroic feats if the circumstances required; the weak and the strong could and must survive together. The mystique that Shackleton acquired as a leader may partly be attributed to the fact that he elicited from his men strength and endurance they had never imagined they possessed; he ennobled them" (1).

Arctic

On 11 May 1986 Jean – Louis Etienne, a French physician, became the first single man to reach the North Pole after hauling (by skiing) his 50 kg sledge about 1100 km in 63 days across sea ice with ambient temperatures of -12°C to -52°C in high winds and blizzards (5). His solitary journey began at Cap Columbia on the northern Arctic coast of Canada on 7 March 1986 when, for the first week, he experienced the colder (-55°C) temperatures. He slept in a nylon tent on a light foam mattress, and wore special light – weight insulated clothing. He was resupplied five times by air with food and gasoline for his stove. Food composition – 10% to 15% protein, 50% to 55% carbohydrate, and 30% to 55% fat – was essentially normal providing about 4000 kcal/day, and he drank melted ice water. He traveled for 5 to 9 hr/day, rested – napped for 1 hr each afternoon, and tried to sleep about 10 hr/night; but sleep quality, moderately good during the first 3 wk, deteriorated progressively thereafter along with body weight due to caloric deficit and dehydration. He usually felt cold, especially at night (5).

Some excerpts from his book (9) indicate the flavor of such an excursion. On the day he departs from Cap Columbia he breaks his signal locator device and had to return for another one; a loss of 2 days. His headlamp short circuits because one of its components froze. He tries to light a candle, but it can't get hot enough to melt a space around the wick because it is frozen so hard. He tries to shave some wax but the

candle shatters. One day the ground–ice under him starts rumbling; perhaps a submarine? The following day he hears ice cracking. He reflects on the dangers of polar bears, and how he has a 44 magnum for protection. One morning everything is frozen inside the tent – even the tent flaps; he sleeps in his clothes, which are wet when he awakens. On another day he is trapped in his tent because of fog. The polar mist destroys visibility; he is surrounded by millions of suspended ice crystals. He spends 2 hours packing, walks a few hundred meters, and then sets up camp again; he is too tired to travel under those conditions. He has only 3.5 liters of stove gas and is worried the resupply plane won't be able to land. At his first resupply point his signal locator is broken again so he must use the emergency Sarsat system so the plane can find him. His worldwide monitoring network call his technical team with his emergency. Finding an appropriately flat landing site was difficult. While waiting for the plane he became progressively colder because of reduced body movement – everything on him freezes. When he climbs into the plane all of the ice on his clothes melts as he changes into dry ones while washing his face and chest. For 2 days he is trapped in his tent because of a blizzard; it is painful to remain recumbent as the snow beneath him melts from body heat and then re-freezes even harder. Another night he experiences intense cramps of the muscles (adductors) inside his thighs, and his index fingers and thumbs are macerated from holding the ski poles making it difficult to light matches or open zippers (9). Another blizzard...

Physiological data on him were collected under controlled laboratory conditions before and after the trip (5): body wt (68 kg) decreased by 6.2%, % body fat (17%) decreased by 9.4%, and maximal O_2 uptake (52 ml•min^{-1}•kg^{-1}) decreased by only 2.2% from 3.56 to 3.48 L•min^{-1}. So superior aerobic capacity is not a requirement for such extended arctic trekking. All post – trip body core and skin temperatures in a thermoneutral environment were not different from pre – trip levels. However, during the laboratory cold – exposure at 1°C, his post – trip body heat debt increased from a pre – trip level of 9.1 to 12.1 kJ•kg^{-1}, Tre decreased (indicating hypothermic acclimatization), and hand Tsk increased indicating increased skin blood flow. Etienne said he could work with bare hands without pain at the end of the journey. Thus his hypothermic – hypometabolic state served to conserve energy already decreased by cold exposure, heavy exercise, and insufficient caloric intake.

Napoleon's retreat from Moscow

The strategy leading up to probably the most infamous retreat of any army, that of Napoleon from Moscow in 1812 – 1813, was one of the grandest military blunders in history. Napoleon declared war on Russia on 22 June at Wilkowiski, Poland located about 75 miles west of the Niemen river. He began his invasion with nine army corps (about 442,000 men) on the northeastern Polish border crossing the Niemen river into Russia in midsummer of 1812 (4). The width of the upper and lower bands in Figure 2 indicates the relative size of his army and its location. On 14 August the Russian army under Kutusov stood and fought at Smolensk (about 724 km from the Niemen) which had been burned to the ground; thus a French pyrrhic victory. Their second major battle at Borodino on 7 September (about 161 km from Moscow) was indecisive. On 14 September Napoleon with only 100,000 men reached Moscow which had been evacuated by Kutusov and set afire by its governor Rostopchin. Unfortunately Napoleon waited for five weeks in the Kremlin for the Tsar to make peace.

On 19 October, after the Russians had attacked his Winkovo camp south of Mo-

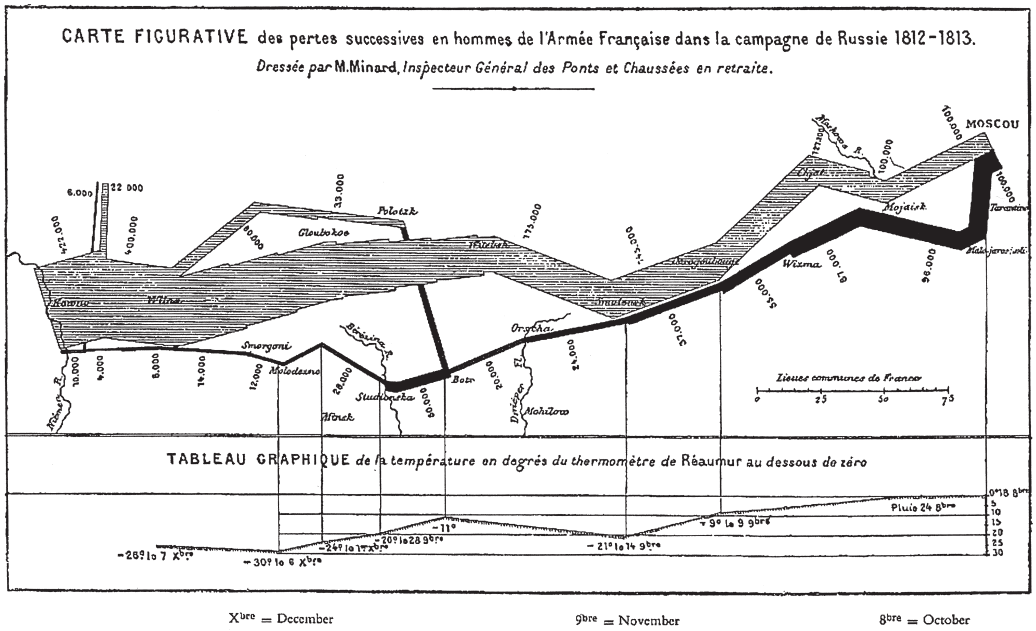

Fig. 2. *Map drawn by C.J. Minard of Napoleon's Russian campaign of 1812 – 1813. From Tufte (ref. 31 with permission).*

scow, he marched southward for Kaluga and the Ukraine with some 110,000 troops and civilians and a baggage train overloaded with the spoils of Moscow (Fig. 2). On 24 October 22,000 of Napoleon's French, Italian, and Croation troops defeated 70,000 Russians at Malojaroslavetz on the road to Kaluga. Once again Kutusov withdrew. Napoleon then decided that it was enough and, on 26 October, ordered his second ever retreat via the devastated Mojaisk – Viazma road to Smolensk »via the desert we ourselves created« to regroup for a second campaign in the spring of 1813 (4). "Between Moscow and Smolensk (...) everything was devastated for more than 300 miles. The villages were ruins. The towns were starving hospitals. The few barns or houses were filled with corpses of men and domestic animals, some half – rotted. You only had to follow the cadaverous stench to be sure you were on your right road" (Albrecht Adam in ref. 4). During this fighting retreat the darker lower band in Figure 2, which also depicts troop strength, is accompanied by time and ambient temperature scales below. In addition to incessant Cossack raids and hypothermia from lack of winter clothing and shelter, troop decimation was accentuated by other factors including wounds, disease, starvation, and desertion that were exacerbated by the cold, which reached -30°C near Molodeczno. One survival incident is noteworthy: "In the wood Seruzier and Klein, heroically defending themselves to the last, are also attacked by Cossack lances, »which I (Seruzier) parried as best I could with my sabre. Then their commander ordered them to fire at me. Six Cossacks fired at a range of fifteen paces, and I was hit by four of their carbines. My horse fell dead, my right leg was caught beneath him. Then these brigands fell on me, gave me 27 lance jabs, tore my clothes off me, seized my decorations, my weapons, my money, and stripped me completely.« Only the extreme cold, by freezing the blood, saves him from bleeding to death: »Though I'd been wounded in the cruelest fashion, the Cossack chief, seeing I'd

got up and judging from the riches I'd been stripped of that I was an officer of note in the French army, was so barbarous as to force me to march, naked, for nine miles in a cold of –27 to –28 degrees, to Hetman Platov's headquarters. It was about 4 p.m.(...) I was in front of an immense bonfire, and the warmth unfroze my wounds. My blood began flowing from all parts of my body«" (4).

The remnants of the Grande Armee, about 10,000 poor souls, reached Kovno on the Neiman in early December after traveling about 1300 km. On 15 December the remaining Headquarters staff returned to Wilkowiski. Twenty – five miles east at Gumbinnen, Prussia (on 18 December) Intendant – General Dumas was drinking coffee when a man in a great brown coat entered the room. He had a long beard, red and gleaming eyes, and a blackened face that appeared to have been burned. "At last I'm here, he said. Why, General Dumas, don't you know me? Why no. Who are you? I'm the rearguard of the Grand Army. I'm Marshal Ney" (4). Meanwhile, Napoleon and Caulaincourt gallop in Paris through the still unfinished Arc de Triomphe and into the courtyard of the Carousel at the Tuileries. On the following morning Napoleon addresses his ministers: "Well gentlemen, fortune has dazzled me. I've let it lead me astray. Instead of following the plan I'd in mind, I went to Moscow. I thought I'd sign peace there. I stayed there too long. I've made a grave mistake, but I'll have the means to repair it" (4).

Because of ethical and humane considerations, it would be inappropriate to ask humans to undergo most of the treatments and treks described above as test subjects. But data and participant comments, logged into diaries and reports while they are participating in such survival situations in cold environments, can add significantly to our knowledge of the physiology and psychology of human acclimatization, the human spirit, and the will to live. It seems that most of us can do more than we thought we could.

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