100 Years Since Scott Reached the Pole: A Century of Learning About the Physiological Demands of Antarctica

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Halsey LG, Stroud MA. 100 Years Since Scott Reached the Pole: A Century of Learning About the Physiological Demands of Antarctica. Physiol Rev 92: 521–536, 2012; doi:10.1152/physrev.00031.2011.—The 1910–1913 Terra Nova Expedition to the Antarctic, led by Captain Robert Falcon Scott, was a venture of science and discovery. It is also a well-known story of heroism and tragedy since his quest to reach the South Pole and conduct research en route, while successful was also fateful. Although Scott and his four companions hauled their sledges to the Pole, they died on their return journey either directly or indirectly from the extreme physiological stresses they experienced. One hundred years on, our understanding of such stresses caused by Antarctic extremes and how the body reacts to severe exercise, malnutrition, hypothermia, high altitude, and sleep deprivation has greatly advanced. On the centenary of Scott’s expedition to the bottom of the Earth, there is still controversy surrounding whether the deaths of those five men could have, or should have, been avoided. This paper reviews present-day knowledge related to the physiology of sustained man-hauling in Antarctica and contrasts this with the comparative ignorance about these issues around the turn of the 20th century. It closes by considering whether, with modern understanding about the effects of such a scenario on the human condition, Scott could have prepared and managed his team differently and so survived the epic 1,600-mile journey. The conclusion is that by carrying rations with a different composition of macromolecules, enabling greater calorific intake at similar overall weight, Scott might have secured the lives of some of the party, and it is also possible that enhanced levels of vitamin C in his rations, albeit difficult to achieve in 1911, could have significantly improved their survival chances. Nevertheless, even with today’s knowledge, a repeat attempt at his expedition would by no means be bound to succeed.

I. LIFE AND DEATH IN THE ANTARCTIC

There is just one continent that supports no permanent inhabitants: Antarctica. Indeed, the terrestrial Antarctic offers little for any large animal species; few vertebrates (sea-birds and seals) live further inland than the coast, and they typically spend much of their lives at sea. There is minimal vegetation or animal matter for food, and with temperatures regularly down to −70°C accompanied by strong katabatic (downslope) winds, the interior of the Antarctic is as inhospitable to human living as are the heights of Everest, and terrestrial travel on the continent is incredibly demanding. Towards the start of the 20th century, in the early days of Antarctic exploration, travel there was accomplished using huskies and cold-weather ponies with varying degrees of success, with much of the food and equipment transported by the explorers themselves, on foot. Long expeditions of this type, with little or no aid from mechanical or animal power, represent a huge physiological challenge for three environmental reasons. First, as a consequence of our African ancestry, we are far more suited physiologically to heat than cold. Second, man-hauling, which is very physically arduous, in combination with the extremely low temperatures, results in levels of energy expenditure so high that the sledging rations which can be pulled (and on some expeditions bolstered by rations stored partway along the route in advance) do not provide sufficient calories to compensate. Third, the most severe area of Antarctica, the polar plateau, is at high altitude (average effective: 2,800 m), resulting in problems of hypoxia in combination with particularly cold ambient conditions.

When the first Antarctic explorers broached its terrain, published knowledge of human physiological responses to this
environment was minimal, while today, although there is still much to learn, we have a far better understanding of its extreme and fascinating effects on the human condition. The hardship of man-hauling in the Antarctic in the early days was undoubtedly exacerbated by the availability of less advanced technologies, in particular in terms of clothing, sledges, and fuel storage. Nonetheless, modern-day unsupported explorers, which include the author Mike Stroud, experience the same gamut of physiological stresses and, somewhat paradoxically, while some of their equipment is superior, that superiority enables them to pull larger loads for longer. Beyond alterations in the macronutrient balance of the rations to enable greater calorific intake at similar overall ration weights and the ingestion of vitamin C-rich foods, an infamous omission to the rations eaten by most early polar explorers, it is therefore questionable whether today’s Antarctic adventurers would manage a man-hauling expedition much differently from Captain Robert Scott (FIG. 1), who, 100 years ago, led a team from Ross Island to the South Pole (FIG. 2) but tragically perished with his men on the way back to the continent’s edge from natural causes induced by acute, chronic physiological stresses.

This paper develops a short essay (45) reviewing present understanding of human physiological responses to the interconnected stressors experienced by Antarctic explorers. Current knowledge on relevant aspects of cold exposure, the energy costs of man-hauling, macro- and micronutrient demands, dehydration, and the effects of sleep deprivation and altitude are reviewed, while flagging up the key areas of scientific ignorance on these topics in Scott’s time. This article then considers the most poignant question: accepting the limitations of the technologies he took on the expedition, had Scott been privy to modern physiological knowledge, could he and his team have returned home alive?

II. POLAR TEMPERATURES

The most overtly hostile aspect of the Antarctic environment is its exceptionally low temperatures which, even during the austral summer when the majority of terrestrial travel is undertaken, are normally below 0°C and can often drop below −40°C. The thermoneutral zone of a naked person is quite high at ~28–31°C, and still above 10°C even when clothed with fairly insulating garments (34). At environmental temperatures below the thermoneutral zone, the body will try to defend core temperature through a combination of physiological and behavioral responses that increase heat production and decrease heat loss (e.g., Ref. 71).

The human body reacts to either cold skin, or a decrease in core body temperature from 37°C down to ~35°C (94), by retaining more heat through an increase in body insulation and generating more heat through shivering (and possibly passive nonshivering mechanisms; Refs. 30, 87, 94). In Scott’s time, the thermoneutral zone had not been quantified, and Scott was unaware of how cold it could become in Antarctica during March (106, entry 12th Mar 1912; “message to the public” Mar 1912, Ref. 108). There was also inadequate understanding of the phenomenon of wind chill (87), which was not empirically assessed until the 1950s by Admiral Byrd during a solo overwintering expedition in Antarctica, with its detrimental effect of increased metabolic rate documented only recently (137). Furthermore, early Antarctic explorers hoped that chronic exposure to the cold would invoke valuable physiological adaptation, although it is now understood that the level of adaptation achieved is not of practical significance for survival. Since the vast majority of human evolution occurred around the equator, humankind is adapted primarily to heat exposure, and physiological adaptations to the cold are not only relatively ineffective (e.g., Ref. 77) but can be counterproductive for man-hauling expeditions in extreme conditions. Shivering, which involves involuntary, rhythmic muscle contractions that generate heat in a similar manner to exercise, can produce up to 4 mets (5 kcal/min) (123) compared with up to ~18 mets (around 22 kcal/min) produced by high-intensity voluntary physical activity. Increasing
physiological insulation, afforded by cold-induced vasocostriction in the skin and superficial muscles, amounts to less than the insulation provided by a standard business suit (94), and the marked reductions in superficial blood flow greatly increase risk of both nonfreezing neurovascular cold injury (4) and frostbite (the growth of ice crystals in and around cells, which at worst can be extremely damaging to large body areas; 106, entry 18th Mar 1912). Even with modern clothing, the cold-induced vasoconstrictor responses therefore remain very problematic (47). While there is some evidence that with repeated cold exposure there are more complicated adjustments to peripheral blood flow with selective peripheral vasodilation (63, 64, 69, 99), these aclimative changes are inadequate to prevent cold injuries and any vasodilation increases rates of body heat loss. Furthermore, the vasoconstrictor responses to cold may also be impaired after multiple days of severe physical exertion (19; see also Ref. 20), and in Scott and his men, it was also likely to have been impaired by their smoking.

In addition to the increased energetic demands of keeping the body warm and the risks of hypothermia or debilitating frostbite, Antarctic temperatures also result in greater fatigue during exercise (92, 123) and a reduced maximal power output (for a review, see Refs. 87, 89), both very detrimental to man-hauling a sledge given the high physical demands. Furthermore, such cold temperatures result in impairment to cognition and psychomotor performance such as reasoning and learning (95), and dexterity (123), although the human body may somewhat acclimatize to the cold in these respects (though see Ref. 73).

Since the first explorations of the Antarctic terrain, it has been evident that during man-hauling expeditions the most effective method of defending from the cold is by undertaking the work required to pull the sledges. This generates considerable heat as a valuable result of inherent muscle inefficiency. For instance, several layers of clothing are required to alleviate shivering in a person who is stationary in an ambient temperature of 5°C while an office suit is sufficient at −18°C during periods of activity (115). Nevertheless, early explorers did recognize that a few relatively thin layers were not really sufficient in very low Antarctic temperatures, even with the hard work of man-hauling (108, p.
109). It is therefore during periods of lower activity that the body is most vulnerable to the cold (1, 106, entry 12th Mar 1912), especially after exhaustive exercise since this increases susceptibility to hypothermia (19). Thus erecting a tent in the Antarctic can be particularly dangerous, and if during such relatively low activity core temperature drops towards $30^\circ C$, hypothalamic control is lost and unconsciousness ensues with the body incapable of escaping cold-induced death unaided. In recent times there have been a number of experiments specifically looking at physiological responses to exercise in cold, wet, and windy conditions. In a wet, windy environment with an ambient temperature of $5^\circ C$, so long as exercise intensity is fairly high, for example, a strong pace of walking, there is no change in core body temperature or rate of energy expenditure compared with thermoneutral conditions (129). Indeed, during periods of man-hauling, sweating and peripheral vasodilation occurs, necessary to dissipate the excess heat produced (60). However, if the work rate is lower, even though this still represents walking at a standard pace (129), core temperature decreases by around $1^\circ C$ while rate of energy expenditure rises (probably primarily due to shivering; Ref. 87), indicating that heat production from the exercise does not offset heat lost to the cold environment. Furthermore, when exposed to cold, individuals with lower body fat levels and who are older are prone to greater heat loss and thus presumably higher rates of shivering and energy expenditure (17). Detrimental effects from exercise-induced carbohydrate depletion can also occur as hypoglycemia impairs control of body temperature (40), limiting the ability to shiver or vasoconstrict the periphery. Thus, as a man-hauling expedition unfolds and the fat levels of the participants decrease, eventually the amount of energy lost to shivering increases while the effectiveness of exercise and shivering at warming the body core becomes progressively less (87). Scott was clearly unaware of this process (106, entry 12th Jan 1912), yet such spiraling deterioration was certainly instrumental in the deaths of him and his men.

**III. ENERGY EXPENDITURE AND ENERGY INTAKE DURING MAN-HAULING**

**A. Metabolic Costs of Sledge Pulling**

Pulling sledges across snow and ice in the Antarctic is so physically demanding (see 106, entry 11th Jan 1912) that overall calorie expenditure far exceeds the calorie costs of coping with the severe cold. In Scott’s time, it was known that greater muscular work during exercise was met by physiological changes, particularly cardiorespiratory (61), resulting in higher energy expenditure and hence larger food requirements. Yet despite early pioneering studies in particular by Zuntz (140), there was little information on how human energy requirements changed with type and intensity of activity. Once a reliable equivalence between oxidation rate and heat loss was observed, it became more straightforward to measure human energy expenditure as rate of oxygen consumption via indirect calorimetry (128). However, in the main, studies measuring energy expenditure in people during activity were only published from soon after Scott’s *Terra Nova* expedition (e.g., Refs. 14, 61), and it was several decades more until an informative amount of data on the costs of human walking on different terrains became available (3, 12, 90). Thus, just after the turn of the century, there was minimal understanding of the power required to sledge pull and how that could change with differing snow conditions and walking gradients.

In fact, not until Mike Stroud measured energy expenditure in man-haulers over several polar expeditions during the 1980s and 1990s was the very high energy costs of polar travel on foot appreciated. During a modern-day, one-way expedition to the South Pole that repeated Scott’s route (“Footsteps of Scott expedition”), an average 25 MJ (6,000 kcal) were expended every 24 h (111, 113), whilst on a foot crossing of Antarctica by Stroud and Sir Ranulph Fiennes in the austral summer of 1992–1993, the two men expended on average 28 MJ/day (nearly 7,000 kcal/day). This included a period of ~10 days while ascending to the plateau averaging 46 MJ/day (nearly 11,000 kcal/day) (112). These incredibly high values are best appreciated compared with the estimate of 25 MJ/day (6,000 kcal/day) in a male distance runner covering ~100 km/day for 1,000 km (29), 30 MJ/day (over 7,000 kcal/day) in two elite male cyclists averaging around 330 km/day for 10 days (39), and 27 MJ/day (6,500 kcal/day) in elite cyclists working in a team to cover in total nearly 4,900 km in 6 days (Race across America, RAAM; Ref. 54). Indeed, sledge-pulling up to the polar plateau requires energy expenditures of a considerably greater daily rate than even exhibited by Tour de France competitors (134) and professional cross-country skiers during training (107). This is presumably possible because, despite the lower fitness levels of man-haulers compared with those of modern-day elite athletes, sledge-pulling on Antarctic treks is typically undertaken during the majority of waking hours (typically 10–12 h), whereas the Tour de France typically demands on average 4–5 h of cycling per day while professional cross-country skiers train for 2.5–4 h/day (107). Furthermore, man-hauling invokes the use of many muscles in the body including those in the torso and arms. **FIGURE 3** summarizes comparisons in daily energy expenditure and distances achieved between modern Antarctic expeditions and elite athletes during endurance racing and training. Such rates of energy expenditure during man-hauling explorations require daily food rations to satisfy them which are greater than can be pulled on a sledge for long journeys and man-haulers traveling for many days are therefore exposing themselves to an inevitable starvation diet.
B. Exercise Starvation

There are two key problems that result from large reductions in body mass in the Antarctic. First, there is an increased chance of hypothermia since reduced fat stores increase heat loss, absolute heat content of the body is reduced, and muscle protein stores decrease heat production from muscular power and shivering. Second, ability to pull a sledge decreases (4), reducing daily mileage and hence elongating exposure to the environment that is causing the weight loss.

Once fat and protein reserves are run down, the body is forced to consume vital tissues (even in the extremes of modern-day body building, elite contestants have 3–6% body fat levels; Ref. 105). Physiological functions begin to deteriorate, and cardiovascular capacity markedly decreases. Mass loss in extremis results in glucose stores becoming exhausted causing hypoglycemia, and although for a while the body adapts to using other substrates in the central nervous system such as ketones and lactate (118), the amounts of these are very limited and soon the body becomes too weak to function properly. Ultimately, metabolic rate will decrease to a point that insufficient heat is produced and too much is lost to prevent deep hypothermia and death from cardiac arrest; in Scott’s case, cardiac arrest may well have been hastened by severe dehydration.

Scott appreciated, at least through experience of hunger himself (96, p. 63, 73) and by his men during previous man-hauling trips, that sledging rations did not always negate body mass loss (e.g., 106, entry 21st November 1911). However, he was wholly unaware of how insufficient the rations he took to the South Pole were relative to energy expenditure, in particular when man-hauling. A previous expedition by Ernest Shackleton, which got to within just over 180 km (112 miles) from the south pole in 1908, had (incorrectly) determined that required rations per day amounted to 34 ounces (964 g) (76), similar to the mean weight of rations used by Scott (100). Unfortunately for Scott, the evidence from a 35-day trip by three of his men who man-hauled to Cape Crozier to collect penguin eggs during the same expedition to the Antarctic and just months before Scott’s assault on the Pole suggested this size of ration was indeed more or less sufficient. Each of the three men: Edward Wilson, Henry Bowers, and Apsley Cherry-Garrard, lost between just a half and two kilograms of mass (35). Key aspects of this journey were similar to the subsequent polar journey, most notably pulling the sledges on often sticky ground (see 108, p. 35–36 and 140–141 for an explanation of this phenomenon) and with a weight to pull per man starting at more than 100 kg. Thus perhaps the most likely reason as to why the men lost little body weight on the earlier journey was because compared with the polar journey they spent a smaller proportion of time active. They progressed on average 6.5 km (4 miles) per day on the earlier journey (though with some relaying of sledges, which increases distances walked) versus 18 km (11 miles) per day on the polar journey (though man-hauling for only 70% of this). It was also likely that early explorers tended to underestimate levels of muscle and fat loss from reductions in weight over an expedition since in Scott’s era it was not appreciated that the body retains fluids in response to malnutrition (hunger edema; Refs. 82, 116).

Despite Scott’s “standard” rations (consumed while off the polar plateau) providing around 17.6 MJ (4,200 kcal) per day (FIG. 4), and “summit” rations (for plateau use) providing around 19 MJ (4,500–4,600 kcal) per day (35, 96), his daily calorie deficits probably peaked as high as 27 MJ (6,500 kcal; see also Ref. 106, entry 13th December 1911). Previous estimates have suggested that those deficits may well have averaged 6–12 MJ (1,500–3,000 kcal) (94, 96, 111), or even somewhat more given up-to-date calculations of the net energy gained from food digestion (68). With the assumption that Scott had lost around 40% of his body weight at time of death, about the maximum amount possible for a person who begins with a relatively low body mass index (28), he would have lost around 1.3 kg of body mass on average each week, which represents a mean daily
calorie deficit of close to 6.3 MJ (1,500 kcal) assuming an average protein ratio of \(~0.3\) for endogenous energy metabolized (28). This value is at the lower end of previous estimates perhaps because the men periodically ate pony meat to supplement their rations once these transport animals had been slaughtered on the first part of the outward journey. The inevitable weight loss is documented by Scott’s team (e.g., Ref. 106, entry 28th January 1912), and towards his final days of man-hauling, fat reserves and blood glucose levels would have been close to zero.

Since Scott did not appreciate the scale of his likely energy-induced calorie deficit, in contrast to modern man-haulers (118), he did not make an obvious attempt to increase body mass before the start of his assault on the South Pole. Nevertheless, even in his time it was understood that there is an inverse association between initial adiposity and the contribution of protein as fuel during a period of starvation (127), although quantitative assessments of this effect were only made recently. It is now known from the Minnesota experiment of semi-starvation that the fraction of fat-free mass lost at the point that fat stores are fully depleted is not influenced by percentage body fat at the start of a period of starvation (28), although such data are not available for man-haulers. This partitioning of protein and fat reserves, such that both reach complete depletion simultaneously, is likely to ensure maximum length of survival. However, there is variation between individuals in the fraction of body protein that can function as the protein energy reserve, and this probably affects the percentage of weight that can be lost during starvation and the proportion of tissue types lost (28).

Since the ground-breaking work of Max Rubner (102) in the 19th century on respiration calorimetry, there has been direct evidence that larger organisms tend to have a higher resting rate of energy expenditure, and this evidence had grown considerably by 1910 (see Ref. 18 for a history of early metabolism studies). The presence of this relationship in humans would have been intuitively clear to Scott (see also Refs. 21, 96, p. 73) and has been confirmed empirically many times (e.g., Ref. 50). Edgar Evans was the first man to die during Scott’s fateful journey to the South Pole. He was also the heaviest and is therefore likely to have suffered the greatest calorie deficit and so utilized his endogenous body stores at a quicker rate (e.g., Ref. 106, entry 28th January 1912). Similarly, Fiennes, who is considerably heavier than Stroud, experienced a greater drop in body mass during their 96-day expedition across Antarctica (24.6 vs. 21.8 kg; Ref. 118), and the larger men on a one-way expedition to the South Pole also experienced greater decreases in weight (111). The same pattern was found in two men pulling sledges on skis across Greenland (38). However, there are also certain energetic advantages for larger people in man-hauling situations. Evans and Fiennes would likely have benefited from larger initial endogenous body stores compared with their respective compatriots, lower mass-specific resting metabolic rates, and greater stride length hence lower stride frequency (41, 110). Thus it is unclear whether fasting endurance, i.e., the time until energy stores are exhausted (50), will tend to be greater in larger or smaller man-haulers. There is evidence, however, that while pulling a sledge particularly hard (e.g., uphill towards the polar plateau), smaller men expend energy faster, which may have a detrimental effect on the deterioration of the muscles, which are clearly important for sustained sledge pulling. Stroud lost considerably more muscle mass than did Fiennes during their trans-Antarctica expedition (6.5 vs. 4.3 kg) (117, 118), and this is perhaps due to the fact that Stroud depleted his available energy stores at a faster rate (total body mass loss during expedition: 26 vs. 29%) and so experienced increased muscle catabolism sooner.

C. Proportions of Macronutrients

By 1905, the proportions of protein, fat, and carbohydrate typically metabolized by people were known (5), providing a useful basis for assessing the approximate ratios of these macronutrients needed for a standard healthy diet. However, man-hauling sledges in extremely low ambient temperatures is clearly not typical, and in Scott’s time there was little information on the relative merits of the different sledging diets employed on earlier expeditions, although scientific opinion of the day suggested particular inclusion of fatty foods (106, entry 27th May 1911). Scott attempted to garner some evidence about the best ratios of macronutrients for sledging from the aforementioned journey to collect penguin eggs at Cape Crozier (106, entry 19th June 1911) with Wilson, Bowers, and Cherry-Garrard purpose-
fully eating different proportions of available foods, at least during the first part of the journey. They reported that too much fat or carbohydrate made the food unpalatable. However, the energy content of macronutrients had been measured by this time (47a), and Scott knew that the energy density of fat is particularly high, hence his rations had a far greater fat content than any previous polar ration (FIG. 3) (35). His “summit rations” for the polar plateau consisted of biscuit, pemmican, butter, sugar, cocoa, and tea, which provided \( \frac{1}{110} \) 210 g of fat (24% of the ration), 257 g of protein (29%), and 417 g of carbohydrate (47%) per day (100). The proportions of macronutrients in his standard rations were similar (111) (FIG. 5).

Nonetheless, not only did the rations eaten by the first man-haulers in the Antarctic typically provide inadequate energy, but they probably still contained too little fat, and too much protein, to be optimal (see also 106, entry 26th February 1912). More recent man-hauling expeditions in the

Antarctic have carried rations averaging 21.3 MJ/day (\( \sim 5,000 \) kcal/day) (112), consisting of 57% fat which provides \( 39.7 \) kJ/g (9.5 kcal/g) and only 8% protein which provides \( 18.4 \) kJ/g (4.4 kcal/g) (FIG. 6). The main consequence of these more modern polar rations is that due to the high energy density of fat, they have a higher energy density than those rations used by Scott, which means that although they weigh about the same as the earlier rations, they contain on average \( \sim 2,900 \) kJ (700 kcal) more energy per day.

This protein intake of these more modern rations may sound surprisingly low in the context of wishing to maintain muscle mass and strength, but there is little evidence that high levels of exercise require increased protein intakes, and the 8% protein content, amounting to \( \sim 80 \) g/day, easily exceeds the amount required to maintain nitrogen balance. Similar ratios of macronutrients were also consumed by Alex Hibbert and George Bullard in 2008 during the longest unsupported polar journey in history (a crossing of the Greenland icecap, Ref. 51).

Scott probably believed that the high levels of muscular exercise during man-hauling need support from a particularly high intake of protein, since the first studies of protein requirements postulated that muscles were broken down to some degree during contractions as an energy supply (79). Even today the dietary protein needs of very prolonged activity are poorly understood. For example, while Stroud (112) notes that various authors have recommended intakes of between 1.3 and 1.6 g/kg during periods of intensive exercise (e.g., Ref. 121), this may not be necessary in fully trained individuals (83). Furthermore, it is interesting to note that for some populations of humans “natural” levels of protein digestion are high (e.g., Refs. 9, 75) and up to 50% of total energy intake (24). However, most studies into protein needs are based on scenarios of energy balance as

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FIGURE 5. Daily energy intake provided by rations on Scott’s expedition to the South Pole (“standard” rations; “summit” rations) and by rations for the crossing of Antarctica by Fiennes and Stroud (F/S). Light gray represents the amount of energy provided by carbohydrate, mid gray represents energy provided by fat, and dark gray represents energy provided by protein.

FIGURE 6. Representation of the daily ration typically eaten by Alex Hibbert during an 8-day Greenland speed crossing expedition in 2011. The 2 kg ration provided 36,000 MJ (8,600 kcal) of energy, as \( \sim 63\% \) carbohydrate, 26% fat, and 11% protein. (Photograph adapted with permission from one provided by Alex Hibbert, http://www.alexhibbert.com.)
opposed to the progressive use of protein stores for energy, and in situations of chronic exercise coupled with a diet deficient in calories, standard protein intakes may be inadequate (36). Also, thermogenesis values for protein are as high as 20–30%, compared with 0–3% for fat and 5–10% for carbohydrate (120), so the extra heat created by assimilating protein may be advantageous during cold days and particularly during cold nights, although disadvantageous in that it represents a raising of metabolic rate. Even less clear is whether being on the plateau, which is at altitude, causes an increase in the proportion of endogenous energy obtained from muscles (57). This is perhaps at least in part to meet an increased requirement by the body for the amino acid glycine (104) because of its involvement in hemoglobin production. Given all this uncertainty, it is a valuable fact that Stroud and Fienness, who experienced very negative energy balances, maintained normal plasma albumin levels throughout their journey, suggesting that protein synthesis remained adequate (117). In reality, it is the presence of sufficient carbohydrate that tends to protect protein stores from the demands for gluconeogenesis during exercise-induced hypoglycemia (65, 109). Furthermore, protein consumed at high levels (above ~2.0–2.5 g/kg body mass per day, i.e., above ~150 g per day for a typical man-hauler) may have unwanted effects on health due to the toxicity of hyperammonemia and hyperaminoacidemia (11, 24), especially as periods of consistently heavy exercise increase levels of free amino acids due to enhanced muscle breakdown.

It might also be thought that the more modern Antarctic rations described above are relatively low in carbohydrate, since there is some evidence that diets containing ~70% energy as carbohydrate can enhance the endurance of some marathon runners (125). Indeed, present-day man-haulers when undertaking relatively short expeditions and traveling at a higher average speed often choose rations that are mostly carbohydrate (FIG. 6). However, the plodding work of man-hauling, conducted at a low average energy intensity, particularly the case during long-distance expeditions, is well suited to fat, a substance that can only be metabolized aerobically, as opposed to carbohydrate utilization. This is because unlike marathon running, man-hauling is less affected by the body’s limitations in sourcing oxygen. Furthermore, high levels of fat ingestion probably increase the time it is possible to sustain intense man-hauling, since even with the lower aerobic work rates, whole body glycogen stores will be run down after 2–3 h of 8–10 h work days regardless of the amount ingested (112), and so beyond this time muscles have to utilize fat as the primary energy substrate anyway. This is because the maximum rate at which exogenous carbohydrate can be oxidized is ~1 MJ/h (240 kcal/h) (56) while man-hauling activities may require up to four times that rate of energy provision (112). Indeed, both Stroud and Fienness experienced periods of hypoglycemia towards the end of their 96-day trip despite the fact that the likelihood of this happening was probably reduced by the high-fat diets they ate both prior to and during their expedition, which probably allowed some adaptation through optimizing mitochondrial fat oxidation (48, 62, 85, but see also Ref. 49).

Nevertheless, in spite of all the new information available, modern explorers remain uncertain about the optimal ratio of dietary substrates for activity of extreme length in Antarctica (112). While high-fat, high-carbohydrate diets are likely best, it is possible that at least some people are incapable of absorbing a high-fat diet well (4, 111), which would reduce the effective calorie content of such rations. Furthermore, the excessive muscle loss and hypoglycemia experienced in particular by Stroud while crossing Antarctica may indicate that modern-day rations have tended to contain a suboptimal proportion of carbohydrates, possibly in part because shivering is largely fuelled by them.

IV. WATER

There was no appreciation in Scott’s time of the effects that even mild decreases in body water can have, yet rates of water loss are typically high during periods of man-hauling such that even on modern expeditions, short-term dehydration is likely, particularly since cold exposure attenuates thirst (38). The intensity of pulling a sledge triggers sweat production on all but the coldest days and also of course elicits high breathing rates (106, entry 17th December 1911) which, coupled with the dry air of the cold Antarctic environment and the phenomenon of cold diuresis (66), exacerbates water loss (25). This is particularly the case on the polar plateau where altitude leads to even higher respiratory rates and increased diuresis (114, 119). Dehydration causes depletion of circulating blood volume (27) and general deterioration in thermoregulatory efficiency during exercise (80). A net of around 5 liters of body fluid can be lost per day and results in noticeable reductions both in physical performance (80) and cognitive functions such as concentration and judgement (42), affects sleep, and increases the chances of peripheral cold injury and mountain sickness at altitude (7). Chronic dehydration on Antarctica rarely develops unless the fuel supplies necessary to melt ice run low, but this problem did confront Scott’s party (108, p. 188) who, on the return journey from the Pole, repeatedly discovered cans of stored oil close to empty due to fuel seepage (35, 96, p. 175). Almost certainly, at least on the return journey, Scott’s party suffered not only from chronic dehydration but also increased energetic costs to defend against hypothermia due to the consumption of ice.

V. VITAMIN C

There was no concept of micronutrients such as vitamins at the turn of the century, and thus no understanding that a chronic lack of vitamins could manifest in diseases such as
rickets or pellagra (vitamins D and B₃, respectively). However, unknowingly, these vitamins were generally present in the necessarily limited diets of sailors (8) and explorers. More problematic was the risk of scurvy. Since James Lind’s Treatise on Scurvy published in 1753, there was a fairly rapid and general acceptance that acidic fruits such as lemons and limes were a valuable addition to ship stores. Lemon juice was consumed on board James Ross’ south Polar expedition 1839–1843. By the turn of the 20th century, ideas about diets to stave off scurvy had broadened, with links made between the occurrence of symptoms including sore gums, bruised legs, suppurating wounds, and loss of teeth, with a dietary deficiency of fruit and vegetables (96, p. 59). It was also believed that fresh meat was prophylactic against scurvy (108) and known that people indigenous to the Arctic are almost no plants yet avoided the disease. Nevertheless, in Scott’s time, the consumption of citrus juices had fallen into disrepute (100), and for Polar explorers on a diet of restricted variety, there was a distinct lack of clarity about the best selection of Antarctic-suitable foods to include in rations (135). Clouded understanding was further confused by a number of hypotheses proposed by scientists (e.g., Refs. 4, 136) as to the cause of scurvy, including the possibility that some foods were scorbaticic (6, 67, 106, entry 18th August 1911), and not until work on guinea pigs by Chick and Hume (22) was it widely conceded that lime juice supplied to the navy at that time had virtually no antiscorbutic value. A wide range of vegetables, jams, and bottled fruits were available to Scott’s men, along with freshly killed seal meat, while on the base at Cape Evans (72) prior to their assault on the Pole. We now know these foods probably provided at least 20 mg of vitamin C per day, sufficient to prevent scurvy (108). This diet gave Scott hope, sometimes even confidence, that scurvy would be avoided during the Southern journey (106, entry 26th May 1911). Furthermore, despite eating only preserved foods (e.g., Ref. 106, entry 6th August 1911), since fruit and vegetables were not suitable for Antarctic sledging due to their bulk and likely bacterial contamination following defrosting on warmer days, scurvy had apparently been avoided during Shackleton’s aforementioned expedition that had got close to the pole (76) and also during the aforementioned trip by the Crozier party. However, unknowst to Scott, it was likely only the pony meat supplementing his sledging rations that provided a small supply of vitamin C (a few milligrams per person per day eaten) (100), especially as with rationing of cooking fuel the polar party ate at least some of this meat semi-raw (21) and thus did not cause so much decomposition of the vitamins or cause them to leach into the cooking water (2, 101).

Modern knowledge of the function of vitamin C is extensive. Ascorbate is an ion of vitamin C necessary for essential metabolic reactions, most relevantly including collagen synthesis. Thus vitamin C is vital for the growth and repair of body tissues including generating skin, scar tissue, and tendons. Most organisms synthesize vitamin C from glucose but, apart from a few exceptions such as bats and guinea pigs, most mammals including humans are reliant on gaining vitamin C by ingesting it. Humans require ~10 mg/day to avoid scurvy (100), and only since the 1930s has vitamin C been synthesized for consumption in pills or artificial supplementation of foodstuffs.

Whether Scott or any of his four men who reached the Pole actually suffered from scurvy is unclear. Wilson, who was a member of the polar party and also the expedition’s observant physician, did not suggest in his diaries that he thought scurvy was present, although he was evidently prepared to report it when diagnosed based on his diaries during a previous Antarctic expedition (108). However, Evans did show signs of poor wound repair even before the team had left the polar plateau (106, enried 23rd, 24th, 30th January 1912). His nose was blistered and starting to rot, and at one point he dislodged two finger nails. A hand wound suffered during an accident many weeks before was also suppurating. Wilson may have attributed such limited recovery from injury to the low temperatures, which are known to slow wound repair probably due to the peripheral vasoconstriction of blood vessels. Nonetheless, Evans was perhaps the member of the five-man party most likely to suffer scurvy since he was a fussy eater adverse to eating raw meats (35) and at the point of his death, he had probably ingested little vitamin C for months. The longest the body can store ascorbic acid is ~12 wk (74), the time that scurvy becomes manifest on a diet devoid of vitamin C (52) and about the time into the journey that Evans’ wounds became more obvious, though serious symptoms are not expected for another couple of weeks (108). In contrast, today’s long-distance Antarctic adventurers never suffer scurvy as they consume fortified freeze-dried meat, often with vegetables (Fig. 6) and multivitamin tablets (111).

### VI. SLEEP

The duration and quality of sleep experienced by Antarctic travellers is affected by their comfort during rest periods, which in turn is affected by temperature, the dryness of their clothes and sleeping bags, and satiation (93). Sleep is also disrupted by frequent awakening at night, typically to a feeling of air hunger, an unpleasant situation experienced by Fienes close to the South Pole (35). While waking to air hunger was medically recognized in the 19th century and named Cheyne-Stokes respiration (oscillations in ventilation including periodic apnea), its occurrence in man-haulers is now thought to usually be due to different reasons than those in seriously ill patients. Man-haulers typically experience air hunger because of a build-up of carbon dioxide when faces are turned into sleeping bags for warmth, and this is exacerbated at altitude on the polar plateau by the tachypneic response to hypoxia (106, entry 3rd February 1912).
A. Physiological and Psychological Effects of Sleep Deprivation

A physiological understanding of the value of sleep to the body, and the deleterious effects of sleep deprivation, were rudimentary in Scott’s time, although it was known that a lack resulted in poorer cognitive and physical performance (91, 97) and lassitude (4, 106, entry 2nd August 1911). The stages of sleep were not described until 1937 (70), and rapid-eye-movement (REM) sleep not for another 20 years (26). Since then, a huge amount of research has been conducted on people and relevant mammalian models to describe sleep and explain the biological value of each stage along with problems occurring with deprivation, and it has become clear that a lack, particularly chronic, impairs both physiological and psychological function (31, 98). Van Dongen et al. (126) reported clear cognitive performance deficits in people exposed to just moderate sleep deprivation (6 h/day) for 2 weeks, while Tharion et al. (122) measured a decrease in the marksmanship of soldiers. Furthermore, for man-haulers already on a starvation diet, insomnia could represent a crucial energetic expense. Sleep deprivation causes an increase in basal metabolic rate, perhaps due to increased peripheral vasoconstriction reducing insulation (103), and periods of wakefulness consume more energy than periods of sleep due to increased physiological arousal (13). Furthermore, rats chronically deprived of sleep not only exhibit increased basal metabolism (59) resulting in weight loss but also reduced rates of healing (43) and compromised immunity (33, 139). The increased basal metabolic rate associated with sleep deprivation in humans may therefore be a response to infectious processes (32). Scott’s party suffered from chronic partial sleep deprivation, at least because they often slept purposefully for only a few hours to increase time man-hauling (e.g., Ref. 106, 15th February 1912); perhaps Evans would have experienced less extensive deterioration of his hand wound and emotional state (106, entry 30th January 1912) had he gained more sleep.

VII. THE POLAR PLATEAU

The polar plateau, which includes the South Pole, has a diameter of ~1,000 km and is at high altitude with the highest point 4,093 m above sea level. For this reason, the temperatures there are the lowest in Antarctica (averaging around ~25°C in summer) with the harshness of the environment epitomized by the complete absence of vertebrate species. Thus, as they approach the South Pole, decreased oxygen availability alongside lower temperatures and higher winds exacerbate the problems for polar travellers and trigger new problems such as mild neuropsychological impairment (15) and altitude sickness. These sometimes subtle but potentially key phenomena were not appreciated in Scott’s time for although deleterious effects of altitude on cognitive function were known about by the end of the 18th century (55), it was not until the 1960s that patterns of neurological impairment at altitude were documented, nor was it realized that there is deterioration in visual acuity (81).

A. Altitude Sickness

Although the average altitude of the polar plateau is only 2,300 m, in terms of oxygen partial pressures the average effective altitude is ~2,800 m. There are two proposed explanations for this: 1) the extreme cold reduces the height of the troposphere, increasing the rate at which atmospheric pressure decreases with altitude (130); and 2) the wind circulating around the continent creates a vortex lowering the pressure (108) (FIG. 7). The partial pressure of inspired oxygen at the edge of the Antarctic is only slightly less than 1 atmosphere (760 mmHg), but on the plateau, it averages ~0.7 atmospheres (~510 mmHg) (130), with oxygen availability reduced by 30%. This initiates both short- and long-term responses that enhance oxygen availability (37). Rapid accommodation through increased ventilation raises oxygen delivery and increases the affinity of hemoglobin for oxygen via respiratory alkalosis, although the latter is offset by renal elimination of excess base as bicarbonate, resulting in diuresis. A gradual acclimatization to altitude, through hypoxia-sensitive gene and protein expression, improves cellular respiration efficiency, and over tens of days, there is an increase in hemoglobin concentration (polycythemia) as a result of a greater production of erythrocytes in combination with a reduction in volume of blood plasma by enhanced excretion of water (and salt) (119). The time taken for full acclimatization to the plateau is affected by a range of factors including rate of ascent and altitude reached and varies considerably between individuals, although the bulk of acclimatization will have been achieved within a week.

Around the end of the 19th century, to start documenting the effects of altitude and acclimatization to altitude (16),

![FIGURE 7. Effects of altitude on the polar plateau on barometric pressure and inspired partial pressures of oxygen. The circles represent the mean and maximum altitude of the polar plateau, while the square represents its mean effective altitude.](http://physrev.physiology.org/)
Paul Bert (10) and others undertook laboratory experiments (44) and field experiments in places such as Moroco-cha and Monte Rosa (140). For example, Bert and Nathan Zuntz demonstrated in animals that it was a reduction in partial pressure of oxygen that typically caused illness or even death at altitude and that high-altitude acclimatization is associated with polycythemia (131). Thus, by the time the polar plateau was discovered during the 1901–1904 Discovery expedition to the Antarctic, it was known that as polar explorers ventured closer to the South Pole, lower oxygen levels could result in deleterious effects. However, the majority of understanding about human physiology at altitude has been gained only in the past half-century, starting with the “Silver Hut” expedition in 1960 on Mount Everest (131), and importantly, some of the more severe effects that result from pulmonary edema were not recognized until well after Scott’s time (53), even though the presence of edema was documented long before (132). Thus Scott did not know that along with a range of relatively minor negative effects his team could in fact suffer seriously debilitating problems on the polar plateau due to its altitude.

The Amundsen-Scott research station was built at the Pole in 1956 at an altitude of 2,771 m, with an effective altitude of 3,350 m. The medical clinic at the station typically records many cases of altitude sickness every year (http://www.antarcticconnection.com/antarctic/news/2006/110706mayo.shtml), with ~1 in 50 people suffering chronic mountain sickness severely enough to need evacuation to sea level (35). Chronic mountain sickness, sometimes known as Monge’s disease (84), has outward symptoms including headaches, tinnitus and, perhaps most pertinently for man-haulers, fatigue, breathlessness, and sleeplessness, with these symptoms exacerbated by dehydration since it causes similar problems. In extreme cases, residents at the station experience cerebral edema or pulmonary edema, although the majority of modern visitors to the Amundsen-Scott station fly there from the edge of Antarctica at sea level, and so experience a step change in oxygen availability (130). In contrast, man-haulers venturing onto the polar plateau take many days to climb to it; for example, Scott spent around 12 days ascending to the plateau via the Beardmore Glacier, to an elevation of 2,700 m (108). This represents a slow rate of ascent and so on reaching the plateau he would have enjoyed valuable physiological acclimatization. Furthermore, as altitude increases up to 3,500 m, the oxygen content of blood falls slowly because the slope of the sigmoid-shaped oxygen dissociation curve is shallow up to arterial concentrations associated with this height (0.08 atmospheres; 60 mmHg). This is perhaps reflected by the fact that over 100 million people permanently live between 3,000 and 5,000 m in the Andes where they often undertake labor-intensive work (94).

Nevertheless, due to the great exertion required to man-haul, the effects of altitude are intensified. Evidence of altitude sickness is present not only in the diaries of Scott and his party during their more than 50-day stay on the plateau, but also from those of Roald Amundsen, whose team noted fatigue from the low oxygen levels and had difficulty sleeping while on the polar plateau to and from the South Pole (35, 96); Ernest Shackleton, whose men reported severe headaches and nosebleeds (see also 76); and more recently from Fiennes and Stroud (114).

B. Weight Loss at Altitude

In contrast to today, in 1911 there was no information to suggest that altitude might further augment rates of body weight loss from man-hauling, a phenomenon which could clearly be dangerous to Antarctic explorers even if it might possibly represent a beneficial adaptation to help reduce oxygen requirements (Denny Levett, personal communication). However, although reductions in body mass at altitude are now well documented, the associated mechanisms remain unclear. While mountaineers typically exhibit a reduced appetite (124) and quicker perception of satiety (133) (Scott reported on the plateau that the rations “continue to amply satisfy”; 106, entry 7th January 1912) resulting in a lower calorie intake, they can sometimes also exhibit increased levels of activity and be exposed to lower temperatures and stronger winds, resulting in a higher energy expenditure. Furthermore, hypobaric hypoxia possibly also results in increased energy expenditure through an increase in basal metabolism (86) during the first days at high altitude, although this then decreases, plateauing at or slightly above normal levels (78, 86). Exposure to the cold and altitude together may increase metabolic rate due to a reduction in peripheral vasoconstriction (23). Another possible reason for an elevation in metabolic rate at altitude could be due to thyroid upregulation in response to cold (86), increased respiratory effort, and/or increased sympathetic drive (78), and it is not even clear as to whether this effect is directly due to low oxygen levels or effects of cold (46). Explorers at altitude may also experience reduced gastrointestinal function from hypoxia that results in delayed gastric emptying and decreased intestinal absorption, although there is little empirical evidence for this below very high altitudes (57). While it might seem unlikely that a loss of appetite on the polar plateau affected Scott’s party since their rations were typically grossly insufficient to supply their daily energy expenditure, this possibility cannot be ruled out as it is unknown whether the onset of satiation at altitude is affected by rates of energy expenditure. Scott and Wilson were unable to finish their special Christmas Day meal while on the plateau, despite expending the energy to average 15 miles a day on an upward gradient (35; see also Ref. 106, entry 13th December 1911), although another explanation for their suppressed appetite could be a response to the very high protein content of their rations.
VIII. COULD SCOTT HAVE SURVIVED?

The major factor that continues to make long man-hauling expeditions in Antarctica extremely physiologically demanding is the inevitable starvation diet. The metabolic requirements of sledging at very low temperatures do not usually represent major physiological risks in themselves (38) but unavoidably become highly detrimental over time since they demand energy expenditures that cannot be fuelled by the food rations it is possible to haul, even if supplemented by depot stores. Other factors such as high altitude and sleep deprivation then have additional damaging effects once loss of body mass has weakened physiological integrity (e.g., Ref. 138).

![Figure 8](http://physrev.physiology.org/)

**Figure 8.** The energetics associated with Scott’s expedition to the South Pole. The full lines represent estimated energy expended per man (black) and estimated energy consumed from rations supplemented with pony meat (gray). The area between these lines represents the energy (calorie) deficit. The stippled line indicates the estimated change in body mass of the men (given a mean starting mass of nearly 77 kg; Ref. 100) as a consequence of this deficit. The crosses denote the time into the trip that the deaths of the party occurred. Calorie intake during the last six or so weeks of the lives of the final party members is difficult to estimate due to more limited documentation, and while greater rations per man became available as group members died, fuel supplies available to heat those rations gradually diminished (108). [Adapted from Piantadosi (94), by permission of Oxford University Press.]

### Table 1

<table>
<thead>
<tr>
<th>Factor</th>
<th>Major Potential Effects</th>
<th>Early Explorers</th>
<th>Modern-Day Adventurers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>Increased metabolic rate; thus increased weight loss</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>Frost bite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emaciation</td>
<td>Increased sensitivity to cold-induced effects</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td></td>
<td>Decreased physical strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vitamin deficiency</td>
<td>Reduced tissue regeneration</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Higher risk of exercise-induced injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suppurating wounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dehydration†</td>
<td>Decreased physical strength and stamina</td>
<td>**</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Decreased general cognitive performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep deprivation</td>
<td>Increased energy expenditure</td>
<td>**</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Compromised immune system and reduced tissue repair</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poorer concentration, vigilance and decision making</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>Headaches</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Tiredness</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increased metabolic rate; thus increased weight loss</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Asterisks denote degree of debilitation; five = highest.†Note that dehydration was probably more debilitating for Scott and his men during the latter part of their journey than was typically the case for early Antarctic explorers during their journeys in general.
Scott’s expedition to the South Pole lasted more than 140 days, during which time he and his polar party covered 2,500 km (1,600 miles), including over 100 days pulling their own sledges. Over the outward journey to the Pole and the subsequent return journey back across the polar plateau and Ross ice shelf, each man would have expended close to 1,000,000 kcal (FIG. 8; see also Ref. 88). Therefore, it is not surprising that Scott and his last two colleagues, Wilson and Bowers, succumbed to the degenerating cycle of emaciation leading to reduced strength to man-haul and reduced heat production and insulation to defend body temperature, thus increasing rates of emaciation and so on until hypothermia and malnutrition overcame them. This cycle would have been accelerated during the final weeks both due to dehydration because of reduced resources to melt water and due to the unusually cold temperatures that they suffered during February and March; these would have served to further decrease pulling power, and increase the energy costs of sledge-pulling due to the friction of snow when below around −30°C (108).

Clearly, the physiological effects of heavy, chronic exercise while on limited rations in the low temperatures of Antarctica are now much better understood than in Scott’s time (see TABLE 1 for a summary) but even so, technology aside, there is a perhaps surprisingly limited amount that can be done differently. The single key difference in the physiological management by today’s long-distance Antarctic traveller centers on the rations consumed. Around 700 kcal more per 24 h are ingested while the macronutrient proportions now favor fat and carbohydrate over protein, reducing rates of physical wasting and degradation in performance. The modern rations also include micronutrients in abundance, and present-day explorers aim to commence their journeys with heightened body mass even though this can prove difficult if they are man-haul training prior to the event (115).

Since Scott and his last two companions, Wilson and Bowers, faltered on their return journey just 11 miles from the next depot, it seems reasonable to conclude that augmented rations based on modern physiological wisdom would have kept them alive, albeit that it would probably have been hard fought for. Most importantly, they would have had more strength because of larger muscles, more insulation due to greater fat deposits, and a greater ability to recover and heal after each period of man-hauling due to adequate vitamin levels in the body. However, whether this would have been sufficient to make the difference for Evans and Lawrence Oates, who died earlier in the journey, is less clear, particularly since Evans fell −250 miles earlier than did Scott and sledge-pulled particularly hard (106, entry 14th December 1911). Arguably, therefore, without a diet considerably higher in calories and vitamin C, neither being an option for Scott, Evans’ fate was always out of their hands. Thus present physiological understanding may not be sufficient to protect everyone on man-hauling expeditions across the Antarctic.

As with the highest mountain in the world, Mount Everest, where altitude and latitude conspire to make summiting only just possible by an unaided person, the return journey to the South Pole from the Antarctic coast is only just within reach for the most capable of people. The four-month summer window each year, during which man-haulers must inevitably pull insufficient food in environmental conditions that conspire to induce rapid wasting, today still represents an enormous, potentially life-threatening physiological challenge (108, 114). In the case of both climbing Everest and reaching the South Pole, technological advancements can now compensate certain limitations of the human condition; however, other weaknesses remain as restricting factors whose capacities must be stretched to a dangerous degree if these feats are to be achieved.

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