The nutritional demands of very prolonged exercise in man

Mike Stroud*

Institute of Human Nutrition, Southampton General Hospital, Southampton SO16 6YD, UK

For many, the marathon is the ultimate example of endurance exercise, but for others it is merely a beginning. In the last 10 or 20 years, there has been a huge increase in much longer races, with 100 km and 100 mile non-stop runs and very extended triathlons added to the already established ultra-distance events like the Tour de France. In addition, there has been a steady increase in mountaineering or other expeditions which also entail considerable physical effort over very protracted periods. All these activities can make huge nutritional demands which must be understood in order to maximize performance and to avoid adverse effects on health.

The following areas of nutritional needs are of interest:

(1) energy requirements and the optimal carbohydrate : fat in their provision;
(2) N requirements;
(3) micronutrient demands, including exceptional demands on specific amino acids;
(4) fluid and electrolyte demands.

The present review is confined to the first two of these areas but, nevertheless, remains difficult. As with all assessments of nutritional interaction with activity, the demands are dependent on the nature, intensity and duration of the exercise; the environment in which it is conducted; and a variety of individual factors such as age, sex, body weight, body composition, predominant muscle fibre type and state of training. However, in the case of very prolonged exertion, such difficulties are compounded by the fact that the literature contains very few formal studies; a dearth which reflects the practical difficulties of making such studies and the relatively recent increased interest in the topic.

Energy requirements

Much of the literature on the nutritional needs of very prolonged exercise combines anecdote with extrapolation from knowledge gained during laboratory studies of exercise periods equivalent to a marathon or shorter. Many of them are based on food intake reporting, with or without records of weight and body composition changes. For example, Eden & Abernethy (1994) reported that a single male distance runner covering 1005 km over 9 d had an average daily intake of 25 MJ, of which 10 % came from protein, 62 % from carbohydrate and 27 % from fat. On this diet there was no change in body weight and so they considered that overall energy demands were also close to 25 MJ. However, prolonged exercise has been shown to increase total body water (Williams *et al.* 1979) and it is possible, therefore, that this masked the loss of some energy stores. A similar study (Gabel *et al.* 1995) examined the dietary intake of two elite male cyclists during a 10 d, 3280 km ride over the original Pony Express route which included crossing seven major mountain ranges. Average intake was 29·8 MJ/d or 472 kJ/kg body weight, with an identical macronutrient content to that reported by Eden & Abernethy (1994). Once again, no weight loss was reported and, hence, energy expenditures must have been close to 30 MJ/d. Interestingly, fluid intake averaged 10·5 litres/d with 620 ml/h drunk during cycling; volumes that have considerable implications for electrolyte balance and emphasize the need for studies on fluid and electrolyte status during very prolonged activities (Noakes, 1992).

Although direct laboratory measurements of the energy costs entailed in very prolonged events are difficult, the isotope-labelled-water technique (Schoeller, 1983; Coward & Cole, 1991) has permitted energy measurements to be made in the field. Several of these studies have come from research establishments interested in defining ration requirements during prolonged military operations. Hoyt *et al.* (1991) made measurements on twenty-three marines during 11 d of severe-cold-weather mountain training, getting good agreement between estimates from isotopes of 20·6 MJ/d and estimates from intake–balance calculations of 19·7 MJ/d. Similar energy expenditure levels of 19·9 MJ/d were identified by Forbes-Ewan *et al.* (1989) in soldiers during 7 d of jungle warfare training and of 18·0 MJ/d by Jones *et al.* (1993) in ten soldiers on Arctic exercises. In all these military studies the men lost weight, sustaining energy deficits of between about 3 and 7 MJ/d with no obvious ill-effects. However, energy expenditures were relatively low in comparison with those that can be achieved by athletes, probably because the demands of military activities are less continuous.

Westerterp *et al.* (1986) reported isotope data from four professional cyclists participating in the Tour de France, a

Abbreviations: V_{O_2max}, maximum O_2 uptake.

***Corresponding author:** Dr M. Stroud, fax +44 (0)1703 796317

race of 22 d covering more than 4000 km, including thirty mountain passages up to 2700 m altitude. The riders' average daily intake was 24·7 MJ consisting of (% total dietary energy): protein 15, carbohydrate 62 and fat 23. The isotope data gave a mean energy expenditure of 33·7 *MJ/d* although it seems likely that these were overestimates since the riders lost no weight, and body composition measured from the ^{18}O-dilution spaces was unchanged.

The competitors in the Tour de France are likely to be amongst the greatest endurance athletes in the world and competing in such an event should provide maximal motivation. Their reported daily energy expenditures, therefore, have been considered as close to the maximum that can be achieved by human subjects and, therefore, Hammond & Diamond (1997) used them to compare human subjects with fifty different animal species in which maximal sustainable energy expenditure data are known. In their animal data, only eleven species of fifty exceeded the value of 4·3 × BMR attained in the Tour de France and no species exceeded a value of 7 × BMR. They suggested four potentially-limiting factors:

(1) food supply (in the case of wild animals);
(2) food or O_2 absorption and distribution or rates of removal of metabolites (limited by gut, liver, heart, lung or kidney function);
(3) energy utilization by end organs;
(4) factors 1, 2 and 3 (matched through the process of evolutionary symmorphosis).

They concluded that end-organ utilization was the most likely limiting factor in most species since maximal metabolic scope varied when energy demand was driven in different ways. For example, in laboratory mice, maximal energy expenditure was 3·6 × BMR for forced physical exercise, 4·8 × BMR for hypothermic heat production and 6·5 × BMR for lactation driven by unnaturally large numbers of dependant young. Nevertheless, they could not be sure that the rates of energy use seen during maximal lactation in the mice were not limited by energy absorption etc.

In man, Hammond & Diamond (1997) concluded that the available data suggest that maximal energy expenditure is also dictated by end-organ use; the work levels that can be maintained by our musculature. If this is the case, values of higher than 4·3 × BMR should be achievable since cycling uses relatively few muscle groups and, hence, other exercise modalities should permit higher energy expenditures. For example, Davies & Thompson (1979) have predicted that an energy expenditure of 58·5 MJ/d might be attained by ultra-long distance runners, which would equate with > 8 × BMR, although such enormous expenditures might not be sustainable in the sense that intake, energy distribution and metabolite clearance may be unable to match them.

As far as I am aware, the literature contains no reports of energy-expenditure measurements made in such a group of elite ultra-endurance runners, although Stroud (unpublished results) has used isotope-labelled water to measure the energy expenditures of four moderately-trained subjects running a total of 240 km in stages of between 20 and 68 km across part of the southern Sahara over 7 d. The event, known as the Marathon of the Sands, also entailed runners carrying their own supplies of food and camping equipment for the duration of the event together with regularly-replenished supplies of water of up to 4 litres at any one time. They had considerable loads, therefore, to add to the problem of running on sand which has been shown to generate nearly twice the energy cost of running on a treadmill (Givoni & Goldman, 1971). During the race, the subjects consumed an average of 14·6 MJ/d consisting of (% total energy): 10 protein, 71 carbohydrate, 19 fat; 35 % of the total energy came from carbohydrate–electrolyte drinks. Mean fluid intakes were 13·5 litres/d with a maximum individual measurement of 18 litres on the day when 68 km were covered. However, despite the sand, the heat and the loads, mean energy expenditures for the 7 d were between 22·0 and 32·5 MJ/d. These are only similar to or less than those seen in the Tour de France, probably because the athletes were not elite performers and the race was divided, making some days relatively easy. It remains likely, therefore, that much higher levels could be achieved by elite competitors in the now common 100 km or 100 mile non-stop runs or in events such as the 'super iron-man' where entrants swim 10 km, cycle 1000 km, and run 100 km non-stop.

Cross-country skiing entails even greater use of muscle groups than running; a feature demonstrated by the very high maximal aerobic capacities that can be achieved using this exercise modality. It would be expected, therefore, that skiers could also maintain higher energy expenditures than cyclists. Sjodin *et al.* (1994) used isotope-labelled water to measure energy expenditures in four males and four females from the Swedish national skiing teams over 1 week of intensive pre-season ski training. Intake measurements, from weighed food inventories, ranged from 15·7 to 20·4 MJ/d in females and from 25·7 to 36·0 MJ/d in males and were closely correlated with the isotope estimates of expenditure which ranged from 15·1 to 20·2 MJ/d in females and from 25·4 to 34·9 MJ/d in males. Since the maximum values for the males were very similar to those seen in the Tour de France, it is tempting to assume that energy expenditures in the 30–35 MJ/d range may be the human limit. However, higher values have been reported in studies of men on polar man-hauling expeditions where the work of cross-country skiing is combined with pulling heavy sledge loads.

In the 1985–6 Footsteps of Scott expedition, three men walked 1400 km to the South Pole over 70 d. Each pulled a 155 kg sledge with no help from other men, animals or machines and they consumed an average of 21 MJ/d, of which 9 % came from protein, 34 % from carbohydrate and 57 % from fat. Weight losses ranged from 6·7 to 10·5 kg, giving energy balance estimates of energy expenditure of between 23·6 and 25·4 MJ/d (Stroud, 1987). In 1990, both isotope-labelled water and dietary intake–body composition studies were made on two men (MS and RF) who were pulling sledges to the North Pole over 48 d (Stroud *et al.* 1993). The isotope-labelled water study gave mean estimates of daily energy expenditure of 28·1 (MS) and 32·4 (RF) MJ, which compared with respective energy balance estimates of 25·7 and 24·9 MJ. Both the level of isotope values and the discrepancy between those values and those estimated from energy balance were similar to those reported for the Tour de France, but in this case there were considerable changes in body composition, with weight losses of 12·8 kg (MS) and 13·5 kg (RF) despite the development of considerable oedema of malnutrition in both men. The energy balance values were likely, therefore, to be underestimates.

In 1992–3, the same two men as on the Arctic expedition attempted to ski across the whole of Antarctica on another self-sustained expedition in which each man towed an exceptionally heavy sledge of 222 kg. Exercise was performed for > 10 h each day for 95 d in temperatures ranging from $-10°$ to $-55°$. For a variety of reasons the planned 23·5 MJ/d diet was not always consumed and the final intake provided an average over the whole journey of 21·3 MJ/d, of which 56·7 % total dietary energy came from fat, 35·5 % from carbohydrate and 7·8 % from protein. Despite these high intakes, the subjects lost 21·8 kg (MS) and 24·6 kg (RF) kg, more than 25 % of their body weights. The losses led to marked debilitation towards the end of the journey (Stroud *et al.* 1997).

During the expedition, energy expenditures were measured using energy balance and isotope-labelled water with isotope doses taken on days 0 and 50. For the first 50 d both methods gave reasonable agreement with energy expenditures of 28·6 (energy balance) and 29·1 (isotope-labelled water) MJ/d in MS and 38·3 (energy balance) and 35·5 (isotope-labelled water) MJ/d in RF. However, these average values for the period masked exceptional levels for days 20–30 when the isotope data gave daily expenditures of 48·7 MJ (MS) and 44·6 MJ (RF). Estimates of energy expenditure for the second part of the expedition were much lower by both techniques.

At well over 40 MJ/d, the levels of energy expenditure between days 21 and 30 are the highest reported in the literature, yet they are credible since they matched the period of maximal rates of weight loss. Although they might be partly explained by metabolic responses to the cold, exercising hard in the cold does not usually entail much increased energy cost (Stroud, 1997) and, hence, the high levels are probably the simple result of the 12 h daily work involved in hauling the heavy sledges uphill from about 50 m to more than 3000 m altitude using all the muscles of the limbs and trunk.

These Antarctic data give maximal energy expenditures of 6–7 × BMR, although they were not actually sustained, in that the men were losing weight rapidly. However, the restriction on food intake was imposed by the self-contained nature of the expedition rather than by ability to eat or absorb more food and it seems likely that had more been available it may have been possible to maintain body weight under these circumstances. It is also of note that the very heavy work outputs entailed in this journey were maintained in the face of food deficits of more than 25 MJ/d although by the end of the expedition the men had become severely debilitated (see pp. 59–60).

The energy expenditure data from the previously described studies on prolonged endurance exercise are summarized in Table 1.

Carbohydrate *v.* fat

Most authorities are in no doubt that adaptation to a high-carbohydrate diet before exercise (for example, see Bergstrom *et al.* 1967; Karlsson & Saltin, 1971) and carbohydrate ingestion during exercise (for example, see Coggan & Coyle, 1987) can enhance exercise performed for more than 2 h at levels approximately at or above 70 % maximum O_2 uptake (V_{O_2max}). A diet containing approximately 70 % or more energy as carbohydrate has become, therefore, the conventional intake for competitors in events such as a marathon and this has been shown to improve run times. For example, Tsintzas *et al.* (1995) studied seven endurance-trained runners completing three treadmill marathons in random order at 4-week intervals. The subjects ingested 3 ml/kg body weight of water, 69 g carbohydrate/l solution or 55 g carbohydrate/l solution immediately before the tests, followed by 2 ml/kg of the same solution at 5 km intervals thereafter. Running times were 193·9 min for water, 192·4 min for the 69 g carbohydrate/l solution and 190·0 min for the 55 g carbohydrate/l solution. Clearly benefits of the order of 4 min on a marathon time are enormous, and hence, most ultra-distance athletes have followed similar dietary regimens in the hope that improvements of a similar order will accrue during their longer periods of exertion. Nevertheless, it is by no means clear that this is optimal policy, for during very prolonged activity the maintenance of glycogen stores must become less relevant.

Ultra-distance events are likely to be performed at lower exercise intensities than shorter races such as marathons, by athletes who are even more endurance trained. This should, therefore, permit an even higher dependence on fat oxidation than in shorter events. Indeed, such dependence is inescapable, for during a 100 mile non-stop run glycogen stores are likely to become severely depleted before even 20 % of the race is over. For the majority of the distance, therefore, the muscles must utilize fat as their main substrate, and this will be true even if carbohydrate-containing foods are freely available. The maximum rate at which exogenous carbohydrate can be absorbed and utilized is only about 60 g/h, which could only provide about 1 MJ/h to support activity which may demand more than four times that much. Furthermore, in many of the ultra-distance events, the nature of the competition will limit exogenous energy intake. For example, during the Marathon of the Sands, the fact that each competitor had to carry all their food for the 7 d course meant that the more they planned to eat, the more they would have to carry. Several of the elite competitors reacted to this constraint by reducing their daily intake to less than 5 MJ, all of which was in the form of 50 g glucose/l–electrolyte drinks in order to maximize fluid absorption while minimizing the chances of developing hypoglycaemia. The vast majority of their muscle substrates, therefore came from body fat stores, yet they suffered no apparent ill effects (Stroud, unpublished results).

There are two obvious macronutrient strategies by which fat oxidation might be improved: starvation or a period of adaptation to a high-fat diet. Studies of the former do not support its use to promote endurance, and in a study of nine

Table 1. Studies of daily energy intakes and expenditures during very prolonged exercise

Study	Nature of event	*n*	Energy intake (MJ)	Dietary composition (% total energy)			Energy expenditure (MJ) measured using:	
				Protein	CHO	Fat	Energy balance	Isotopes
Eden & Abernethy (1994)	1005 km running, 9 d	1	25·0	11	62	27	25·0	–
Gabel *et al.* (1995)	3280 km cycling, 10 d	2	29·8	10	63	28	29·8	–
Hoyt *et al.* (1991)	Military mountain training, 11 d	23	13·1	13	49	38	19·7	20·6
Forbes Ewan *et al.* (1989)	Military jungle training, 7 d	4	16·9	–	–	–	23·3	19·9
Jones *et al.* (1993)	Military Arctic training, 10 d	10	11·0	18	47	35	13·5	18·0
Westerterp *et al.* (1986)	Tour de France, 20 d	4	24·7	15	62	23	25·0	33·7
Stroud (unpublished results)	Sahara multi-marathon, 7 d	4	14·6	10	71	19	–	22·0–32·5
Sjodin *et al.* (1994)	Cross-country skiing, 7 d	4 males	25·7–36·0	13	58	28	–	25·4–34·9
		4 females	15·7–20·4	13	58	28	–	15·1–20·2
Stroud (1987)	South Pole expedition, 70 d	3	21·0	9	34	57	23·6–25·4	–
Stroud *et al.* (1993)	North Pole expedition, 48 d	2	19·2	8	33	59	25·7–24·9	28·1–32·4
Stroud *et al.* (1997)	Trans-Antarctic expedition: Day 0–50	2	19·9	8	37	55	28·6–38·3	29·1–35·5
	Day 51–95	2	22·2	9	42	57	24·1–26·8	18·8–23·1
	Maximum: Day 21–30	2	22·2	9	42	57	Approximately 46·0	44·6–48·7

CHO, carbohydrate.

male marathon runners who ran to exhaustion at treadmill speeds equivalent to their marathon performance, times to exhaustion decreased by 44·7 % following a 27 h fast (Nieman *et al.* 1987). However, a period of adaptation to fat appears to be of benefit and Phinney *et al.* (1983) showed that following a diet of more than 60 % dietary energy as fat for 2 weeks, the ability to exercise for 2·5–3 h at slightly less than 70 % V_{O_2max} was unaffected despite much lower rates of carbohydrate oxidation. Furthermore, studies using less-severely-depleted carbohydrate diets have been more promising and have even shown benefits at relatively higher exercise intensities. Muoio *et al.* (1994) showed that running time to exhaustion at 75–85 % V_{O_2max} was 91 min following 7 d on a diet containing (% total energy) 38 fat and 50 carbohydrate compared with only 76 min on a more-conventional endurance-athlete's diet containing (% total energy) 15 fat and 73 carbohydrate. Similarly, Lambert *et al.* (1994) found that following 2 weeks on diets containing (% total energy) 70 fat and 7 carbohydrate *v.* 12 fat and 74 carbohydrate, times to exhaustion at 90 % V_{O_2max} were no different, while the time to exhaustion at 60 % V_{O_2max} was extended to 80 min following the high fat intake, compared with just 43 min on the carbohydrate diet. This was despite the high-fat diet leading to lower glycogen levels before the 60 % V_{O_2max} test of 32 *v.* 73 mmol/kg wet mass.

It is interesting that in the Muoio *et al.* (1994) and Lambert *et al.* (1994) studies, the high-fat diets granted greater benefits to exercise endurance than they did in the earlier Phinney *et al.* (1983) study. The most likely explanation for this is that in the later studies, the lower exercise intensities followed very-high-intensity exercise; an incremental maximal test 30 min before the 75–85 % V_{O_2max} test in the Muoio *et al.* (1994) study and a 90 % V_{O_2max} test to exhaustion preceding the 60 % V_{O_2max} test in the Lambert *et al.* (1994) study. Carbohydrate depletion, therefore, was much more marked at the beginning of the lower intensity of exercise compared with the Phinney *et al.* (1983) study, suggesting that a high-fat diet grants a particular advantage when glycogen stores are already depleted. The finding, therefore, does not run contrary to the hypothesis that depletion of glycogen is one of the main causes of fatigue in prolonged exercise. Instead, it suggests that in a glycogen-depleted state, fatigue is lessened if the systems that maximize mitochondrial fat oxidation are optimal. If this is the case, ultra-distance athletes might do well to ignore the tenets of nutrition accepted for more-moderate distances.

There has been concern that problems with hypoglycaemia may arise if a high-fat diet is used during prolonged exertion, and certainly this occurred during the Antarctic crossing reported by Stroud *et al.* (1997). On that journey, blood samples taken at 10 d intervals revealed mean end-of-day glucose levels of just 3·0 mmol/l in RF and 2·8 mmol/l in MS, and on two occasions (days 70 and 95) both men were apparently grossly hypoglycaemic, with values of 0·3 mmol/l. This occurred despite carbohydrate intakes that were actually quite reasonable, for although the relative carbohydrate intake was low, the full ration contained 490 g/d. However, carbohydrate metabolism on the expedition was clearly very disturbed towards the end of the trip, with abnormally high insulin levels in the face of hypoglycaemia and elevated cortisol and growth hormone levels. It is unclear, therefore, to what extent this problem would arise when the combination of prolonged exertion, a high-fat diet and overall undernutrition were less extreme.

It has been suggested also that, even if food is freely available, it may be impossible to maintain energy balance unless carbohydrate drinks are used during events. Brouns *et al.* (1989) found that during a simulated 2 d of cycling, where energy expenditures of 26 MJ/d were reached, a diet of 62 % total energy as carbohydrate with water as fluid led to a shortfall of 5–10 MJ/d which was eliminated if 200 g carbohydrate/l drinks were used. However, energy balance might have been achieved with fat snacking or a higher fat content in the meals.

Nitrogen demands

The national reference nutrient intakes for protein vary, but generally lie close to 0·7 g/kg body weight (for example, see Department of Health, 1991). These values are based on fairly sedentary requirements, although they do include a safety margin which is probably adequate to cover the needs of most people involved in sporting activities. However, in several situations exercise may increase demands well beyond the reference nutrient intakes:

(1) early in training programmes, particularly strength-related programmes, rapid increases in muscle mass can create excessive demands for amino acids;
(2) when overall energy balance is negative, N balance can only be achieved with higher protein intakes (Munro, 1951);
(3) when the diet is deficient in carbohydrate, N balance can only be achieved with higher intakes (Maclean *et al.* 1989);
(4) during prolonged activity, the usual 5–15 % of energy that is provided by protein oxidation will become significant even if energy balance and carbohydrate supplies are adequate.

Studies of these factors have led various authors to recommend daily protein intakes for endurance athletes in training of between 1·3 and 1·6 g/kg (for example, see Tarnopolsky *et al.* 1988; Paul, 1989; Lemon, 1991). It is accepted, however, that these levels of protein requirement may not be needed once muscle building has been completed, and Millward *et al.* (1994) concluded that in fully-trained individuals, additional N losses associated with physical activity are likely to be minimal. Nevertheless, this conclusion assumes that individuals will be in overall energy balance, which may well not be the case during very prolonged exertion, particularly if the nature of the event restricts food intake due to weight considerations.

The literature regarding this point is very limited and once again, I draw on data from the crossing of Antarctica. Studies of N balance on that journey (Stroud *et al.* 1996) showed that for the first 50 d, MS was in negative balance with losses of −4·8 g N/d whereas RF was in positive balance of +0·9 g N/d. The same pattern was then maintained during the latter 45 d of the journey, with mean losses of $-0{\cdot}9$ g N/d for MS and gains of $+0{\cdot}2$ g N/d for RF. The values are interesting since both men ate an average of 101 g protein/d and they suggest, therefore, that the smaller MS (starting weight 75 kg) had a N requirement of about 1·8 g/kg whereas the much larger RF (starting weight 96 kg) had a requirement nearer 1·0 g/kg, despite smaller weight losses for MS (21·3 kg) than RF (24·8 kg). This apparent discrepancy may have been due to the fact that the smaller MS pulled a sledge of equal weight to that of RF and, hence, had to work at relatively higher exercise intensities during the journey which would have promoted protein utilization by muscles, although the situation may have also been complicated by the tendency for both men to develop hypoglycaemia which could have created demands for amino acid-C skeletons for use in gluconeogenesis.

Measurements of rates of protein synthesis were also made during the trans-Antarctic expedition using the [^{15}N] glycine single-dose endproduct method (Stroud *et al.* 1996). The main purpose of these measurements was to examine how the process responded to conditions of extreme stress and negative energy balance imposed over a long period. In subjects exposed to infection or trauma, protein synthesis and breakdown are increased, with breakdown predominating to produce a negative N balance (for example, see Tomkins *et al.* 1983; Jeevenandam *et al.* 1986), while with undernourishment, the rate of protein turnover is reduced (Waterlow, 1992). The Antarctic expedition provided a scenario in which all three of these elements affecting protein turnover were combined: intense exertion, some degree of infection and trauma, and food deficit. The average values during the expedition of 3·3 g protein/kg per 12 h for MS and 4·6 g protein/kg per 12 h for RF were higher than mean values for protein synthesis in normal subjects of between 2 and 3 g protein/kg per 12 h. It seems, therefore, that even in the face of great exertion, negative energy balance and serious physical deterioration, the vital function of protein synthesis can be maintained, as long as adequate, or approximately adequate dietary protein is provided. However, this does not necessarily protect an individual from excessive protein breakdown and in the case of the Antarctic journey this is exactly what did happen. The N balance studies were only apparent in that they did not account for any non-urinary N losses and, in reality, both men were probably in negative N balance for the entire 95 d duration of the trip. This led to both considerable losses of lean body mass and to considerable declines in markers of exercise performance. Following the expedition, both MS and RF showed declines in V_{O_2max} from 58·1 to 46·0 ml O_2/kg per min and from 53·6 to 41·2 ml O_2/kg per min respectively. Maximal voluntary isometric force production in different muscle groups also declined by up to 55·8 % in MS and 19·9 % in RF and with this decline, muscle biopsy studies showed huge decreases in both cytoplasmic and mitochondrial skeletal muscle enzyme activities of up to 63 % in MS and 56 % in RF. Clearly, these changes are the opposite of those that have usually been reported following periods of endurance training (for example, see Holloszy, 1981; Wibom *et al.* 1992), but most studies have reported the effects of training combined with adequate nutrition and it seems likely, therefore, that the changes seen in the Antarctic expedition results can be attributed to the negative energy balance and the need for muscle protein oxidation to offset the energy deficit. The relevance of these findings to ultra-distance events of a less extreme nature is not known, but it can be assumed that less marked declines in function and enzyme systems may occur in longer events where nutritional intake is inadequate, and that such changes could be of significance during periods of very heavy training where food intake may not keep up with expenditure, with consequent weight loss.

Conclusion

The data regarding the nutritional needs of very prolonged exercise are inadequate but it seems likely that:

(1) energy requirements of as much as 30 MJ/d may not be uncommon and they may be even greater in activities involving many muscle groups and work of 12 h/d or more. Very high overall demands may occur, even if work levels are far lower than those sustained by elite athletes in traditional continuous events such as the marathon or in staged ultra-distance events such as the Tour de France;

(2) the uncritical assumption that providing approximately 70 % of energy as carbohydrate must be optimal because it has been proved as such in shorter endurance events is not entirely logical, and the best balance of dietary substrates for very prolonged activity remains unclear. Maximizing mitochondrial fat oxidation rates may be more important than in activities of conventional length;

(3) the dietary protein needs of very prolonged activity are also poorly understood, and may be considerable if the logistics of the exercise mean that energy and carbohydrate requirements are not being met.

These and several other nutritional aspects of very prolonged activity deserve further investigation and, although fraught with practical difficulties, they should now be amenable to study. With the increasing popularity of very-prolonged-exercise events, it seems likely that this area of research will grow.

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