Fasting and recovery from exercise

Louise Burke

Correspondence to
Dr Louise Burke, Australian Institute of Sport, PO Box 176, Belconnen ACT 2616, Australia; louise.burke@ausport.gov.au

Accepted 4 March 2010

ABSTRACT

Recovery after strenuous exercise involves processes that are dependent on fluid and food intake. Current sports nutrition guidelines provide recommendations for the quantity and timing of consumption of nutrients to optimise recovery issues such as refuelling, rehydration and protein synthesis for repair and adaptation. Recovery of immune and antioxidant systems is important but less well documented. In some cases, there is little effective recovery until nutrients are supplied, while in others, the stimulus for recovery is strongest in the period immediately after exercise. Lack of appropriate nutritional support will reduce adaption to exercise and impair preparation for future bouts. Ramadan represents a special case of intermittent fasting undertaken by many athletes during periods of training as well as important competitive events. The avoidance of fluid and food intake from sunrise to sundown involves prolonged periods without intake of nutrients, inflexibility with the timing of eating and drinking over the day and around an exercise session, and changes to usual dietary choices due to the special foods involved with various rituals. These outcomes will all challenge the athlete's ability to recover optimally between exercise sessions undertaken during the fast or from day to day.

INTRODUCTION

The training programme of an elite athlete involves one or more workouts each day, typically allowing 6–24 h for recovery between sessions, while competition timetables can include a series of events or stages with 1–48 h between performances.

Recovery involves a complex array of processes that help to restore homeostasis or allow the body to adapt to physiological stress. The better understood processes include restoration of muscle and liver glycogen stores, replacement of fluid and electrolytes lost in sweat, protein synthesis for repair and adaptation, and responses of the immune and antioxidant systems to help the athlete stay healthy. Many of these processes are highly dependent on the provision of nutrients via eating or drinking in the hours after the session. Indeed, there is a sophisticated body of science underpinning the guidelines for 'Recovery Nutrition' for athletes, as well as an appreciation that various practical issues can interfere with their ability to achieve the recommended patterns and choices of intake of foods and fluids during the period between workouts or competition. Fasting—the abstention from eating or drinking for religious or cultural reasons—represents one such issue.

The aim of this review is to summarise our current recommendations for Recovery Nutrition in the context of fasting practices. It will begin by summarising the evidence-based guidelines for optimising each of these aspects of recovery, noting recommendations for the amounts of key nutrients that should be consumed. Next, it will cover specific issues of the timing of nutrient intake in terms of how they may be affected by fasting. Challenges could include withholding the first intake of nutrients after exercise, limitations on the frequency and timing of subsequent intake of nutrients, and effects of a reduced period of fluid and food intake on ability to meet total nutrient intake goals. It is beyond the scope of this review to cover the outcomes of suboptimal recovery nutrition caused by fasting on the training adaptations or competition performance of athletes. Indeed, these effects play a role in the larger picture of fasting and sports performance which is covered by Maughan and colleagues.[1]

The present review will conclude by considering the best way to structure the timing of exercise and fluid/food intake within the restrictions and allowances of a real life practice of fasting. The convention of Ramadan fasting will be chosen for this demonstration due to topicality of the overlap in 2012 between the month of Ramadan (20 July to 18 August) and the schedule of the London Olympic Games (27 July to 12 August). Fasting during Ramadan, the 9th month of the lunar calendar, is one of the five pillars of the Muslim faith. Briefly, such fasting involves the abstention from all fluid and food intake during the period from first light to sunset (Itfar), as well as rituals involved with the breaking of the fast and various prayer and feasts throughout the night. Such fasting can result in prolonged periods without intake of nutrients or food volume, inflexibility with the timing of eating and drinking over the day and around an exercise session, and changes to usual dietary choices due to the special foods involved with various rituals. Depending on the timing of the specific event within the Games programme, the Olympic athlete may be practising their fast during a reasonably heavy training load, a pre-competition taper and/or competition itself. It is, of course, recognised that many other fasting practices occur in various cultures and religions, and that many Muslim athletes train and compete in a variety of sports/events during the month of Ramadan each year. Nevertheless, it is likely that the high profile of the Olympic Games will focus attention on the challenges of combining sports nutrition goals within a practice that places limits on access to food and fluid intake.

RESTORATION OF MUSCLE GLYCOGEN

Following an exercise bout which depletes glycogen stores, there is a relatively rapid restoration

Br J Sports Med 2010;**44**:502–508. doi:10.1136/bjsm.2007.071472

phase lasting for about an hour followed by a slower insulin dependent phase lasting up to several days.[2] High-intensity exercise which results in high concentrations of lactate is associated with recovery of glycogen stores in the absence of additional carbohydrate feeding.[3] After moderate-intensity exercise, however, high rates of muscle glycogen synthesis are dependent on provision of a dietary source of carbohydrate. At a mean restoration rate of 5–6 mmol/h, it can take ~24 h to normalise depleted stores.

Type and amount of carbohydrate intake

The major dietary factor involved in postexercise refuelling is the amount of carbohydrate consumed. As long as total energy intake is adequate,[4] increased carbohydrate intake promotes increased muscle glycogen storage until the threshold for glycogen synthesis is reached. The most recent guidelines for the carbohydrate needs of athletes recognise a scaling of requirements according to the fuel cost of training or competition and the athlete's body size.[5] Glycogen storage in the first couple of hours after exercise appears to be saturated with a carbohydrate intake of ~1 g per kilogram of the athlete's body mass (BM) per hour; this amount is higher than that suggested by early studies.[6] The total carbohydrate requirement over a day is typically within the range of 3–10 g/kg BM depending on the athlete's training or competition schedule (see table 1). Even so, these guidelines are considered to be 'ball park' figures that must be fine-tuned according to the athlete's total energy needs, overall nutritional goals and feedback about their performance and recovery.[5]

It has been hypothesised that the type of carbohydrate foods may affect the rate of glycogen restoration, based on its ability to enhance blood glucose availability or increase insulin concentrations. Indeed, moderate and high glycaemic index carbohydrate-rich foods and drinks were reported to promote greater glycogen storage than an equivalent amount of carbohydrate from low glycaemic index choices.[7] However, the mechanisms which explain this finding probably include factors such as the malabsorption of low glycaemic index foods, reducing the actual amount of available carbohydrate, rather than differences in the glycaemic/insulinemic responses per se.[7] Whether carbohydrates are consumed as liquids or solids does not appear to affect glycogen synthesis.[8 9]

Early research indicated that glycogen synthesis was enhanced by the addition of protein to carbohydrate snacks consumed after exercise, with the proposed explanation being that protein stimulated and enhanced the insulin response.[10] However, these findings have been refuted in other studies, especially when the energy content of the protein is matched.[11] A recent consensus[5] found that that coingestion of protein or amino acids with carbohydrate does not clearly enhance glycogen synthesis but that benefits to muscle glycogen storage may occur limited to the first hour of recovery[12] or to situations where protein is added to an amount of carbohydrate or pattern of intake that is below the threshold for maximal glycogen synthesis.[10 12 13] Of course, the intake of protein within carbohydrate-rich recovery meals may enhance muscle protein synthesis after exercise (see below).

Timing of carbohydrate intake

Athletes are advised to consume carbohydrate as soon as possible after the completion of a workout or event to enhance refuelling. There is a potential for high rates of muscle glycogen storage during the first 2–4 h after exercise[14] as a result of the depletion-activated stimulation of glycogen synthase enzyme and exercise-induced increases in muscle membrane permeability and insulin sensitivity. This potential can only be realised if carbohydrate is consumed during this period; if not, refuelling rates are very low. But even in the face of carbohydrate intake, refuelling rates decline after 2–4 h.[14] This observation has created the idea of a 'window of opportunity' for glycogen storage during the early period of postexercise recovery. It should be appreciated, however, that consuming carbohydrate following strenuous exercise is most valuable because it provides an immediate source of substrate to the muscle cell to start effective recovery rather than simply because of a few hours of moderately enhanced glycogen synthesis. The corollary of delaying carbohydrate intake is that there will be very low rates of glycogen restoration until feeding occurs. Any delay is important when there is only 4–8 h between exercise sessions,[14] but it may have less impact over a longer recovery period, as long as sufficient carbohydrate is consumed. For example, there was no difference in glycogen storage after 8 and 24 h of recovery whether meals providing a targeted amount of carbohydrate intake started immediately after exercise or were delayed for 2 h.[15] However, the impact of withholding the start of carbohydrate intake for longer periods—for example, a 4–8 gap between the finish of exercise and the intake of carbohydrate—has not been systematically studied.

Once the athlete is able to consume carbohydrate, it is of interest to see whether glycogen storage is altered by changing the pattern and timing of meals or snacks. There is indirect evidence that maximal glycogen storage during the first 4 h after exercise is achieved by a pattern of small frequent meals providing a total carbohydrate intake of ~1 g/kg/h.[6] Over longer-term recovery (12–24 h), however, muscle glycogen storage was the same when carbohydrate was divided into two or seven meals[16] or consumed as four large meals compared with 16 hourly snacks.[17] The question of whether there is a better feeding pattern to promote refuelling from an insufficient carbohydrate intake has not been addressed.

On the basis of this current knowledge, fasting has the potential to interfere with postexercise refuelling in a number of ways summarised in table 1.

RESTORATION OF FLUID BALANCE

Even when athletes are able to consume fluid during a bout of exercise, in most situations they can expect to be at least mildly dehydrated by the end of the session. High fluid deficits will occur in hot environments, during high-intensity exercise of prolonged nature and/or in situations where fluid intake during exercise is limited. In weight-division sports such as boxing and wrestling, the athlete may purposely undertake dehydrating techniques to acutely reduce BM before the competition weigh-in. Ideally, the athlete should fully restore fluid losses after one exercise session so that the next workout can be commenced in fluid balance. This is difficult when there is a moderate to high fluid deficit—equivalent to 2–5% BM or greater—and the rehydration period is less than 6–8 h. The success of rehydration strategies depends on how much the athlete drinks and then how much of this fluid is retained and re-equilibrated within body fluid compartments.

Optimal type and amount of fluid

After exercise or other situations producing a fluid deficit, many people fail to drink sufficient volumes of fluid to restore

Table 1 Summary of current guidelines for recovery after exercise and potential effects of fasting

Issue	Summary of current guidelines	Potential effects of fasting
Glycogen restoration	► Total amount of carbohydrate is the most important factor in daily refuelling. Daily carbohydrate needs depend on fuel cost of training or competition programme, with approximate guidelines: – Light exercise (low intensity or skill based training): 3–5 g/kg/day. – Moderate exercise (ie, ~1 h per day): 5–7 g/kg/day. – Heavy/endurance programme (ie, 1–3 h per day of moderate-to high-intensity exercise or carbohydrate loading): 6–10 g/kg/day. – Very heavy exercise (ie, >4–5 h per day of intense exercise). (Note that large athletes and athletes undertaking a weight loss programme may be better suited to the fuel needs of the previous category.) ► Intake of carbohydrate (~1 g/kg) after exercise starts effective refuelling. – Rates of glycogen storage are moderately enhanced in the 1–2 h after exercise when carbohydrate is consumed, compared with later rates of refuelling. ► When recovery time is less than 8 h, carbohydrate intake should start as soon after exercise as is practical to maximise the effective refuelling time. The importance of this early start or the enhanced period of storage is less when there are longer recovery times (>8 h recovery). In this case, total carbohydrate intake is likely to be more important rather than when feedings commenced. ► Frequency/pattern of carbohydrate intake over the day is probably not important as long as carbohydrate needs are met. – It is likely that small frequent snacks enhance refuelling during the first 2–4 h or recovery from exercise.	► Refuelling is minimal until carbohydrate is consumed. – Without carbohydrate intake, there may be little refuelling between exercise bouts undertaken during the period of fast. – In the case of recovery for exercise bouts on a subsequent day, there may not be time for adequate recovery if carbohydrate intake is delayed for lengthy periods. ► When eating opportunities are limited, it may be difficult to consume enough carbohydrate to meet targets for high fuel needs. – It can be difficult to consume large amounts of carbohydrate over a small eating period – Carbohydrate intake may be further limited if the available 'eating time' in a day also needs to be committed to other activities (prayers, sleep, etc). – Ritual or cultural food choices may not be carbohydrate-focused. ► Inadequate energy intake may reduce glycogen storage from a given carbohydrate intake.
Rehydration	► Fluid intake equal to 125–150% of a postexercise fluid deficit will be needed to accommodate further sweat and urine losses and restore fluid balance. ► Thirst may not guarantee adequate fluid intake: when the fluid deficit is >2% body mass, an athlete should have a fluid plan and access to a supply of palatable beverages – Sweetened, cool drinks encourage voluntary intake of fluids. ► Rehydration requires replacement of the electrolytes lost in sweat, especially sodium. Fluid intake in the absence of electrolyte replacement will reduce plasma osmolarity and result in large urine losses. – Sodium can be replaced via special drinks such as oral rehydration solutions (50–80 mmol/l) or higher salt-containing sports drinks (30–35 mmol/l). – Alternatively, sodium can be consumed in foods or added to the meals eaten in conjunction with fluid intake. ► Where possible, it is better to space fluid intake out over a period rather than consuming large volumes at a single time: this pattern will reduce urine losses and maximise fluid retention	► Rehydration cannot occur until fluids and electrolytes are consumed. – Fluid deficits will accumulate between exercise bouts undertaken during the period of fast. ► When opportunities for fluid intake are concentrated to a small period, it may be difficult to consume enough fluid to replace large deficits. ► Although it may be preferable to spread fluid intake more evenly over the possible drinking period, Ramadan intake is generally focused on the postsundown and predawn. ► Intake of large volumes of fluid at the breaking of the fast may be associated with large urine losses, reducing the effectiveness of rehydration and interfering with restful sleep.
Repair and adaptation (Protein synthesis)	► Protein should be consumed soon after an exercise session to promote the synthesis of new proteins as dictated by the specific exercise stimulus. o An intake of 20–25 g of protein is sufficient to optimise the response to exercise. o Protein intake should include high quality proteins such as animal sources (eg, dairy, eggs, meats). ► Although previous discussion on increased protein requirements for athletes remain unresolved, it is likely that all needs can be met from an intake of 1.2–1.6 g/kg/day. o Guidelines for the spread of protein over the day are not yet available, but there is logic in consuming protein in modest amounts (20–25 g) spread over a number of eating occasions to take advantage of the increased potential for muscle protein synthesis in the 24 h after an exercise bout.	► Although exercise increases protein synthesis, net protein balance remains negative (breakdown>synthesis) in the absence of protein intake. ► The inability to consume protein soon after an exercise bout will sacrifice the most effective time for adaptive protein synthesis. ► Long periods without intake of energy or protein will increase net protein loss.

fluid balance, even when fluids and opportunity are available.[18] The flavouring of drinks is known to contribute to voluntary fluid intake, with studies reporting greater fluid intake during postexercise recovery with sweetened drinks than with plain water.[19] The intake of sodium in or with a fluid helps to preserve thirst, thus increasing intake,[20] while the temperature of drinks also affects intake. Although very cold fluids (0°C) may be regarded as the most pleasurable, cool drinks (15°C) are more likely to be consumed quickly and in larger quantities.[21] Because sweating and obligatory urine losses continue during the rehydration phase, athletes must replace more than their postexercise fluid deficit to achieve fluid restoration.

Typically, a volume of fluid equivalent to 125–150% of the deficit must be consumed to compensate for these ongoing losses and ensure that fluid balance is achieved over the first 4–6 h of recovery.[22]

Fluid replacement alone will not guarantee that rehydration goals are achieved. Unless there is simultaneous replacement of the electrolytes lost in sweat, particularly sodium, consumption of large amounts of fluid will simply result in large urine losses.[22] The addition of sodium to rehydration fluids has been shown to better maintain equilibrium between plasma volume and plasma osmolality, reduce urine losses, and enhance net fluid balance at the end of 6 h of recovery.[22,23] In contrast, with no or little replacement of sodium along with fluid intake, participants were still substantially dehydrated at the end of the 6 h recovery period, despite drinking 150% of the volume of their postexercise fluid deficit.[22] On a practical note, fluid replacement without sodium intake may return a false positive for good hydration status, at least in the acute phase of recovery. The production of copious amounts of clear urine, or urine with a low osmolality and specific gravity, may be useful as an overall sign of euhydration, particularly when early morning urine is used to monitor day-to-day variations in hydration.[24] However, during the hours immediately after a substantial fluid deficit is replaced without attention to sodium losses, athletes are likely to produce large amounts of urine with characteristics suggesting the return of fluid balance, when in reality they are still in substantial fluid deficit.[22]

The optimal sodium level in a rehydration drink appears to be ~50–80 mmol/l,[23] explaining the composition of oral rehydration solutions manufactured for the treatment of diarrhoea. This is higher, however, than the concentrations found in commercial carbohydrate–electrolyte (sports) drinks, which are typically 10–25 mmol/l but include specialised products for endurance sports at 30–35 mmol/l. Sport drinks may confer some rehydration advantages over plain water, in terms of palatability as well as fluid retention.[25] Nevertheless, where maximum fluid retention is desired, there may be benefits in increasing the sodium level of rehydration fluids and trading off the reduction in palatability. Alternatively, sodium may be consumed during recovery via everyday foods containing sodium or by adding salt to meals. These methods are all effective in enhancing rehydration.[26,27]

Because alcohol increases diuresis, consumption of beverages with a significant alcohol content during the rehydration period may result in greater fluid losses compared with other fluids.[28] Of course, the intake of large amounts of alcoholic beverages after exercise will interfere with other aspects of recovery, particularly by distracting the athlete from following recommended dietary practices and by promoting high-risk behaviour.[29] Athletes are also often told that caffeine-containing beverages such as tea, coffee and cola or guarana drinks are diuretics and should be avoided in situations where there is a risk of developing dehydration. However, a recent review found that the effect of caffeine on urine losses or dehydration is overstated and may be minimal in people who are habitual caffeine consumers.[30] In addition, increased fluid losses from caffeine-containing or low-alcohol drinks may be more than offset by the increased voluntary intake of fluids that are well liked by the athlete or part of social rituals and eating behaviours. If the athlete is suddenly asked to remove such beverages from their diet or postexercise meals, they may not compensate by drinking an equal volume of other less familiar or well-liked fluids.

Optimal timing of fluid

Rehydration can only commence with the intake of fluids; however, only a few studies have investigated the effect of the pattern of fluid intake on restoration of fluid balance. Kovacs and colleagues compared the intake of a large amount of fluid in the immediate postexercise period with the same total volume of fluid being spread equally over 5 to 6 h of recovery.[31] Early replacement of large volumes of fluid was associated with better restoration of fluid balance during the first hours of recovery despite an increase in urinary output; however, differences in fluid restoration between hydration patterns disappeared by 5 to 6 h of recovery. In another study, spacing fluid intake over several hours of recovery after exercise reduced urine losses and was more effective in restoring fluid balance than consuming the fluid as a large bolus immediately after the exercise.[32]

Based on this information, table 1 summarises a number of ways in which fasting can delay rehydration.

PROTEIN SYNTHESIS FOR REPAIR AND ADAPTATION

At any particular moment in time, net muscle protein balance is a product of muscle protein synthesis minus muscle protein breakdown, and over a day the direction and degree of the balance continually alters according to factors such as intake of dietary protein, exercise and periods without food. Protein synthesis plays a large role in the adaptation or recovery from most exercise bouts, since it encompasses among other proteins the synthesis of new myofibrillar tissue in response to resistance exercise, the repair of damaged tissue and the synthesis of sarcoplasmic and mitochondrial proteins in response to endurance or intermittent high-intensity exercise.[33] Although most of the research on protein synthesis and exercise has concentrated on resistance exercise, it is assumed that in trained subjects, a similar response also occurs to other forms of exercise, with the ensuing cascade of protein synthesis targeting the specific proteins that contribute to that particular activity.

Optimal type and amount of protein

In the period immediately after exercise, there is a substantial increase in rates of muscle protein synthesis, especially in trained individuals.[34] This is most evident in the hours immediately after the bout, and in trained subjects, it may not return to basal levels until at least 24 h of recovery.[34] However, while exercise reduces the degree of negative protein balance that occurs between meals, the response remains negative (ie, breakdown>synthesis) unless the athlete consumes a source of protein,[35] or more specifically, the essential amino acids is consumed.[36] A dose–response study has recently identified that the maximal protein synthetic response to a resistance exercise bout is achieved with the intake of ~20–25 g of high-quality protein.[37] Protein consumed in excess of this stimulates increased rates of irreversible oxidation. The increase in muscle protein synthesis that occurs in the hours after exercise and protein feeding is still evident in the 24 h picture of net protein balance[38] and leads to measurable differences in protein gain and functional outcomes in the chronic training situation.[39,40]

Although previous interest on the protein requirements of athletes has focused on the controversial areas of total daily protein requirements for nitrogen balance or enhanced athletic performance,[41] it now seems more important to consider the type of protein that is consumed and its timing of intake in relation to training, and perhaps also its spread over a day. There is current interest in differences in muscle protein synthetic response to various types of dietary protein and amino acid sources consumed in relation to exercise. Milk protein has been shown to be superior to an equivalent amount of soy protein.[39] Meanwhile, although whey and soy stimulate a higher muscle protein synthesis rate than casein,[42] whey and casein may produce an equal effect on net protein balance (synthesis vs breakdown) after a resistance training bout.[43] These studies identify that the amino acid composition and rate of digestion of the protein ('fast' vs 'slow') may determine its overall effect on protein synthesis. However, there is currently insufficient information to identify the best source(s) of dietary protein, other than they should be of high quality or biological value—that is, containing all the essential amino acids, and particularly leucine.

Optimal timing of protein intake

The maximal protein synthetic response to exercise occurs when there is good availability of plasma essential amino acids in the period around exercise. Muscle protein synthesis was increased when free amino acids were ingested before and after resistance exercise, with the pre-exercise feeding protocol providing the best results.[44] However, similar responses were found when whey protein was consumed prior to, or following, a resistance bout.[45] In another study, there was similar muscle protein synthesis when an amino-acid-containing drink was consumed 1 h or 3 h following resistance exercise.[46] While these acute investigations of the response to exercise and nutrition show general benefits of consuming a source of amino acids intake soon after a workout, rather than pinpointing an ideal time for feeding, there is evidence from a chronic training study to show the advantages of early nutrition support. Young men who consumed a source of protein immediately after resistance training gained a greater increase in muscle fibre hypertrophy and lean mass compared with a group who delayed their intake by 2 h but consumed equal energy and macronutrients over a day.[39]

Unfortunately, no studies have examined the issue of protein over the whole day following a bout of exercise, so there are no firm guidelines as to the best way to spread protein intake over meals and snacks for the remainder of the time during which muscle protein synthesis is stimulated. However, it makes sense to arrange regular feeding over the day, with 20–25 g of high-quality protein remaining a benchmark for the maximum protein need at any single feeding.

Based on this information, fasting is likely to interfere with the adaptive response to an exercise bout as well as cause greater and sustained periods of negative protein balance (see table 1).

IMMUNE AND ANTIOXIDANT SYSTEMS

A single bout of exercise provides a stress to the body's immune and antioxidant status, with chronic exercise (ie,

Table 2 Special strategies for exercise and nutrition during Ramadan fasting

Guidelines regarding exercise

During periods of competition, the athlete may not be able to modify their exercise timetable. However, during periods of training they may have more flexibility to change training times to take advantage of times that they can consume food and fluids. In all cases, the athlete should make sensible decisions about the health and safety of exercise.

- The duration and intensity of exercise should be modified to suit nutritional preparation, hydration levels and environmental conditions such as heat and humidity. The athlete should take care not to exceed their exercise capacity.
- Sessions undertaken in the morning after sunrise will benefit from good eating and drinking strategies undertaken during the previous evening and before dawn. However, the athlete will have little opportunity to refuel, rehydrate and recover after these sessions.
- Sessions that are scheduled to finish just before *Itfar* (breaking fast) will benefit from the ability to eat for recovery at the break of the fast and during the evening.
- Sessions undertaken 2–3 h after the break of the fast will benefit from the best opportunities to fuel and hydrate before, during and afterwards. However, the athlete should balance this against the importance of keeping regular hours of sleep.
- Resistance training reduces negative protein balance, although in the absence of protein intake, net protein balance will remain negative. Scheduling a resistance session during a prolonged period of fasting may help to reduce total protein losses over the day and preserve muscle mass.
- The athlete should make use of other strategies to minimise sweat losses and assist temperature regulation in the heat such as staying out of a hot environment when there is an alternative, and using cooling techniques such as plunge pools and ice vests before, during and after exercise

Guidelines regarding fluid and food

Two meals are important in Ramadan: The break of the fast ('*ftou*') can be chosen from customary foods but should be adapted in quantity and in quality to meet the athlete's special needs for fluid, carbohydrate and protein. The last meal ('*shour*') should be eaten as close as possible to sunrise and should contribute to sporting goals for the day ahead. General recommendations can be made but should be individualised for each athlete:

- Carbohydrate needs vary according to the fuel needs of the athlete's exercise programme. Carbohydrate-rich foods should be included in the the *ftour* meal, especially if the athlete needs to refuel after completing a session of training or competition. High-quality protein is also needed for recovery after resistance training or prolonged high-quality workouts/events and should also be included in the *ftour* meal or snack.
- Fortunately, many of the traditional foods consumed at *ftour* are good sources of carbohydrate (eg, dates) and high-quality protein (eg, milk). The athlete should consume these as a recovery snack after exercise that is scheduled just prior to *Itfar*, followed by meals and further training sessions according to their schedule.
- The athlete should take advantage of opportunities to fuel and hydrate *during* exercise that is done after *Itfar* as well as straight after. This may enhance performance during that session, as well as contribute to total nutritional targets. Special sports foods such as sports drinks, gels and bars may provide a compact form of nutrition that is easy to consume in such a situation.
- The *shour* meal should provide a good source of fluid and fuel for the day's activities, as well as protein and other nutrients towards overall goals.
- The athlete should assess their hydration by monitoring changes in body mass (BM) and the colour/quantity of urine produced when they first wake in the morning. Monitoring changes in BM over an exercise session helps to determine the sweat losses that need to be replaced. However, the athlete will probably need to drink a volume of fluid that is 150% of this amount to account for other losses over the day (ie, 1500 ml to replace a loss of 1 kg).
- The athlete should replace salt at the same time as drinking fluids. This can be done either by drinking at the same as eating (most foods contain some salt) or by drinking oral rehydration solutions that contain salt especially to aid rehydration. This will retain fluid and, in the case of drinks consumed before going to bed, help to minimise the disturbance to sleep arising from toilet visits during the night.
- Spacing fluids over the available time rather than drinking large volumes on a single occasion also helps to reduce unnecessary urine losses. This may be difficult to balance against the need for sleep.
- In the case of competition, organisers should ensure that there is access to suitable foods and fluids at the break of the fast for athletes and officials.

training) promoting adaptations in these systems. Unlike the situation with the previously discussed issues in postexercise recovery, specific nutritional strategies to promote or preserve optimal antioxidant and immune function in athletes are not well described. This is unfortunate, since illness is likely to have a marked effect on performance of many sporting events. Because of the lack of specific guidelines on nutrient goals for immune and antioxidant health, this review will be limited to a few brief comments. There is evidence that reduced carbohydrate availability during exercise induces larger increases in stress hormones and greater perturbation of immune function parameters in the 'window' of immunosuppression after the exercise bout.[47] Immune function is also disturbed by substantial restrictions in intake of energy and protein as well as inadequate status of various micronutrients. However, detecting a link between changes in nutritional status decreases in concentration or activity of various immune system parameters, and the incidence of common illnesses such as upper-respiratory-tract infections is exceedingly complicated. The body's antioxidant system is a similarly complicated arrangement, and even less is known about the acute effects of suppressed antioxidant status on muscle damage or performance.[48] Only when further research is undertaken on these topics can we identify specific factors that may occur during fasting to impair performance via the immune and antioxidant system dysfunction.

CONCLUSIONS

Recovery after strenuous exercise involves an array of processes that are dependent on the provision of nutrients. The quantity of nutrients is important, but the timing of these is also important. In some cases (eg, protein synthesis), the stimulus for recovery is strongest in the period immediately after exercise, and a lack of nutritional support at this time will reduce the total response to exercise. In other cases, there is no effective recovery until the nutrients are supplied. When the rate at which the recovery process is limited (eg, glycogen synthesis), and there are a finite number of hours exercise between sessions, the delay in supplying nutrients will also cause a substantial reduction in preparation for the subsequent session.

Ramadan represents a special case of fasting which is undertaken by many of the world's best athletes during periods of training as well as important competitive events. Therefore, there is merit in considering ways in which exercise and nutrition patterns can be manipulated within the rules or timetable of a sport, and the requirements of the fast. Some suggestions are summarised in table 2.

Competing interests None.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1. **Maughan RJ** *et al.* Review from this series.
2. **Ivy JL**, Kuo CH. Regulation of GLUT4 protein and glycogen synthase during muscle glycogen synthesis after exercise. *Acta Physiol Scand* 1998;**162**:295–304.
3. **Hermansen L**, Vaage O. Lactate disappearance and glycogen synthesis in human muscle after maximal exercise. *Am J Physiol* 1977;**233**:E422–9.
4. **Tarnopolsky MA**, Zawada C, Richmond LB, *et al.* Gender differences in carbohydrate loading are related to energy intake. *J Appl Physiol* 2001;**91**:225–30.
5. **Burke LM**, Kiens B, Ivy JL. Carbohydrates and fat for training and recovery. *J Sports Sci* 2004;**22**:15–30.
6. **Jentjens R**, Jeukendrup A. Determinants of post-exercise glycogen synthesis during short-term recovery. *Sports Med* 2003;**33**:117–44.
7. **Burke LM**, Collier GR, Hargreaves M. Muscle glycogen storage after prolonged exercise: effect of the glycemic index of carbohydrate feedings. *J Appl Physiol* 1993;**75**:1019–23.
8. **Keizer HA**, Kuipers H, van Kranenburg G, *et al.* Influence of liquid and solid meals on muscle glycogen resynthesis, plasma fuel hormone response, and maximal physical working capacity. *Int J Sports Med* 1987;**8**:99–104.
9. **Reed MJ**, Brozinick JT Jr, Lee MC, *et al.* Muscle glycogen storage postexercise: effect of mode of carbohydrate administration. *J Appl Physiol* 1989;**66**:720–6.
10. **Zawadzki KM**, Yaspelkis BB 3rd, Ivy JL. Carbohydrate-protein complex increases the rate of muscle glycogen storage after exercise. *J Appl Physiol* 1992;**72**:1854–9.
11. **Beelen M**, Berghuis J, Bonaparte B, *et al.* Carbohydrate mouth rinsing in the fed state: lack of enhancement of time-trial performance. *Int J Sport Nutr Exerc Metab* 2009;**19**:400–9.
12. **Ivy JL**, Goforth HW Jr, Damon BM, *et al.* Early postexercise muscle glycogen recovery is enhanced with a carbohydrate–protein supplement. *J Appl Physiol* 2002;**93**:1337–44.
13. **van Loon LJ**, Saris WH, Kruijshoop M, *et al.* Maximizing postexercise muscle glycogen synthesis: carbohydrate supplementation and the application of amino acid or protein hydrolysate mixtures. *Am J Clin Nutr* 2000;**72**:106–11.
14. **Ivy JL**, Katz AL, Cutler CL, *et al.* Muscle glycogen synthesis after exercise: effect of time of carbohydrate ingestion. *J Appl Physiol* 1988;**64**:1480–5.
15. **Parkin JA**, Carey MF, Martin IK, *et al.* Muscle glycogen storage following prolonged exercise: effect of timing of ingestion of high glycemic index food. *Med Sci Sports Exerc* 1997;**29**:220–4.
16. **Burke LM**, Collier GR, Davis PG, *et al.* Muscle glycogen storage after prolonged exercise: effect of the frequency of carbohydrate feedings. *Am J Clin Nutr* 1996;**64**:115–19.
17. **Costill DL**, Sherman WM, Fink WJ, *et al.* The role of dietary carbohydrates in muscle glycogen resynthesis after strenuous running. *Am J Clin Nutr* 1981;**34**:1831–6.
18. **Nadel ER**, Mack GW, Nose H. Influence of fluid replacement beverages on body fluid homeostasis during exercise and recovery. In: Gisolfi CV, Lamb DR. eds. *Perspectives in exercise science and sports medicine. Fluid homeostasis during exercise*. Vol 3. Carmel, Indianapolis: Benchmark Press, 1990:181–205.
19. **Carter JE**, Gisolfi CV. Fluid replacement during and after exercise in the heat. *Med Sci Sports Exerc* 1989;**21**:532–9.
20. **Nose H**, Mack GW, Shi XR, *et al.* Role of osmolality and plasma volume during rehydration in humans. *J Appl Physiol* 1988;**65**:325–31.
21. **Hubbard RW**, Szlyk PC, Armstrong LE. Influence of thirst and fluid palatability on fluid ingestion during exercise. In: Gisolfi CV, Lamb DR. eds. *Perspectives in exercise science and sports medicine. Fluid homeostasis during exercise.* Vol 3. Carmel, Indianapolis: Benchmark Press, 1990:39–95.
22. **Shirreffs SM**, Taylor AJ, Leiper JB, *et al.* Post-exercise rehydration in man: effects of volume consumed and drink sodium content. *Med Sci Sports Exerc* 1996;**28**:1260–71.
23. **Maughan RJ**, Leiper JB. Sodium intake and post-exercise rehydration in man. *Eur J Appl Physiol Occup Physiol* 1995;**71**:311–9.
24. **Shirreffs SM**, Maughan RJ. Urine osmolality and conductivity as indices of hydration status in athletes in the heat. *Med Sci Sports Exerc* 1998;**30**:1598–602.
25. **González-Alonso J**, Heaps CL, Coyle EF. Rehydration after exercise with common beverages and water. *Int J Sports Med* 1992;**13**:399–406.
26. **Maughan RJ**, Leiper JB, Shirreffs SM. Restoration of fluid balance after exercise-induced dehydration: effects of food and fluid intake. *Eur J Appl Physiol Occup Physiol* 1996;**73**:317–25.
27. **Ray ML**, Bryan MW, Ruden TM, *et al.* Effect of sodium in a rehydration beverage when consumed as a fluid or meal. *J Appl Physiol* 1998;**85**:1329–36.
28. **Shirreffs SM**, Maughan RJ. Restoration of fluid balance after exercise-induced dehydration: effects of alcohol consumption. *J Appl Physiol* 1997;**83**:1152–8.
29. **Burke LM**, Maughan RJ. Alcohol in sport. In: Maughan RJ. ed. *Nutrition in sport*. Oxford, UK: Blackwell Science, 2000:405–414.
30. **Armstrong LE**. Caffeine, body fluid-electrolyte balance, and exercise performance. *Int J Sport Nutr Exerc Metab* 2002;**12**:189–206.
31. **Kovacs EM**, Schmahl RM, Senden JM, *et al.* Effect of high and low rates of fluid intake on post-exercise rehydration. *Int J Sport Nutr Exerc Metab* 2002;**12**:14–23.
32. **Archer DT**, Shirreffs SM. Effect of fluid ingestion rate on post-exercise rehydration in human subjects. *Proc Nutr Soc* 2001;**60**:200A.
33. **Burd NA**, Tang JE, Moore DR, *et al.* Exercise training and protein metabolism: influences of contraction, protein intake, and sex-based differences. *J Appl Physiol* 2009;**106**:1692–701.
34. **Tang JE**, Perco JG, Moore DR, *et al.* Resistance training alters the response of fed state mixed muscle protein synthesis in young men. *Am J Physiol Regul Integr Comp Physiol* 2008;**294**:R172–8.

35. **Biolo G**, Tipton KD, Klein S, *et al.* An abundant supply of amino acids enhances the metabolic effect of exercise on muscle protein. *Am J Physiol* 1997;**273**:E122–9.
36. **Tipton KD**, Gurkin BE, Matin S, *et al.* Nonessential amino acids are not necessary to stimulate net muscle protein synthesis in healthy volunteers. *J Nutr Biochem* 1999;**10**:89–95.
37. **Moore DR**, Robinson MJ, Fry JL, *et al.* Ingested protein dose response of muscle and albumin protein synthesis after resistance exercise in young men. *Am J Clin Nutr* 2009;**89**:161–8.
38. **Tipton KD**, Borsheim E, Wolf SE, *et al.* Acute response of net muscle protein balance reflects 24-h balance after exercise and amino acid ingestion. *Am J Physiol Endocrinol Metab* 2003;**284**:E76–89.
39. **Hartman JW**, Tang JE, Wilkinson SB, *et al.* Consumption of fat-free fluid milk after resistance exercise promotes greater lean mass accretion than does consumption of soy or carbohydrate in young, novice, male weightlifters. *Am J Clin Nutr* 2007;**86**:373–81.
40. **Josse AR**, Tang JE, Tarnopolsky MA, *et al.* Body composition and strength changes in women with milk and resistance exercise. *Med Sci Sports Exerc* 2009.
41. **Phillips SM**. Dietary protein for athletes: from requirements to metabolic advantage. *Appl Physiol Nutr Metab* 2006;**31**:647–54.
42. **Tang JE**, Moore DR, Kujbida GW, *et al.* Ingestion of whey hydrolysate, casein, or soy protein isolate: effects on mixed muscle protein synthesis at rest and following resistance exercise in young men. *J Appl Physiol* 2009;**107**:987–92.
43. **Tipton KD**, Elliott TA, Cree MG, *et al.* Ingestion of casein and whey proteins result in muscle anabolism after resistance exercise. *Med Sci Sports Exerc* 2004;**36**:2073–81.
44. **Tipton KD**, Rasmussen BB, Miller SL, *et al.* Timing of amino acid–carbohydrate ingestion alters anabolic response of muscle to resistance exercise. *Am J Physiol Endocrinol Metab* 2001;**281**:E197–206.
45. **Tipton KD**, Elliott TA, Cree MG, *et al.* Stimulation of net muscle protein synthesis by whey protein ingestion before and after exercise. *Am J Physiol Endocrinol Metab* 2007;**292**:E71–6.
46. **Rasmussen BB**, Tipton KD, Miller SL, *et al.* An oral essential amino acid–carbohydrate supplement enhances muscle protein anabolism after resistance exercise. *J Appl Physiol* 2000;**88**:386–92.
47. **Gleeson M**. Immune function in sport and exercise. *J Appl Physiol* 2007;**103**:693–9.
48. **Reid MB**. Free radicals and muscle fatigue: Of ROS, canaries, and the IOC. *Free Radic Biol Med* 2008;**44**:169–79.

Fasting and recovery from exercise

Louise Burke

Br J Sports Med 2010 44: 502-508 originally published online May 10, 2010
doi: 10.1136/bjsm.2007.071472