

The effects of fasting on metabolism and performance

R J Maughan,¹ J Fallah S,^{1,2} E F Coyle³

¹School of Sports and Exercise and Health Sciences, Loughborough University, Loughborough, UK

²Sports Medicine Research Centre, Tehran University of Medical Sciences, Tehran, Iran

³Department of Kinesiology and Health Education, The University of Texas at Austin, Austin, Texas, USA

Correspondence to

Dr R J Maughan, School of Sports and Exercise and Health Sciences, Loughborough University, Loughborough LE11 3TU, UK; r.maughan@lboro.ac.uk

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ABSTRACT

An overnight fast of 8–10 h is normal for most people. Fasting is characterised by a coordinated set of metabolic changes designed to spare carbohydrate and increase reliance on fat as a substrate for energy supply. As well as sparing the limited endogenous carbohydrate, and increased rate of gluconeogenesis from amino acids, glycerol and ketone bodies help maintain the supply of carbohydrate. Many individuals undergo periodic fasts for health, religious or cultural reasons. Ramadan fasting, involving 1 month of abstinence from food and fluid intake during daylight hours, is practised by a large part of the world population. This period involves a shift in the pattern of intake from daytime to the hours of darkness. There seems to be little effect on overall daily dietary intake and only small metabolic effects, but there may be implications for both physical and cognitive function. The limited evidence suggests that effects of Ramadan-style fasting on exercise performance are generally small. This needs to be balanced, however, against the observation that small differences in performance are critical in determining the outcomes of sporting events. Studies involving challenging sporting events (prolonged sustained or intermittent high-intensity events, hot and humid environments) are needed. Increases in subjective sensations of fatigue may be the result of loss of sleep or disruption of normal sleep patterns. Modifications to the competition timetable may minimise or even eliminate any effect on performance in sport, but there may be negative effects on performance in some events.

INTRODUCTION

Fasting can be defined as the absence of food and fluid intake, but there is no clear definition of the time after the last intake at which fasting might be said to begin. The postingestive period certainly lasts for several hours, but the duration will depend on the amount and type of the food that is ingested. Any consideration of the response to short-term fasting cannot therefore easily be separated from the effects of the last food intake.

While it is clear that prolonged periods without food intake are harmful to both health and performance, it is less clear that shorter periods of total abstinence from food intake, or more prolonged periods of intermittent fasting, are necessarily harmful. The intervals between intake of food or drinks may be short during the day, but most people experience an overnight fast of about 8–12 h on a daily basis. Fasting, often in combination with exercise, has long been used as a tool for the study of regulation of intermediary

metabolism, and there is an extensive literature in this area. These studies have focused on total fasts lasting from a few hours to a few days or on energy restricted diets, usually in obese individuals, of longer duration. In some, but not all, of these studies, water intake has been allowed in order to separate the effects of dehydration from the metabolic effects of the absence of exogenous nutrient intake. There have been some studies on intermittent fasting, as practised by Muslims during the period of Ramadan fasting, but in many ways this represents simply a shift in the time base: instead of fasting during the night while asleep, the period of fasting is shifted to the daylight hours. Changes in sleeping patterns and other lifestyle factors complicate the interpretation of any metabolic or performance effects.

More recently, there has been an interest in the performance effects of Ramadan-style intermittent fasting as global participation in international sport has increased. Muslim athletes now represent a significant fraction of the competitors in major sporting events: when these events take place during Ramadan, some athletes will defer fasting on competition days but will continue to train, while others will observe the fast on competition days. The absence of food and fluid intake in the hours before or after competition or training, as well as during the exercise period itself, may have significant implications for performance or for the adaptations that take place in response to training. This review will cover the metabolic responses to short-term fasting and the consequences for exercise performance before considering the specific implications of intermittent fasting as practised during Ramadan.

METABOLIC RESPONSES TO FEEDING

The metabolic response to food intake depends on many different factors. The size (energy content) and macronutrient composition (fat, carbohydrate, protein, alcohol) of meals and the presence of other nutrients and non-nutritive components will all have significant effects. The food structure and consistency will also influence digestibility. Other factors, too, are important, and Stock showed that the metabolic response to a standard meal ingested after an overnight fast was different after a day of fasting when compared with a day of overeating.¹ These metabolic responses are important, as they will affect the recovery of the liver and muscle glycogen stores as well as influencing protein synthetic pathways by virtue of effects on the substrate and hormonal profile.

The response to feeding begins with the cephalic responses that are initiated by the sight and smell of food and are further influenced by taste, texture and other organoleptic properties of the food. Cephalically stimulated activities are estimated to contribute to a large part—perhaps 50%—of the secretory responses to food ingestion as well as to a part of the motor response. There has been much interest recently in the effect of the presence of nutrients—specifically carbohydrate—in the mouth on the ability to complete an exercise task. Carter *et al* showed that swilling the mouth with a carbohydrate drink at intervals during a cycling time trial that lasted about 60 min gave a significantly better performance than swilling with a water placebo.²

Ingestion of food causes simultaneous activation of gastrointestinal motility, gastric and pancreatic secretion and release of a range of gastrointestinal hormones that have both local and systemic actions. These hormones include cholecystokinin, ghrelin, pancreatic polypeptide and incretins.³ As blood glucose and amino acid concentrations rise after ingestion of a mixed meal, so insulin secretion is stimulated to promote storage of the ingested nutrients and to suppress mobilisation of endogenous carbohydrate and lipid stores.

The period after digestion and absorption of ingested nutrients is marked by storage of carbohydrate in liver and muscle, with rates of muscle glycogen synthesis determined by the preingestion glycogen store, the amount of carbohydrate consumed, the glycaemic index of the meal and the presence of other nutrients.⁴ There has been much interest recently in the effects of protein ingestion on the rates of protein synthesis and breakdown. In the postabsorptive state, the rate of protein breakdown will exceed the synthetic rate, leading to a net loss of lean tissue. Even short periods of fasting will therefore result in some loss of lean tissue. Feeding carbohydrate will result in a net positive protein balance as a result of the effects of insulin, which will inhibit breakdown as well as stimulating synthesis.⁵ Feeding protein will also result in an increase in circulating insulin levels in addition to increasing the availability of essential amino acids for incorporation into protein.

METABOLIC RESPONSES TO FASTING

The first stage of fasting is the postabsorptive period, which begins once all of the nutrients ingested at the last meal have been absorbed from the small intestine. The timing will depend on the size and the composition of the meal, but this may be as soon as 3–4 h or as long as 7–8 h. The early stages of fasting last for about 24 h after the last meal as the body adjusts to the absence of the nutrients that would normally be ingested during this time. Blood glucose is well maintained during this time as the liver glycogen store is progressively hydrolysed and released as glucose into the circulation. In the postabsorptive state, the liver glycogen content after a period of ad libitum diet is highly variable, amounting to about 14–80 g/kg, with a mean value of about 44 g/kg.⁶ Assuming a liver mass of 1.2–1.5 kg, this gives on average a glycogen store of about 60 g. In the early stages of fasting, the liver releases its glycogen store at a rate of about 4 g of glucose per hour.⁷

Metabolic rate is not substantially affected by fasting, so there is a continued need for oxidative metabolism to meet energy needs. It is well established that the rate of carbohydrate utilisation is decreased in the fasted state and that the

energy demand is met by an increased rate of fat oxidation.⁸ The effect of this is to spare the body's limited carbohydrate reserves for those tissues that are obligatory users of carbohydrate, including especially the central nervous system and the erythrocytes. One of the primary responses to fasting is the mobilisation of part of the substantial reserves of triglyceride contained within adipose tissue, leading to an increase in the circulating concentration of free fatty acids in the plasma and therefore to an increased availability of this fuel source to the muscles.⁸ There is also an increase in the release of glycerol from adipose cells, and this is a valuable precursor for gluconeogenesis in the liver, contributing to the pool of available carbohydrate. The integrated metabolic response that involves mobilisation of fat stores and hepatic gluconeogenesis is regulated by changes in the hormonal environment, including a reduction in the plasma insulin concentration and increased circulating concentrations of glucagon, catecholamines, growth hormone, thyroid-stimulating hormone and corticosteroids.⁹ The intracellular mechanisms by which increased fatty acid availability can suppress the oxidation of carbohydrate in human skeletal muscle have been the subject of much investigation, but they remain unclear.

It is rather clear that increasing the availability of carbohydrate substrate will increase the rate of carbohydrate oxidation and decrease the rate of lipid oxidation at rest and during exercise. Ingestion of carbohydrate prior to exercise will stimulate insulin release, inhibiting fatty acid mobilisation from adipose tissue and thereby reducing the oxidation of plasma-derived fatty acids.¹⁰ Coyle *et al* showed that the oxidation of intramuscular lipid is also suppressed when carbohydrate is consumed before exercise, with approximately equal reductions in the oxidation of these two sources of substrate.¹¹ To determine how long a meal will affect the metabolic response to exercise, Montain *et al* fed carbohydrate (2 g/kg body mass) to nine endurance-trained and nine untrained subjects who then cycled for 30 min at 70% of $\dot{V}O_2$ peak after an interval of 2, 4, 6, 8 and 12 h.¹² They showed that glucose homeostasis and carbohydrate oxidation were not significantly different on the trials at 8 and 12 h after ingestion, suggesting that the postprandial response even for this small meal lasts at least 6 h. In contrast, when carbohydrate is fed after exercise has begun, lipolysis is not suppressed.¹⁰

Part of the body's need for carbohydrate is met during fasting by hepatic glycogenolysis and part by gluconeogenesis, which occurs primarily in the liver but also in the kidney. In the early stages of fasting, the requirement for glucose is typically about 105 g/day for the average adult male, but this falls after a few days to about 75 g/day.¹³ This is accounted for, at least in part, by an increased availability of ketone bodies as a fuel that can be used by cardiac muscle, brain and other tissues. The primary substrates for gluconeogenesis are lactate released by glycolysis in red blood cells, the carbon skeletons of some amino acids and the glycerol that is released from adipose tissue when lipolysis rates are high. Krebs calculated that the synthesis of 1 g of glucose by gluconeogenesis using only amino acids as precursors would require the catabolism of 1.75 g of protein.¹⁴ Clearly, such a contribution to gluconeogenesis cannot be sustained for long without a loss of functional capacity. The tissues of the gut may be able to supply some amino acids for gluconeogenesis during short periods of fasting, but other tissues cannot do so without some loss of function.

PERFORMANCE EFFECTS OF FASTING: HIGH-INTENSITY EXERCISE

The focus of studies that have examined the effects of fasting on exercise performance has generally been on endurance exercise, where the withdrawal of dietary carbohydrate might be expected to reduce exercise performance. In high-intensity exercise, there is little time or opportunity for the ingestion of food or fluids during the exercise period itself, so the implications of fasting are restricted to a consideration of the nutrient intake—or absence thereof—in the hours and days prior to exercise. It is also the case that the factors that may be responsible for fatigue in prolonged exercise—including carbohydrate depletion, hyperthermia and dehydration—are unlikely to be relevant in exercise lasting only a few seconds or a few minutes.

Gleeson *et al* showed that a 24 h fast is detrimental to cycling performance at an intensity of 100% Vo_2max : the mean endurance time (212 ± 27 s) was lower when exercise was performed 24 h after the last meal than when the same meal was eaten 4 h before exercise (243 ± 17 s).¹⁵ A similar loss of performance was seen when a low-carbohydrate diet was substituted for the normal mixed diet: exercise time at 104% of Vo_2max was reduced from 4.87 min on a mixed diet to 3.32 min on a low-carbohydrate (3% CHO) diet.¹⁶ Greenhaff *et al* reported that time to fatigue at 100% of Vo_2max was reduced from 5.13 to 3.68 min after 3 days on a low-carbohydrate (10% CHO) diet.¹⁷

There may be some effect of a reduction in the muscle glycogen store on the maximal rates of muscle glycogenolysis with a consequent loss of exercise performance during high-intensity exercise, but a few days of fasting in the absence of exercise has little effect on muscle glycogen content.¹⁸ It seems likely, however, that at least part of the early onset of fatigue when high-intensity exercise is performed in the fasted state can be ascribed to the metabolic acidosis that accompanies fasting. A similar response is seen when a low carbohydrate diet is consumed, perhaps due to the increased protein catabolism that results in increased acid formation.¹⁹ There must, however, be other mechanisms involved, as the acute reversal of a diet-induced metabolic acidosis does not restore endurance capacity during high-intensity exercise in man.²⁰

PERFORMANCE EFFECTS OF FASTING IN THE PRE-EXERCISE PERIOD: ENDURANCE EXERCISE

An extensive review of the older literature on the effects of fasting on endurance performance was published by Aragón-Vargas.²¹ The conclusion of this review was that a short period (24 h to 4 days) of fasting in humans resulted in a decreased capacity to perform endurance exercise. In spite of a rather consistent effect of fasting, however, there was no clear evidence as to the mechanism responsible for the earlier onset of fatigue.

Loy *et al* had a group of experienced cyclists exercise to fatigue at 86% of Vo_2max on two occasions: one trial was 3 h after the last meal, and one was 24 h after the same last meal.²² The exercise time was 115 ± 26 min on the fed trial, but this was reduced to 42 ± 6 min on the 24 h fasted trial. A separate group of subjects followed the same protocol but exercised at 79% of Vo_2max : they fatigued after 191 ± 25 min on the fed trial, but only for 142 ± 20 min on the 24 h fasted trial. Maughan and Gleeson showed that a power output that could be sustained for 119.5 ± 5.8 min after an overnight 12 h fast could be

sustained for only 77.7 ± 6.8 min after a 36 h fast.²³ These are very substantial reductions in exercise capacity.

EFFECTS OF CARBOHYDRATE FEEDING DURING EXERCISE

It has long been known that ingestion of carbohydrate during prolonged exercise can improve exercise performance, and the older studies were reviewed by Maughan.²⁴ Carbohydrate is usually consumed in solution, and it may be difficult to separate the effects of fluid intake from that of carbohydrate. However, when the carbohydrate content is equal, the blood glucose and insulin responses during exercise are the same when carbohydrate is ingested in liquid or solid form, and both give a higher blood glucose concentration than a sweet placebo.²⁵ No difference in time-trial performance was seen when either solid or liquid carbohydrate was consumed during a preceding period of steady-state cycling.²⁶ Most athletes, though, will prefer to take carbohydrate in liquid form. Fatigue can be reduced by adding carbohydrate to fluids consumed so that about 30–60 g of rapidly absorbed carbohydrate is ingested throughout each hour of an athletic event.²⁷ There is also good evidence that regular intake of carbohydrate during exercise can enhance performance in repeated sprint models designed to simulate movement patterns in team games such as football as well as preserving performance of skilled movements.²⁸ Some recent data suggest that regular carbohydrate ingestion during a 90 min intermittent exercise protocol might preserve footballing skills better than a flavoured placebo.²⁹ The availability, and hence oxidation, of ingested carbohydrate may be limited by the rate of absorption in the small intestine, and combinations of CHO that use different intestinal transporters for absorption (eg, glucose and fructose) can result in higher oxidation rates than can be achieved by single carbohydrate sources.³⁰ There is some evidence that the beneficial effects of carbohydrate ingestion on exercise performance are more marked in subjects who have fasted for several (10–12) hours than when carbohydrate is fed within a few hours before the start of exercise,²⁸ but there remain advantages of consuming some carbohydrate during prolonged exercise. Some of the improved performance with carbohydrate ingestion during exercise may come from the stimulation of carbohydrate receptors in the mouth.²

METABOLIC AND PERFORMANCE EFFECTS OF RAMADAN-STYLE FASTING

Ramadan-style fasting differs from the model used in many studies of the metabolic and performance effects of fasting in that it involves repeated days without food and fluid intake during the hours of daylight but with no restrictions on intake during the hours of darkness. The duration of each day's period of fasting during Ramadan is relatively short, though it will depend upon both latitude and season. At high latitudes in summer time, the daily period of fasting may be 18 h or even more. The London Olympic Games of 2012 will begin on 27 July and end on 12 August: on the opening day, the sun will rise in London at 05:17 and will not set until 20:56, giving almost 16 h of daylight. Typically, however, the daily period of fasting is not more than about 12–15 h and may be substantially shorter than this. This is not much longer than the normal overnight fast that most people experience while sleeping, and Ramadan fasting is therefore less a formal fast and more a phase shift in food intake with a change in sleep cycles to accommodate the change in the timing of food intake.^{31 32} It is not entirely clear whether short periods of fasting have

any effect on competitive sports performance, although it is well established that metabolic responses are already apparent in the first few hours after food intake.³³ The available literature does not include research on the most challenging events or exercise protocols (sustained or intermittent high-intensity exercise with overlay of skills/cognitive function—such as marathon running, 90 min of high level soccer, tennis matches, cycling road races, etc—especially in hot conditions). Many events involve heats and finals or repeated matches, so the carryover effect of intermittent fasting on subsequent performances needs to be studied.

Particular challenges may be faced by athletes who fast during competition in events lasting longer than about 30 min when the ambient temperature is high. Where events take place late in the day, there is a danger that athletes will be hypohydrated prior to the start of competition, likely leading to a loss of performance.³⁴ Even if athletes successfully avoid exposure to the environment and thus limit pre-event hypohydration, the inability to take fluids during exercise is likely to lead to some loss of performance.³⁵ For athletes with another round of competition late the same day or on the following day, the inability to replace sweat losses and to ingest carbohydrate to begin the process of muscle glycogen replenishment in the immediate postevent recovery period will also present a challenge.^{4,36}

In general, Ramadan fasting seems to have little effect on lipid, carbohydrate or protein metabolism, or hormonal levels.^{37,38} The small increases that are observed to occur in variables such as uric acid or urea are usually attributed to mild dehydration.³⁸ Similar small changes, that were attributed to changes in patterns of food consumption during Ramadan, changes in activity patterns and hypohydration were also observed in a large population of young football players who fasted during Ramadan.³⁹ Clearly, however, there will be changes over the course of the day, and these will be influenced by whether or not food is consumed, when it is consumed and the composition of meals.

In addition to changes in the timing of food intake, and possibly also in the amount of intake, there may be changes in the composition of the diet during Ramadan.⁴⁰ Changes in the composition of the diet may affect the protein synthetic response to an exercise bout, even when this takes place after an overnight fast. Increasing the protein content of the diet results in proportional increases in protein oxidation during exercise, but very high intakes (3.6 g/kg/day) may result in a reduction in fractional synthetic rate after exercise when compared with low (0.8 g/kg/day) or moderate (1.8 g/kg/day) intakes.⁴¹ The intake of even small amounts of protein, amino acids and/or carbohydrate in the period just before or just after training will influence the rates of protein synthesis and degradation.⁴² This, in turn, can influence the metabolic and functional adaptations taking place in response to the training stimulus.^{43,44} Most sports nutrition guidelines recommend an intake of protein,⁴⁵ carbohydrate⁴ and fluid³⁶ in the period after training to promote recovery and to stimulate the process of adaptation taking place within the exercised muscles. Athletes training through the month of Ramadan in preparation for competitions to be held soon after the end of the fasting period might therefore consider changing the time of their training sessions to late evening or very early morning.

The effects of Ramadan fasting on measures of physical performance are unclear. Some studies have shown that performance is impaired, while others have shown no effect.

The performance of trained runners in 100 and 800 m races was adversely affected by Ramadan fasting.⁴⁶ Impairments in a variety of other submaximal and maximal exercise performance tasks have also been shown.^{47–50} Zerguini *et al* showed that endurance performance declined throughout the fast in young football players.⁵¹ Meckel *et al* also showed that some performance measures (3000 m run time, 6 × 40 m run time and jump performance) were adversely affected during Ramadan in young football players, but other measures (sprint performance, 4 × 10 m shuttle run) were not significantly affected.⁵² Another recent study using well-trained judokas as subjects also found that some performance components were affected: 30 m sprint performance, multistage shuttle run test performance, squat jump and countermovement jump did not change during Ramadan, but there was a small reduction in average power during a 30 s repeated jump test at the end of Ramadan.⁵² Kirkendall *et al*, however, showed no negative effects of fasting on a range of performance measures.⁵³ Karli *et al* also showed no effect of Ramadan fasting on performance of the Wingate anaerobic exercise test.⁵⁴

There have been few studies on the effects of Ramadan fasting on cognitive function, but both mild dehydration and carbohydrate deprivation may adversely affect cognitive ability.^{55,56} The subjects in these studies may, however, have been influenced to some degree by their expectation of a negative response to the withdrawal of food and fluids. Others, however, have found no effect of 2 days of energy restriction on any aspect of cognitive performance or mood state when meals with or without energy content but indistinguishable in sensory characteristics were fed.⁵⁷ The results of this study indicate that psychological factors related to awareness of the fact that meals were being withheld may be more important than the absence of food itself. This suggests in turn that athletes who plan to fast during competition periods should not anticipate negative effects on performance. There is anecdotal evidence that some Muslim athletes believe that the importance of observing the Ramadan fasting is so strong that this in itself may be able to counteract at least some of the physiological effects.

In summary, the effects of short-term fasting are far from clear. Even in the laboratory environment where external factors are controlled, it seems that there will be little or no effect in many exercise tasks. Nonetheless, there may be some negative effects on more prolonged exercise tasks, on tasks that pose combined physical and mental challenges and in situations where recovery between rounds of a competition may be compromised. The effects of high environmental temperature and humidity may be a particular problem in some situations. These factors are described in other papers in this issue.

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