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Symposium 2: Exercise and protein nutrition
Efficacy and consequences of very-high-protein diets for athletes and exercisers

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Athletes and exercisers have utilised high-protein diets for centuries. The objective of this review is to examine the evidence for the efficacy and potential dangers of high-protein diets. One important factor to consider is the definition of a 'high-protein diet'. There are several ways to consider protein content of a diet. The composition of the diet can be determined as the absolute amount of the protein (or other nutrient of interest), the % of total energy (calories) as protein and the amount of protein ingested per kg of body weight. Many athletes consume very high amounts of protein. High-protein diets most often are associated with muscle hypertrophy and strength, but now also are advocated for weight loss and recovery from intense exercise or injuries. Prolonged intake of a large amount of protein has been associated with potential dangers, such as bone mineral loss and kidney damage. In otherwise healthy individuals, there is little evidence that high protein intake is dangerous. However, kidney damage may be an issue for individuals with already existing kidney dysfunction. Increased protein intake necessarily means that overall energy intake must increase or consumption of either carbohydrate or fat must decrease. In conclusion, high protein intake may be appropriate for some athletes, but there are potential negative consequences that must be carefully considered before adopting such a diet. In particular, care must be taken to ensure that there is sufficient intake of other nutrients to support the training load.

Very-high-protein diets: Efficacy: Potential dangers: Athletes and exercisers

High protein intakes have been long popular with athletes and other exercisers. Historical references to high-protein diets extend as far back as ancient Greece and the legendary wrestler, Milo of Kroton. Body builders and weight lifters have long advocated not only the efficacy but also the necessity of high protein intake for success in their sports. More recently, high protein intake has been advocated during weight loss. Clearly, diets high in protein content have been utilised for quite some time and for a variety of reasons.

An important consideration is what amount of protein consumption would be considered high[1]. Protein intake may be considered in terms of the absolute amount of protein consumed, the proportion of total energy intake as protein or the amount relative to body weight. Protein intake among athletes and exercisers is usually reported to be somewhere in the range of 1·2–1·6 g protein/kg body mass per d[2]. The USA RDA for protein is 0·8 g protein/kg body mass per d. Thus, for an 80 kg weight lifter, the RDA would be 64 g protein/d. If that athlete consumes 12 552 kJ/d (3000 kcal/d), then the protein intake would be about 8·5% of total energy intake. The average protein intake, at least in Western countries, is 15–16% of total energy[3]. Thus, the RDA would be roughly half of what is habitually consumed, i.e. seemingly very low. It should be noted that the RDA is established to provide an 'adequate' amount of protein. It is highly unlikely that an athlete training for many hours per week would be satisfied with

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the 'adequate' amount. Nevertheless, many consider a high-protein diet to be anything more than the RDA[1]. Others might consider a high-protein diet to be anything more than the average habitual intake of 15–16% of total energy[3]. The Institute of Medicine of the USA set the accepted macronutrient distribution range at 10–35% of total energy intake[4]. So, we could consider anything above 35% of energy intake as high. Moreover, the absolute amount of protein that may be considered high on a given energy intake may then be considered moderate or even low, if the energy intake is increased. Careful definition of what a high protein intake entails should be included in any discussion of studies on high-protein diets.

The appropriate or optimal amount of protein for exercisers to consume is unknown and likely varies with the particular activity and feeding situation. Consumption of large amounts of protein raises health concerns, primarily associated with bone and renal health. This review will focus on the evidence of efficacy of high protein intakes in young, healthy athletes and other exercisers. Furthermore, the potential problems associated with high protein intakes and the evidence for the development of these problems will be examined.

Potential situations for high protein intake

Muscle hypertrophy

Probably the reason most often cited for consuming a high-protein diet is to increase muscle mass, particularly among body builders, power lifters and other strength athletes. Strength and power athletes commonly eat well over 2 g protein/kg body mass per d and many well over 3 g protein/kg body mass per d[2,5]. It is commonly accepted by many strength athletes that high protein intake is necessary for optimal muscle building. This belief is based on the metabolic response to protein ingestion following resistance exercise. The following discussion will be predicated on the assumption that appropriate training is included in any regime dedicated to increasing muscle mass and strength.

The metabolic mechanism for changes in muscle protein is net muscle protein balance (NBAL)[2,5–8]. Muscle proteins, in fact all body proteins, are constantly being synthesised and degraded. Changes in muscle mass result from changes in the balance of the synthesis and breakdown of muscle myofibrillar, i.e. structural proteins, such as actin, myosin, troponin etc. The magnitude and duration of the positive periods of NBAL will determine the extent of muscle hypertrophy[5,6,9,10]. Nutritional intake and exercise are both potent modulators of the duration and magnitude of these periods of positive and negative NBAL. An in-depth discussion of these processes is beyond the scope of this review; interested readers should see one of the many excellent recent reviews on this topic[2,5–8,11,12], including one from this symposium[13].

The rationale for the importance of a high-protein diet for muscle hypertrophy with training stems from the desire to provide amino acids following exercise to build more muscle proteins, thus increasing muscle hypertrophy[2]. Resistance exercise increases the synthesis of muscle myofibrillar proteins[14]. Sufficient amino acids must be consumed to support increased synthesis. The impact of resistance exercise on muscle protein synthesis and NBAL lasts for 48 h or more[15]. Thus, ingestion of protein within that time period results in the interactive effect on muscle protein synthesis and NBAL[16] contributing to increased myofibrillar protein accretion. Any protein containing meals consumed within 24–48 h following a resistance exercise session will contribute to muscle hypertrophy. Therefore, the notion that ingesting greater amounts of protein will provide more substrate for synthesis of myofibrillar proteins leading to greater hypertrophy stems from the interactive response to resistance exercise and protein ingestion.

Another aspect of the rationale for high protein intake and muscle hypertrophy stems from the impact of exercise on muscle proteins. Resistance exercise, particularly with a strong eccentric component, leads to damaged muscle tissues and disruption of the myofibres[17,18]. The increased rate of muscle protein breakdown following resistance exercise[15,19] likely results, at least in part, from the need to degrade these damaged proteins. Whereas the amino acids from these proteins are then reutilised for the increased rate of muscle protein synthesis, transport of amino acids from the blood into the muscle also is increased[19,20]. Therefore, a source of exogenous amino acids would enhance the ability of the muscle to rebuild and remodel the damaged proteins. Increasing the amount of ingested protein is thought to contribute the amino acids necessary, not only to build new protein, but also to rebuild and remodel damaged proteins such that the muscle function is enhanced[21,22]. However, there is some controversy as to the necessity for consumption of very large amounts of dietary protein as is often practised[2,8,23].

Elevated protein requirements for strength and power athletes, for the reasons discussed above, are often cited as a rationale for recommendations for high-protein diets. Protein requirements for strength and power athletes are usually said to be in the range of 1·5–2·0 g protein/kg body mass per d[2,10,24–26]. These numbers are derived primarily from carefully controlled N balance studies[27–29]. Thus, the methodology used to establish the RDA for protein suggests that strength athletes need approximately double that amount of protein just to stay in N balance. Of course, if the athlete simply achieves N balance there will be no muscle hypertrophy. So, the requirements must be, and often are, considered to be the bare minimum and much more protein should be consumed to increase muscle mass. In fact, N balance studies on athletes suggest that the greater the protein intake, the greater the positive N balance, at least up to levels investigated to date[2]. It follows that, assuming positive N balance leads to muscle hypertrophy, very-high-protein diets would lead to very large gains in muscle mass.

It should be noted that there seems to be a disconnect, both quantitative and qualitative, between positive N balance and muscle hypertrophy. An examination of the available data suggests that an intake of about 2·5 g protein/kg body mass per d may result in N retention of about 15 g N/d[2]. If we assume that all of that N is converted into protein for increased muscle mass, admittedly an overestimation, then about 375 g of muscle would be deposited

each day or about 137 kg in a year. An increase in lean body mass of even 10 % of that number would be remarkable in already well-trained athletes. It is clear that short-term N balance data may be unreliable as an estimator of long-term gains in muscle mass, particularly at the high end of protein intake[2,8,30]. That theoretical argument is supported by data from a study conducted in the early 1990s. N balance was greater when bodybuilders consumed 2·62 g protein/kg body mass per d compared to 1·35 g protein/kg body mass per d[27]. However, differences in muscle mass and strength were lacking. Thus, recommendations of very-high protein intakes based solely on N balance data should be considered somewhat problematic.

N balance data alone are not the only data used to support the necessity for high protein intakes. Recent, chronic feeding studies can be found to support both enhanced muscle hypertrophy with increased protein intake[31] or to refute that notion[27]. However, the equivocation is likely due to the inherent difficulties in conducting longitudinal training and feeding studies. The control of these studies is extremely difficult and small differences may not be detected[8]. Moreover, a recent meta-analysis determined that increased protein intake does not enhance muscle hypertrophy with training[32]. Moreover, there is evidence that increased protein intake increases basal levels of muscle protein synthesis[33]. However, this study was not conducted in the context of training and the results may not apply. Moreover, the high protein intake was accompanied by decreased carbohydrate intake to maintain energy balance. Given the potential detrimental impact of suboptimal carbohydrate intake on resistance training[10], this situation may be untenable for maximal muscle hypertrophy (see later for a more extensive discussion of this topic). Therefore, it is difficult to utilise data from these types of studies to make firm conclusions, either in support of or to refute, concerning the efficacy of high protein intake for optimising muscle hypertrophy.

A logical extension to the argument that very-high protein intakes are necessary for muscle hypertrophy is that no hypertrophy will occur on lower protein intakes. This argument is patently false. Over 100 years ago, Chittenden[34] showed that muscle mass can be gained on protein intakes as low as 1 g protein/kg per d. There are more recent studies showing that protein intakes as low as 1·2 g protein/kg body mass per d are sufficient for increased muscle mass[35,36]. Thus, it seems that support for high protein intakes in the scientific literature must be considered, at the very least, equivocal.

The argument contrary to recommendations that high protein intakes are not necessary for maximal hypertrophy may be made considering the evidence that exercise training increases the efficiency of utilisation of amino acids from ingested protein. Elegant studies from the laboratory of the late Gail Butterfield in the 1980s showed that exercise increased amino acid utilisation[37,38]. However, the applicability of these results to intense resistance exercise training may be criticised on the basis of the low-exercise intensities used in those studies[39]. Recently, two investigations utilised a 12-week, longitudinal training design to investigate this question. Both demonstrated that not only was lean body mass gained on 1·2–1·4 g protein/kg body

mass per d, but that retention of ingested N was greater following training than before training[35,36]. The authors suggested that the anabolic stimulus of the resistance exercise results in greater disposal of the amino acids due to the increase in muscle protein synthesis following each exercise bout[15,19]. Thus, greater efficiency of N utilisation with training may actually decrease the need for protein making very-high-protein diets quite unnecessary for weightlifters.

Another consideration that may impact a decision on the efficacy of high-protein diets for muscle hypertrophy is the amount of ingested protein that provides the maximal anabolic response after an exercise bout. Since the acute interactive response to protein ingestion and exercise ultimately leads to accumulation of muscle during training[8,9,40], the optimal acute response is critical. Recent data suggest that ingestion of 20–25 g protein results in maximal rates of muscle protein synthesis following resistance exercise[41]. This amount of protein provides about 8·5 g of essential amino acids, roughly the amount that maximally stimulated protein synthesis at rest in both young and elderly subjects[42]. Thus, it seems that the amount of protein necessary to maximally stimulate muscle protein synthesis is similar, if not slightly less, following exercise than at rest. Moreover, at higher doses of ingested protein, amino acid oxidation was increased[41] suggesting that the excess amino acids are not used for other amino acid requiring processes in the body. If we assume that this response is similar for each meal, then it seems that about 100 g of high-quality protein would be what is required to optimise the anabolic response[10]. If those feedings were solely responsible for muscle hypertrophy, these data could be interpreted to suggest that about 1·25 g protein/kg body mass per d is optimal; roughly the amount determined in N balance studies. Then again, this supposition does not include any protein ingested at other times. It is clear that the anabolic response is not the same at all times of day and at all times in relation to exercise[8,10]. Thus, the timing of protein intake will influence the overall anabolic response such that hypertrophy may be quite different despite identical total protein intakes. Moreover, it is known that the anabolic response is refractory to continuous hyperaminoacidemia, at least at rest[43]. However, muscle protein synthesis does respond to successive bolus ingestions of amino acids after resistance exercise[44,45]. Therefore, it could be argued that the optimal amount of protein ingested per day is greater than 100 g, but the optimal amount is certainly unknown. Moreover, the type of protein[46–49], timing of protein ingestion and the combination of the type and timing[49,50], as well as other factors such as type and intensity of exercise[16] determine the actual anabolic response. Thus, determination of the optimal amount of dietary protein to maximise muscle hypertrophy is much more complex than simply naming an amount of protein for all situations[8]. More research must be done to determine, definitively, the optimal amount of protein ingested to maximise muscle hypertrophy in various training and nutritional situations.

In summary, it is clear that ingestion of protein following exercise stimulates muscle myofibrillar protein synthesis resulting in positive NBAL. This response is the

metabolic mechanism for increased muscle mass with training. Evidence from short-term N balance studies suggests that increasing amounts of protein result in continually increasing positive N balance. These results are often interpreted to mean that very high levels of protein in the diet result in superior muscle gains with training. However, issues with N balance measurements, particularly at high protein intakes, increased efficiency of protein utilisation with training and limits to the acute anabolic response to each protein ingestion can be used to argue that very high amounts of protein are unnecessary and the extra protein is oxidised for energy. Properly controlled longitudinal, endpoint studies showing that increased protein intake results in increased muscle growth are rare and, at best, the results of such studies can only be considered equivocal. Additionally, it is probably overly simplistic to assume that a given amount of protein would be optimal in all training and feeding situations and for all individuals. There are many factors, e.g. timing of protein intake, quality of protein source, co-ingestion of other nutrients that influence the anabolic response of muscle to protein. Thus, the amount of protein in the diet may not be the most important factor to consider[5–8]. On the other hand, given that there may be some advantage to higher protein intakes, what is the down side? If there are no negative repercussions, then erring on the side of elevated protein intake may be advisable. This determination should be made for each individual given that person's particular training situation and exercise goals. The risks of high protein intakes will be discussed below.

Hypoenergetic weight loss

Another situation in which high protein intakes (usually in the range of 30% of total energy or greater) are widely recommended is during energy-restricted weight loss. There is mounting evidence that diets high in protein result in increased weight and fat loss during hypoenergetic dieting in overweight and obese individuals[5,51–56]. In these studies, dietary protein was typically increased at the expense of carbohydrate. Often, energy intake was reduced simply by reducing carbohydrate intake resulting in relatively greater protein intake. Moreover, addition of exercise enhanced the weight loss with high-protein diets[5,51–56]. Perhaps more importantly, the loss of lean mass during hypoenergetic weight loss is reduced with higher protein intakes[5,51–56]. Given the increase in NBAL following exercise[15,19] and the known response of muscle protein metabolism to protein intake following exercise[20,47–49], the decrease in muscle loss should not be surprising.

The mechanisms for the increased fat and weight loss and decreased muscle loss with higher-protein diets are not entirely clear. Ultimately, the first law of thermodynamics means that energy is energy. However, it should be remembered that gross energy is not the same as metabolisable energy[57]. Increased thermic effect of food, increased gluconeogenesis, substrate cycling and increased protein synthesis may all be involved in increased energy expenditure with high-protein v. high-carbohydrate intake[5,58–60]. However, Buchholz and Schoeller[57] suggest that, whereas these processes may contribute to greater fat loss, it cannot be explained solely by these increases[57]. More recently, Feinman and Fine[60] put forward the argument that these explanations are based on equilibrium thermodynamics, but living organisms are far from equilibrium[60]. Thus, non-equilibrium thermodynamics due to variable substrate fluxes has been suggested to help explain the differences.

The leucine content of the protein may be important for the increased fat loss and retention of lean body mass during weight loss dieting[58]. The notion that muscle protein synthesis is increased by the leucine in the protein is behind this proposed mechanism[61]. Muscle protein synthesis is an energetically expensive process. It is estimated that the addition of each amino acid during elongation requires 4 M ATP[62]. Given the limited energy available inherent to hypoenergetic dieting, the energy must come from endogenous stores. Since these diets are low-carbohydrate, the energy likely comes from fat oxidation. Moreover, there is evidence that protein intake stimulates fat oxidation to a greater extent than other nutrients[63] and fat oxidation is greater following high protein intakes during energy restricted weight loss[64,65]. Moreover, exercise-induced fat oxidation is greater following high protein intake[66]. Thus, fat oxidation is increased by the ingestion of protein, per se, and to supply energy for protein synthesis. Furthermore, as the diet is successful in preserving muscle mass, more energy will be necessary, further separating the muscle loss from a lower-protein situation.

In addition to increased weight and fat loss with high protein intakes, it seems that elevated protein helps reduce weight regain following weight loss[67,68]. Moreover, and perhaps more importantly, the weight gained after 6 months of high protein intake was entirely lean body mass, whereas weight regain on habitual dietary intake was both lean and fat mass[67,68]. Interestingly, these differences were apparent despite a relatively modest difference in protein intake. The difference in protein intake between groups was only about 3% of total energy[67,68]. Furthermore, these results suggest another mechanism unlikely to be apparent in the studies mentioned earlier involving clamped energy intake. Satiety was greater in the protein group than the habitual energy group[67]. Increased satiety has been shown to result from acute protein consumption and high-protein diets[69–72]. Satiety measured in the postabsorptive state may be attributed to increased resting energy expenditure[68–70]. Interestingly, satiety may be influenced by the type of protein ingested[69], as well as the sex of the individual[73]. Thus, higher protein intake not only leads to increased weight loss during hypoenergetic dieting but also contributes to better maintenance of weight loss when otherwise habitual energy levels are consumed in obese and overweight individuals.

Whereas there is ample evidence for amelioration of lean body mass loss during hypoenergetic weight loss in overweight and obese populations consuming high-protein diets, there is relatively little information available on healthy athletes and exercisers. The metabolic and training status of athletic individuals differs from that of obese and overweight, particularly sedentary, individuals. Thus, the metabolic situation is different and may impact the

response to high-protein hypoenergetic diets. We recently demonstrated that a high-protein diet maintained muscle mass during rather severe energy restriction for 2 weeks in weightlifters[74]. These athletes consumed approximately 60 % of their normal energy intake, while maintaining their normal training load. One group consumed their habitual macronutrient composition and the other increased their protein intake (about 2·3 g protein/kg body mass per d or 35 % of total energy) during the 2 weeks of hypoenergetic dieting. The high-protein group lost much less lean mass than the control group. However, unlike the situation in obese and overweight individuals[51,53,75,76], the total weight loss was greater in the group that maintained their habitual dietary composition[74]. Thus, for athletes desiring more total mass loss without regard for composition of the mass that is lost, high protein intake may not be the best choice. Whereas this situation is unlikely to apply to most athletes, there are scenarios, e.g. a climber in cycling, in which this approach may be considered. Alternately, if preservation of lean body mass is the main goal, increased protein intake seems advisable. Moreover, the amount of fat lost by the high protein and control groups was almost identical. Similar results were reported previously[77]. It seems that the pattern of body composition changes during hyopenergetic weight loss may be different for lean exercisers than for overweight or obese individuals even when the latter are exercising[51,53,75,76].

The differences in body composition changes between overweight and obese individuals and exercisers may be due to inherent metabolic differences between the two groups or due to methodological differences in studies. Dietary fat oxidation is inversely proportional to body fatness[78,79]. Another factor may be the composition of the hypoenergetic diets. In studies with overweight populations, protein intake often is increased at the expense of carbohydrate intake[51,53,75,76]. This switch would be untenable to an athlete desiring to maintain training quality and quantity[10,80]. Therefore, in our study, protein intake was increased at the expense of fat intake[74]. It is conceivable that the relatively greater carbohydrate intake in the obese subjects decreased fat oxidation in those studies[51,53,75,76], but since carbohydrate intake was similar in both groups no such difference was noted in our study[74]. Thus, macronutrient composition may explain greater fat and weight loss with high-protein diets in sedentary, overweight v. lean, athletic individuals.

Otherwise or in addition to dietary differences, differences in the exercise performed by the subjects also may contribute to differences noted between athletes and overweight individuals during weight loss. Whereas the studies of overweight individuals often included some fairly limited resistance exercise[53,75,76], the weightlifters in our study maintained a fairly intense training load, including a high volume of resistance exercise training, during the 2 weeks of weight loss[74]. Given the inherent stimulation of muscle protein synthesis by resistance exercise[15,19] and the interactive effect of protein ingestion with the resistance exercise for up to 24 h after the exercise[16,20], the greater volume of exercise[81] likely resulted in more periods of protein deposition in the trained individuals contributing to the maintenance of muscle mass. Moreover,

it is clear that the intensity of the resistance exercise must be high to fully stimulate muscle protein synthesis[16,82]. Thus, the differences in the distribution of weight loss between overweight and athletic populations may be due to any of several factors and is almost certainly multifactorial.

Recovery from intense exercise

Another situation in which high-protein diets have been advocated is for recovery from intense exercise. Intense exercise, particularly exercise with a high-eccentric component, may lead to decrements in the ability to perform subsequent exercise sessions, muscle soreness and damage to muscle proteins[83]. High protein intake during recovery has been advocated to ameliorate these detrimental consequences of intense exercise.

The most common model used to investigate impact of dietary manipulations on the response to intense exercise is an eccentric exercise, muscle damage model. Recently, we investigated the efficacy of short-term, i.e. 72 h, high protein intake on indices of recovery from intense eccentric exercise. In these studies, we found that an increase in protein intake from about 1·5 to about 2·0 g protein/kg body mass per d had no impact on recovery of muscle function, soreness or plasma creatine kinase concentration, often touted as an indicator of muscle damage (OC Witard, SR Jackman and KD Tipton unpublished results). However, when protein intake was increased to 3 g protein/kg body mass per d, muscle soreness was decreased in the immediate aftermath, i.e. during the first 24 h, of the exercise bout (SR Jackman, OC Witard and KD Tipton, unpublished results). The amelioration of muscle soreness may be due to the branched-chain amino acid content of the extra protein[84]; however, the physiological mechanism remains to be elucidated.

The practical implications of these data are not clear. Muscle soreness over the entire 72 h period was no better with high protein intake. Furthermore, there was no impact on creatine kinase or muscle function, arguably the most important aspect of recovery. Finally, the subjects in those studies were untrained. It is not clear if the impact of the protein would have been similar in trained individuals, more accustomed to high-intensity exercise. Thus, the efficacy of high protein intake for recovery from intense eccentric exercise seems rather limited, even at a rather high level of protein intake.

Intense training sessions repeated over a prolonged period of time may result in overreaching or overtraining[85,86]. This situation may result in detriments in the ability to perform exercise and thus may impair the effectiveness of training or competitive performance. We recently investigated the impact of a high-protein diet on emotional responses, immune function and decrements in performance with a week of intensified training[87]. Cycling time-trial performance, immune markers and mood state deteriorated in trained cyclists after a week of training at approximately double the volume and intensity of normal training. Doubling the protein intake to 3 g protein/kg body mass per d had a possibly beneficial effect on time trial performance as assessed by inferential statistics[88,89]. However, the effect could not be explained by

any physiological indices we measured. Thus, it seems, it may be due to a central effect. Whereas, the mood state of the cyclists deteriorated in both trials, the high protein intake clearly ameliorated this effect. Moreover, there were indications that immune impairment with intense training was somewhat alleviated by the high protein intake. Our data suggest that high protein intake may help athletes tolerate intense training.

The improvements in tolerance of increased training loads noted in our study[87] must be considered in context before these data are used to make recommendations. First, the amount of protein consumed was very high and, anecdotally, was difficult to tolerate for many of the cyclists. Very few endurance athletes consume such large amounts of protein[39,90]. Moreover, in order to maintain energy balance, it was necessary to clamp carbohydrate intake at 6 g carbohydrate/kg body mass per d. That level of carbohydrate intake is below the recommendation for that level of training[90,91]. Thus, our results must be considered in the context of a relatively low carbohydrate intake for that situation. It remains to be seen if a lower, more practical, level of protein intake would engender similar results and/or if those results would be similar with sufficient carbohydrate intake. Nevertheless, these studies offer the suggestion that perhaps high protein intake is supportive of intense training. The mechanisms for any impact of protein remain to be elucidated.

Potential problems with high-protein diets

Given the popularity of high-protein diets for athletes, particularly strength athletes, it is unsurprising that a good deal of attention has been given to potential problems. High protein intake has been associated with metabolic and clinical problems[92–95]. The two most commonly described negative consequences of chronic consumption of large amounts of protein are renal dysfunction and loss of bone mass. The accepted macronutrient distribution range for protein set by the US Institute of Medicine is 10–35 %[4]. Moreover, the Institute of Medicine set no upper limit on protein intake due to the lack of clear cause and effect of high protein intake with health problems. Of course, it should be noted that the lack of an upper limit on protein intake does not necessarily mean that there is no potential for danger at very high levels of protein consumption[4]. If we use the maximum rate of urea synthesis and the protein requirement (expressed as the RDA) as the basis for estimates of the maximal safe level of protein intake, then as much as 300 g protein/d could safely be consumed by an 80 kg male[96]; more if increases in muscle protein synthesis and NBAL with training and exercise are considered[5,8,10,97]. It is clear that there are a number of athletes, primarily strength and power athletes that do consume this much protein[2], yet the safety of this practice, particularly in the long term, is unknown and debatable.

The impact of dietary protein on renal function is one of the more common concerns. It is clear that protein intake can have an impact on renal function. The Brenner Hypothesis may be the most cited reference on this topic[95]. Brenner and co-workers proposed that the sustained increase in glomerular filtration rate from high dietary protein intake would be detrimental for kidney function leading to a potential increase in risk of renal disease[98]. However, there is a lack of solid support for this hypothesis in otherwise healthy individuals[93,95]. Certainly, individuals with otherwise compromised renal function should be very cautious about increasing their protein intake[92,93,95]. Moreover, the interaction between exercise, particularly resistance exercise, with protein intake could change the impact on kidney function[94]. Yet, little is known about the impact of exercise combined with high protein intakes on kidney function[94,95]. Studies directly measuring the impact of protein intake on kidney function in exercisers are scarce. However, what data are available suggest no relationship of high protein intake with renal dysfunction in athletes[99,100]. Given the paucity of data on this subject, particularly with regard to the length of time of measurement, the number of individuals consuming large amounts of protein diets and the potential for dangers, it is clear that more research is needed, particularly on the long-term impact of high protein intake.

Another issue related to renal function and protein is the impact of dietary protein on hydration. Since, increased protein intake leads to increased solute excretion, including urea and other nitrogenous wastes[94,95], the notion that increased fluid excretion is necessary to support this excretion has been put forward[101]. Given that exercise increases sweat losses, another potential danger of high-protein diets is chronic dehydration. Recently, Martin and co-workers measured indices of hydration status in volunteers consuming three levels of protein (0·8, 1·8 and 3·6 g protein/kg body mass per d) for 4 weeks each. Whereas blood urea N was increased on the highest protein intake, other markers of hydration status were similar[101]. It should be noted that the activity patterns of these subjects were not reported. Therefore, it is difficult to determine how much high protein intake would impact hydration with high levels of physical activity and sweating.

Another issue that is commonly associated with increased protein intake is bone loss[93,94,102]. However, as with renal issues, loss of bone with high protein intake is not substantiated by the available data. Evidence of increased calciuria with high protein intake often is used to support the impact on bone loss[93,102]. Increased Ca excretion seems to be observed only with purified protein sources and not food sources even with as much as 30 % energy as protein. The increase in calciuria can be ameliorated by increased P intake, as when food sources of protein are consumed and with sufficient fruit and vegetables in the diet[93,102]. Moreover, increased calciuria does not necessarily relate to bone loss. In fact, there is evidence that increased protein intake leads to improved bone health[93,102]. Certainly, synthesis of bone collagen is increased by protein ingestion[103]. Given that many modes of exercise, e.g. resistance exercise, walking, running, etc., are stimulatory for increased bone mineralisation, as well as the issues mentioned above, it seems unlikely that most high-protein diets will lead to bone problems in regular exercisers. It seems sensible to recommend that most of the protein intake is in the form of food and consumption of sufficient fruits and vegetables is sufficient if high-protein diets are to be practised.

Other possible metabolic and health consequences, including kidney stones and atherogenesis, of high protein intakes have been mentioned[92,93]. As with the other issues mentioned earlier, these potential consequences have not been studied in healthy exercisers consuming large amounts of protein. This factor could be important. For example, the impact of exercise, *per se*, on metabolic and cardiovascular health makes these concerns potentially less important in that group. Moreover, much of the evidence for those issues seems to be fairly equivocal and not well supported[92,93]. Thus, at the very least, more research into metabolic health problems with high-protein diets in exercisers is necessary.

One interesting potential issue that is unlikely to be a health issue, but rather a performance issue, is with the response of muscle protein synthesis. Runners who consumed a high-protein diet for 4 weeks had a reduced response of muscle protein synthesis to running[104]. The impact of this reduction is unclear. It is possible that it is merely a reflection of reduced turnover and not reduced production of proteins. Further, the type of proteins impacted is not known. In that study only mixed muscle protein synthesis was measured[104]. Thus, if there were differential effects on various protein pools in the muscle, the result may be advantageous or detrimental. More information is necessary to make clear conclusions on the detrimental impact of high-protein consumption in exercisers.

The potential problem with high protein intake most likely for the majority of healthy exercisers and athletes is the substitution of protein for other macronutrients, particularly carbohydrate. Assuming an individual has an upper limit for energy intake, as protein intake increases, intake of energy in the form of other nutrients must decrease. In most cases, if it is fat intake that is reduced, there is unlikely to be a problem. For some with very low fat intakes anyway, it is possible, albeit unlikely, that essential fatty acid intake could be compromised. On the other hand, if it is carbohydrate intake that is replaced by the extra protein, then problems may result. Increasingly high protein intake would necessitate greater and greater decreases in carbohydrate intake[10]. Given the popularity of low-carbohydrate diets, particularly for those interested in weight control or loss, this possibility is not unlikely. Clearly, this issue would be aggravated by energy restriction for weight loss.

The energy requirement of an athlete would influence the likelihood of problems due to substitution of protein for carbohydrate. Given high energy intakes, carbohydrate intake may still be sufficient even with elevated protein intakes[10]. However, unless energy intake is very high, then carbohydrate intake will necessarily be lower than that sufficient to support moderate to intense training[80], even with protein intake that many would consider moderate[10].

This issue would likely be more detrimental to endurance athletes, but should not be ignored by strength and power athletes. It is clear that resistance exercise depletes glycogen stores[105]. Thus, sufficient carbohydrate intake to restore muscle glycogen would be necessary to support high-intensity training. Moreover, the response of transcriptional[106] and translational pathways[107], as well as the rate of muscle protein synthesis[108], is impaired when resistance exercise is performed in the glycogen-depleted state. Thus, resistance training with insufficient carbohydrate intake will lead to suboptimal muscle hypertrophy by decreasing the ability to perform intense training, as well as impairment of the anabolic response to the training.

Conclusions

Athletes and exercisers consume high-protein diets for a number of reasons. Probably, the most prevalent reason for high protein intake is to enhance gains of strength and mass with resistance training. Muscle mass and strength can be gained on a wide range of protein intakes, from as little as the RDA up to very large amounts. There is little support for the necessity of very high amounts, e.g. >2 g protein/kg body mass per d, for optimal muscle hypertrophy during energy balance or excess. On the other hand, during energy restriction, increased protein intake, i.e. the maintenance of protein intake in the face of decreased energy leading to a relative increase, seems to increase loss of mass, in obese individuals, and protects muscle mass, in both athletic and obese populations. There seems to be preliminary evidence that high protein intake may increase tolerance of intense training. However, the practicality of such high protein intakes remains to be established. Thus, there may be some situations in which a high-protein diet is efficacious. Athletes and exercisers should consider their own training and competitive goals prior to any nutritional decisions. A cost–benefit type analysis seems warranted.

This review is in no way intended to advocate high protein intakes for athletes and exercisers. Yet, the risks of high protein intake seem to be minimal for otherwise healthy athletes. Primarily, exercisers should consider their protein intake in the context of their overall energy requirements, as well as the necessity for the other macronutrients, particularly carbohydrate. Protein intake that supplants carbohydrate intake may interfere with training adaptations and/or limit the ability to train effectively. Certainly, the difference between a high-protein diet and an *excessive* protein diet must be considered. At some point, likely dependent on a combination of factors including muscle mass type, intensity and frequency of physical activity, energy expenditure and ingestion, ingestion of other nutrients, timing of protein ingestion, age, training status and undoubtedly others, amino acids from ingested protein will no longer be incorporated into body proteins or used for other amino acid requiring pathways[41]. The amino acids will be deaminated and the C skeletons utilised for ATP production or gluconeogenesis, while the N is excreted as urea[109]. Thus, careful consideration of appropriate and optimal protein intake is quite complex. In most cases, there seems to be little, if any, rationale for protein intakes above the habitual norm of 1·5–2·0 g protein/kg body mass per d.

Human beings have long been associated with high-protein diets. Today, protein intake in Western societies is generally 15–16 % of total energy[3]. However, it almost certainly was much higher in ancestral *Homo sapiens*. Estimates of protein intake in pre-agricultural human subjects

are usually greater than 30 % of energy[110]. Prior to the advent of agriculture, human beings evolved with hunted game as a large contributor to food intake[111]. Moreover, most evidence suggests that ancestral human beings were much more active than most modern human beings[112]. Given that our genome has not changed since those times, it could be suggested that high-protein diets are natural for athletes. As mentioned, this review is not meant to advocate high-protein diets. However, there may be situations in which some athletes may benefit from higher protein intakes given careful consideration of each individual training situation, competitive goals and safety of the nutritional regime.

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