REVIEW ARTICLE

Nutritional Considerations for Vegetarian Athletes

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With the growing interest in the potential health benefits of plant-based diets, it is relevant to consider whether vegetarian dietary practices could influence athletic performance. Accordingly, this review examines whether nutrients that may differ between vegetarian and omnivorous diets could affect physical performance. We also describe recent studies that attempt to assess the effects of a vegetarian diet on performance and comment on other nutritional aspects of vegetarianism of relevance to athletes. Although well-controlled long-term studies assessing the effects of vegetarian diets on athletes have not been conducted, the following observations can be made: 1) well-planned, appropriately supplemented vegetarian diets appear to effectively support athletic performance; 2) provided protein intakes are adequate to meet needs for total nitrogen and the essential amino acids, plant and animal protein sources appear to provide equivalent support to athletic training and performance; 3) vegetarians (particularly women) are at increased risk for non-anemic iron deficiency, which may limit endurance performance; and 4) as a group, vegetarians have lower mean muscle creatine concentrations than do omnivores, and this may affect supramaximal exercise performance. Because their initial muscle creatine concentrations are lower, vegetarians are likely to experience greater performance increments after creatine loading in activities that rely on the adenosine triphosphate/phosphocreatine system. 5) Coaches and trainers should be aware that some athletes may adopt a vegetarian diet as a strategy for weight control. Accordingly, the possibility of a disordered eating pattern should be investigated if a vegetarian diet is accompanied by unwarranted weight loss. *Nutrition* 2004;20:696–703. ©Elsevier Inc. 2004

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INTRODUCTION

Vegetarian and semivegetarian diets have attracted considerable scientific and popular attention in Western countries in recent years. Recent estimates suggest that approximately 2.5% of American adults[1,2] and 4% of Canadian adults[3] report following a vegetarian diet. Motivations for such dietary practices may include religious or cultural customs, perceived health benefits of a vegetarian diet, and ethical or philosophical beliefs, among others.[4] Not surprisingly, these different rationales for vegetarianism are associated with heterogeneous dietary practices. The nutritional implications of vegetarian diets are correspondingly varied.[5] Individuals who self-identify as vegetarian fall along a continuum of food habits with respect to the extent that foods derived from animals are avoided, ranging from those who exclude or rarely eat red meat, to those who avoid any food products containing ingredients derived from animal sources.[6] Table I presents the range of dietary patterns that could be classified as vegetarian. In this review, we define vegetarian diets as those that exclude tissue proteins (i.e., meat, fish, and poultry).

Although the classification of dietary patterns as vegetarian or omnivorous is somewhat vague due to the wide variability within these two categories,[7] interest in exploring the consequences of a so-called vegetarian diet continues. Initially, investigations of vegetarian diets explored their nutritional adequacy; more recently, research has tended to focus on the health implications of vegetarianism. Positive health effects have been reported in association with vegetarian diets, including reduced risks for obesity, type 2 diabetes, hypertension, cardiovascular disease, and some cancers.[8–10] However, whether these associations are primarily due to the consumption of a plant-based diet (and the avoidance of animal tissue proteins) or other lifestyle practices associated with vegetarianism can be difficult to ascertain. Health benefits attributed to a vegetarian diet could be due to other lifestyle factors, given that mortality rates are similar among vegetarians and health-conscious omnivores.[11]

TABLE I.

CLASSIFICATION OF VARIOUS VEGETARIAN DIETS

Type of vegetarian diet	Definition
Semivegetarian	Avoids some, but not all, animal-derived foods (e.g., meat, poultry, fish, eggs, and dairy products). Most often red meats are avoided or consumed in a limited amount.
Lacto-ovo-vegetarian	Includes milk, other dairy products, and eggs; avoids meat, poultry, fish, and other seafood.
Ovovegetarian/lactovegetarian	Ovovegetarians include eggs but avoid milk and other dairy products, meat, poultry, fish, and other seafood. Conversely, lactovegetarians include dairy products but exclude eggs and other animal-derived products.
Vegan	Avoids all animal-derived foods (including milk, other dairy products, eggs, meat, poultry, fish, and other seafood).
Macrobiotic	Avoids most animal-derived foods and emphasizes unprocessed organic foods.

The question of whether vegetarianism is associated with beneficial, or detrimental, effects on athletic performance has also

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been considered.[12,13] Observational studies of vegetarian and non-vegetarian athletes[14,15] and elderly long-term vegetarian and non-vegetarian recreational exercisers[16] have not found differences in performance or fitness associated with the amount of animal protein consumed. Short-term interventional studies in which subjects consumed vegetarian or non-vegetarian diets for test periods (ranging from 2 to 6 wk) also detected no difference in performance parameters based on the presence or absence of foods derived from animal tissues.[13,17] In line with these findings, previous reviews of the scientific literature have concluded that a well-planned and varied vegetarian diet can meet the needs of athletes.[12] However, it is appropriate to revisit the topic of vegetarianism and athletic performance now in light of recent research findings.

In this review, we examine possible mechanisms by which vegetarian dietary practices could theoretically influence athletic performance. We consider the impact of the macronutrients protein and carbohydrate; micronutrients such as iron, vitamin B12, and the antioxidants; and other dietary components such as creatine. We describe studies that have attempted to assess the effects of vegetarianism on physical performance and explore other nutritional aspects of vegetarianism of relevance to athletes, such as the female athlete triad and vegetarianism in youth. We summarize key observations regarding the effects of a vegetarian diet on performance in athletes. It should be noted that this report is not intended to provide a comprehensive review of the nutritional implications of vegetarianism; rather, it focuses on aspects of the vegetarian diet that may affect physical performance. Information on nutrients of concern and recommended food patterns is available elsewhere.[18,19]

MACRONUTRIENTS

Athletic performance depends on appropriate nutrition. The macronutrient composition of the athlete's diet must be sufficient for energy needs to be met.[20] Two classes of macronutrients deserve consideration when examining the possible impact of a vegetarian diet on athletic performance: protein and carbohydrate.

Protein

EFFECT OF EXERCISE AND VEGETARIANISM ON PROTEIN REQUIREMENTS. There is ongoing controversy about whether athletes' protein requirements exceed those of normally active adults. Several investigators have suggested that physical activity increases protein requirements to different extents depending on the type and amount of activity.[21] Typical recommendations are 1.2 to 1.4 g/kg/d for endurance athletes and up to 1.7 g/kg/d for resistance and strength-trained athletes, particularly those in the initial stage of training.[20] However, the Institute of Medicine recently concluded that the evidence for increased requirements for physically active individuals was not compelling and suggested that the recommended dietary allowance (RDA) of 0.8 g of protein per kilogram of body weight per day was appropriate for healthy adults undertaking resistance or endurance exercise.[22]

The protein requirements of vegetarians were also examined by the Institute of Medicine.[22] It was concluded that a separate recommendation for protein consumption was not required for vegetarians who consume dairy products or eggs and complementary mixtures of high-quality plant proteins. However, the issue of protein quality was recognized as a potential concern for individuals who avoid all animal protein sources (e.g., vegans) because plant proteins may be limiting in lysine, threonine, tryptophan, or sulfur-containing amino acids. Accordingly, a protein scoring pattern was developed that indicates the amounts of these essential amino acids that must be present per gram of total protein to meet the RDA for the essential amino acid (when total protein intake is equal to the RDA).[22] The essential amino acid composition of various dietary protein sources is compared with the protein scoring pattern developed by the Institute of Medicine in Table II. Because the scoring pattern is intended for use with all individuals 1 y and older, amounts of amino acids per gram of protein for those of various ages are approximate rather than exact. For example, a 50-kg adult would have an RDA for protein of 40 g/d (0.8 g/kg/d $\times$ 50 kg) and an RDA for lysine of approximately 2 g/d (38 mg/kg/d $\times$ 50 kg). If that individual consumed the RDA for total protein, each gram of protein would need to provide approximately 51 mg of lysine to meet the RDA for lysine (2 g lysine is approximately equal to 40 g of protein $\times$ 0.051 g of lysine per gram of protein).

TABLE II.

COMPARISON OF THE ESSENTIAL AMINO ACID CONTENT OF DIETARY PROTEIN SOURCES TO THE FOOD AND NUTRITION BOARD/INSTITUTE OF MEDICINE SCORING PATTERN FOR LYSINE, THREONINE, TRYPTOPHAN AND SULFUR-CONTAINING AMINO ACIDS.

	Essential amino acid (mg/g of protein)			
Protein source	Lysine	Threonine	Tryptophan	Sulfur containing
Pattern*	51	27	7	25
Beef	83	44	11	37
Egg	70	49	16	56
Wheat	28	30	13	39
Brown rice	38	37	13	35
Almonds	29	32	15	25
Chickpeas	67	37	10	28
Soybeans	63	41	14	28

* The Food and Nutrition Board/Institute of Medicine pattern[22] represents milligrams of an essential amino acid that must be present per gram of dietary protein to meet the recommended daily allowance for the essential amino acid when total protein intake is equal to the recommended daily allowance. It is appropriate for use with those 1 y and older.

As shown in Table II, animal proteins (e.g., beef and egg) contain essential amino acids in amounts above those specified in the scoring pattern, and this is also true for many beans and legumes. Although most other plant protein sources are also sufficient in threonine, tryptophan, and the sulfur-containing amino acids, many are low in lysine. Thus, a vegan diet meeting but not exceeding the RDA for protein would likely be below the RDA for lysine, unless almost all protein was provided by beans and legumes, which contain more lysine than is needed to meet the scoring pattern. As an example, consider the same 50-kg adult discussed above. If that individual consumed a diet containing 40 g of protein (the RDA), 25% of which was provided from each of wheat, rice, almonds, and chickpeas, this would provide only 1.6 g of lysine (less than the RDA of about 2 g). However, if total protein intake was increased to 50 g or more (using a similar mixture of proteins), this would provide at least 2 g of lysine, thereby meeting or exceeding the RDA.

PROTEIN INTAKES OF VEGETARIANS. The literature is consistent in reporting that vegetarians' protein intakes are lower than those of omnivores.[18,23–29] However, protein intakes are generally well above the RDA in both groups, suggesting that in most cases adequacy of protein intake is not a concern. Further, typical diets provide an average of approximately 15% of energy from protein, with 5th and 95th percentiles at about 11% and 20% of energy, respectively,[22] and vegetarian diets also fall within this range. Because athletes typically have higher energy requirements than the general population, even diets with relatively low percentages of energy from protein provide generous amounts of protein when energy intakes are high. For example, if the 50-kg individual discussed earlier was a normally active young woman, her energy requirement might be approximately 2000 kcal/d.[22] If she was a vegetarian with a relatively low protein intake (e.g., 11% of energy), her diet would provide 55 g of protein (0.11 × 2000 kcal/4 kcal per gram of protein = 55 g of protein), considerably above her RDA of 40 g/d. If she was an athlete expending 3000 kcal/d (with a corresponding increase in energy intake), still with 11% from protein, her protein intake would further increase to 82 g/d. Thus, it is clear that, for practical purposes, inadequate intakes of total protein and essential amino acids are unlikely to be a concern for vegetarian athletes. The possible exception could be athletes following low-protein vegan diets who are also attempting to limit their energy intake.

Carbohydrate

It is worth considering the performance implications of differences in carbohydrate intake among vegetarian and non-vegetarian athletes, given that the importance of dietary carbohydrate on endurance performance is well-recognized[20] and that plant-based diets may contain a greater proportion of energy from carbohydrates.[18,30] If a vegetarian diet was more likely to ensure optimal carbohydrate intake, it could benefit those athletes involved in endurance sports such as long-distance running. However, provided energy intakes are adequate to meet energy expenditure, diets of omnivores and vegetarians can readily provide the 7 to 8 g of carbohydrate per kilogram of body weight per day recommended to maintain glycogen stores from day to day.[20] For example, a 60-kg endurance athlete expending 3600 kcal/d would receive more than 8 g of carbohydrate per kilogram of body per day even if the diet provided only 55% of energy from carbohydrate.

MICRONUTRIENTS

Several dietary micronutrients also have the potential to influence athletic performance, and intakes or status may differ between vegetarians and omnivores. In this section we discuss iron, vitamin B12, and the antioxidant vitamins C and E.

Iron

IRON CONTENT AND BIOAVAILABILITY IN VEGETARIAN DIETS. Numerous studies have demonstrated that the total iron intake of vegetarians is similar to or greater than that of non-vegetarians, whereas few (if any) studies have reported lower iron intakes among vegetarians.[23–29,31–33] However, total iron intake provides almost no indication of the amount of absorbed iron, which varies inversely with body iron stores and is influenced by the chemical form of the iron and the presence of other dietary factors that can enhance or inhibit absorption.[34]

Iron occurs in the food supply in two chemical forms: heme and non-heme. Heme iron represents about 40% of the iron in meat, fish, and poultry. It is more efficiently absorbed (about 15% to 40% absorption) than non-heme iron, (about 1% to 15% absorption), which comprises the remaining iron in meat, fish, and poultry and all iron in other foods).[34] By definition, vegetarian diets contain no heme iron, whereas diets with substantial amounts of red meats provide approximately 10% to 12% of total iron in the heme form. Semivegetarian diets containing chicken or fish provide less heme iron, in proportion to the lower amounts of total iron in these foods (e.g., the total iron contents of 100 g of cooked lean beef, chicken breast, and halibut are 3.3, 1.0, and 1.1 mg, respectively).

In addition to differences in the amount of heme iron provided, vegetarian and omnivorous diets may vary with respect to other dietary factors that can enhance or inhibit iron absorption. As reviewed by Hallberg and Hulthen,[35] non-heme iron absorption is *enhanced* by tissue protein factor (found in meat, fish, and poultry), vitamin C, alcohol, and possibly retinol and carotenoids. Conversely, non-heme iron absorption is *inhibited* by phytic acid in whole grains, legumes, lentils, and nuts; polyphenols in tea, coffee, red wines, and certain vegetables; soy protein; eggs; and calcium and phosphate salts. In most vegetarian diets, the possible increase in enhancers (vitamin C and carotenoids from higher intakes of vegetables and fruits) does not offset the possible increase in inhibiting factors and the absence of tissue protein factor. For example, Hunt and Roughead[36] used a crossover design to assess iron absorption from vegetarian and non-vegetarian diets in young women. The diets, which were followed for 4 wk before iron absorption was assessed, contained similar amounts of total iron, vitamin A, and calcium, but the vegetarian diet contained 2.5 times as much fiber, 3 times as much phytic acid, and no heme iron. Vitamin C intake was high in both diets but was about 20% higher on the vegetarian diet. Compared with the non-vegetarian diet, non-heme iron absorption from the vegetarian diet was 70% lower (1.1% versus 3.8%, or 0.14 mg versus 0.48 mg), and total iron absorption was approximately one-sixth (0.14 mg versus 0.89 mg).

Based on these various considerations, recommended iron intakes for vegetarians are increased by 80% to compensate for the reduced bioavailability of iron from vegetarian diets.[37] The RDAs for omnivorous adult men and premenopausal women are 8 mg/d and 18 mg/d respectively; for vegetarians, the recommendations are 14 mg/d and 32 mg/d.[37]

IRON STATUS OF VEGETARIANS. Most studies have indicated that the prevalence of iron-deficiency anemia is similar among vegetarians and omnivores.[26–28,33] However, given the reduced bioavailability of iron from vegetarian diets and that iron intakes in vegetarian diets are similar to or only somewhat higher than those of omnivores, it is not surprising that iron stores are lower in vegetarians, as demonstrated by lower levels of serum ferritin.[25,26,28,29,31–33,38–41] Many of these studies also found that vegetarians are more likely to have non-anemic iron deficiency (i.e., depleted iron stores with serum ferritin <12 μg/L but normal hemoglobin concentration).[25,26,29,32,40,41]

Very few studies have assessed the iron status of vegetarian athletes. It is possible that findings would be similar to those in normally active vegetarians and omnivores reported above; however, because certain types of physical activity may increase athletes' iron losses (e.g., gastrointestinal blood loss; hematuria from footstrike hemolysis in runners),[37] the tendency for vegetarians to have suboptimal iron status could be exacerbated among athletes.

IRON STATUS AND PHYSICAL PERFORMANCE. During maximal exercise, oxygen transport to muscle is the limiting factor for aerobic performance. Accordingly, higher hemoglobin levels are associated with greater oxygen transport and improved aerobic performance.[42] The beneficial effects of an increase in hemoglobin within the normal range have been clearly demonstrated by studies using blood doping or erythropoietin.[42] This was illustrated by the effect of reinfusion of 900 mL of autologous freeze-preserved blood in a double-blind, sham-controlled crossover study of elite runners.[43] Mean hemoglobin concentration increased significantly from 151 to 165 g/L and was associated with a 34% increase in treadmill running time.

The converse is also true: lower hemoglobin levels are associated with reduced oxygen transport and, hence, impaired aerobic performance. It is well established that clinical anemia interferes with exercise performance, but it appears that even reduced hemoglobin within the normal range can negatively affect performance. For example, blood withdrawal was used to decrease hemoglobin concentration by 18 g/L in five men and five women. The procedure did not result in clinical anemia but was associated with a 14% decrease in endurance performance time.[42]

Controversy has existed regarding whether exercise performance is impaired in individuals with non-anemic iron deficiency.[44] Some studies have found that providing iron supplements to this group is beneficial to performance,[45–47] whereas others have found it to be ineffective.[48,49] In part, the discrepant results appear to be related to whether supplementation led to an increase in hemoglobin concentration, suggesting that functional anemia was present at baseline. Functional anemia refers to a hemoglobin concentration within the normal range that is lower than physiologically normal for an individual and therefore responds to supplementation with an increase. It can be diagnosed only retrospectively after supplementation (e.g., a woman with an initial hemoglobin concentration of 131 g/L would be diagnosed as having had functional anemia if her hemoglobin increased after supplementation; if her hemoglobin did not increase, she would not have had functional anemia). Clearly, the risk of functional anemia is restricted to those with low or depleted iron stores, which is more common among vegetarians.

Recent research has suggested that tissue iron deficiency may impair the adaptation to physical training. Tissue iron deficiency is detected by elevated serum transferrin receptor concentrations and may or may not be present in those with depleted iron stores as assessed with serum ferritin. Brownlie et al.[50] studied the response to aerobic training in 41 women with non-anemic iron depletion (serum ferritin < 16 μg/L, hemoglobin > 120 g/L). In this double-blind study, women were randomly assigned to receive iron supplementation (16 mg/d of iron) or placebo for 6 wk, during which time they took part in 4 wk of endurance training on cycle ergometers. The iron and placebo groups improved their endurance capacity, but improvement was greater in the iron group. Further analysis indicated that the performance benefits in the iron group were limited to participants with tissue iron deficiency at baseline, as indicated by an increased serum transferrin receptor concentration. Improvement in endurance capacity among those with normal serum transferrin receptor concentrations did not differ between the iron and placebo groups.[50]

Vitamin B12

Vegetarians who exclude all foods from animal sources (e.g., vegans) do not have a reliable source of vitamin B12 in their diet without use of fortified foods or a supplement. Although vitamin B12 does not have an ergogenic effect in those with adequate intakes,[51] over time inadequate intakes will lead to macrocytic anemia. Like other anemias, macrocytic anemia is associated with reduced oxygen transport and, hence, impaired aerobic performance. An additional concern about vitamin B12 deficiency in vegetarians is that macrocytic anemia may be masked by high folate intakes, which would be expected in vegetarians with generous intakes of fruits, vegetables, legumes, and whole or enriched grains. This means that other symptoms of vitamin B12 deficiency, including damage to the spinal cord, could progress to the point that they become irreversible.

As a vegetarian diet becomes more restricted, it is increasingly likely that vitamin B12 intake will be deficient.[52] Strict vegetarians have lower serum vitamin B12 levels than do lacto-ovo vegetarians (LOVs) or individuals who occasionally consume meat.[53] Thus, vegan athletes (like others who adhere to a vegan diet) need to include synthetic vitamin B12 in their diets to prevent macrocytic anemia. Supplements or fortified foods may be used to meet the need for vitamin B12.

Antioxidants

EXERCISE AND OXIDATIVE STRESS. Exercise, especially that of high intensity and long duration, can lead to increased production of reactive oxygen species (e.g., free radicals) and consequent oxidative stress on tissues.[54–57] It should be noted that this is not a consistent finding: discrepancies among studies may relate to different levels of training of the subjects, different types and intensities of exercise, and different measures of oxidative stress.[54,57] Nevertheless, to the extent that it occurs, oxidative stress can contribute to lipid peroxidation, which in turn affects membrane fluidity and integrity and the activity of membrane-bound receptors and enzymes.[57] Alterations in protein may also occur, as may DNA-strand breakage, further affecting cellular function.[57] These cellular changes have been hypothesized to contribute to muscle damage and soreness and to affect recovery of muscle damage after exercise. Thus, it is conceivable that antioxidant needs of athletes may be greater than those of sedentary individuals. Vegetarian diets, which typically contain higher amounts of the dietary antioxidants vitamin E, vitamin C, and β-carotene, might provide better protection than omnivorous diets against exercise-associated oxidative stress. Exploring this possibility requires an examination of whether antioxidant status differs between vegetarians and omnivores and an assessment of the effects of antioxidant supplementation.

ANTIOXIDANT STATUS OF VEGETARIANS AND OMNIVORES. Rauma and Mykkanen[58] summarized the available data on antioxidant status of vegetarians versus omnivores. They found that serum or plasma vitamin C and β-carotene concentrations are consistently higher in vegetarians than in omnivores. Among the five studies reporting serum or plasma vitamin E concentrations, two found higher levels in vegetarians and three found that levels were similar between dietary groups. However, because the majority of plasma vitamin E is found in the low-density lipoprotein fraction, which also carries the majority of plasma cholesterol, it may be more appropriate to express vitamin E concentrations relative to cholesterol. When this was done, the ratio was higher in vegetarians in the three studies in which total plasma vitamin E concentrations did not differ between groups. Thus, the available data suggest that vegetarians' status with regard to antioxidant vitamins is superior to that of omnivores. However, data assessing the antioxidant status of vegetarian and omnivorous athletes were not located.

EFFECTS OF ANTIOXIDANT SUPPLEMENTATION. As summarized by Clarkson and Thompson,[57] several studies have suggested that vitamin C supplements ranging from 200 mg to 3 g appear to reduce postexercise muscle soreness. However, the differences in dietary vitamin C intake between vegetarians and omnivores are usually considerably less than even the lowest supplemental intake tested; thus, it cannot be determined whether non-supplemented vegetarians and omnivores would differ in terms of postexercise soreness. In terms of strength or endurance performance, Clarkson and Thompson[57] concluded that most well-controlled studies reported no beneficial effects of supplementation, a view supported by Evans.[56] Similarly, restricting vitamin C intake to 10 to 25 mg/d for 7 wk had no adverse effects on maximal oxygen consumption.

Several reviews have also concluded that supplemental vitamin E does not have beneficial effects on aerobic or endurance capacity, even in long-term studies.[54,56,57] The one exception may be studies done at high altitude, in which oxidative stress would be further increased. Although supplementation does not generally lead to performance benefits, vitamin E supplements ranging from 300 mg/d to 1200 IU did appear to reduce markers of lipid peroxidation with exercise.[54,56,57] These data do not indicate whether vegetarian athletes would experience less oxidative damage than omnivores because the supplement doses associated with antioxidant protection in these studies were considerably larger than typical differences in dietary intakes.

Thus, although vegetarians may have somewhat better antioxidant status than omnivores, it does not appear that this would be associated with important differences in exercise-related muscle damage. It should also be noted that there is no consensus in terms of whether the increase in oxidative stress that occurs with exercise is harmful, leading to muscle damage and impairing recovery, or whether it may be necessary for muscle adaptation to occur.[54] Recent evidence suggests that free radicals may serve as signaling agents that stimulate adaptation.[59]

OTHER DIETARY COMPONENTS

Creatine: A Potential Ergogenic Aid

Creatine is a nitrogen-containing compound found in meat, fish, and poultry, and typical omnivorous diets provide approximately 1 g/d. Creatine is also synthesized endogenously at a rate of about 1 g/d from arginine, glycine, and methionine.[60] A large majority of the body creatine pool is found in muscle, primarily in the form of phosphocreatine, and serves as a temporary storage site for adenosine triphosphate (ATP). During periods of rest, creatine combines with ATP to form phosphocreatine and adenosine diphosphate. During exercise, phosphocreatine is split to yield creatine and ATP, which is in turn used to fuel muscle contraction. Thus, a larger body creatine pool could prolong supramaximal intensity exercise and/or shorten recovery time between repeated bouts of supramaximal exercise.

Over the past decade, many studies have been conducted to assess the possibility that creatine could function as an ergogenic aid. Typically, subjects undergo creatine loading with intakes of about 20 g/d for 3 to 6 d, which clearly exceed the amounts that could be provided through diet alone. However, smaller intakes of 3 g/d over a longer period (approximately 4 wk) have also been found to increase muscle creatine levels to a similar extent, and achieving such intakes through diet alone could occur in those with high intakes of tissue protein.[61] Although results of individual studies are not completely consistent, two meta-analyses[62,63] and one review article[60] have drawn the following conclusions regarding creatine supplementation: 1) most individuals experience an ergogenic effect; 2) creatine supplementation is most effective for brief repeated bouts of supramaximal exercise, particularly when recovery time between successive bouts is limited; and 3) the mechanism by which creatine acts in acute exercise is likely related to increased ATP availability, whereas creatine during long-term exercise may enhance muscle growth and/or permit more intense training.

Several reasons have been advanced to explain the inconsistency among studies assessing the ergogenic effects of creatine supplementation,[60] including the fact that presupplementation muscle creatine levels are variable, and benefits may be restricted to those with lower basal levels that increase with supplementation. Conceivably, some individuals with high meat intakes may already be creatine loaded before supplementation occurs and thus would not benefit from further increases. This argument has two direct implications for vegetarians. First, basal muscle creatine levels would likely be lower in vegetarians because their diets do not provide creatine. Thus, it could be hypothesized that vegetarians' performance could be impaired in athletic events that rely on the high-energy phosphate system, such as short sprints, throws, weight lifting, etc. Second, it could be suggested that vegetarians would be more likely than non-vegetarians to benefit from creatine loading. Evidence regarding each of these areas is presented below.

MUSCLE CREATINE CONCENTRATIONS AND VEGETARIAN DIETS. Few studies have systematically compared muscle creatine concentrations between vegetarians and omnivores. However, Lukaszuk et al.[64] found that adopting a vegetarian diet led to a reduction in muscle creatine concentration. They randomly assigned 26 healthy men who normally consumed an omnivorous diet to receive a weight-maintaining LOV diet providing 1.5 g of protein per kilogram of body weight per day or an omnivorous diet that was eucaloric and contained the same amount of protein. After 3 wk, muscle total creatine, phosphocreatine, and free creatine levels were unchanged in the omnivorous diet group, whereas significant decreases in total and free creatine were observed in the LOV diet group.

EFFECT OF CREATINE SUPPLEMENTATION IN VEGETARIANS AND OMNIVORES. Whether the lower muscle creatine levels seen in individuals on vegetarian diets are accompanied by performance deficits has received less attention but was assessed in two recent studies. Shomrat et al.[65] provided seven vegetarians and nine omnivores with creatine supplements (21 g/d) for 1 wk and assessed anaerobic exercise performance before and after supplementation. Both groups experienced an increase in anaerobic performance. The percentage improvement tended to be greater in vegetarians, but the difference between groups was not significant, possibly because of limited statistical power. The data of Burke et al.,[66] however, suggested that vegetarians experience a greater benefit from creatine supplementation than do omnivores. In their double-blind study, 18 vegetarian and 24 omnivorous adult male and female recreational athletes took part in an 8-wk resistance-training program. They were randomly assigned to receive creatine supplementation or placebo in a stratified block design based on habitual diet and sex. Supplementation consisted of a 7-d loading phase with 0.25 g of creatine per kilogram of lean mass per day (mean intake, 17 g/d) and a 49-d maintenance phase with 0.0625 g of creatine per kilogram of lean mass per day (mean, 4 g/d). At baseline, total intramuscular creatine levels were significantly lower in vegetarians than in omnivores (117 versus 130 mM/kg; $P < 0.05$). Subjects who consumed creatine had significantly greater increases in muscle creatine, benchpress strength, type II muscle fiber area, and whole-body lean mass than did subjects who consumed placebo. Moreover, compared with omnivores who took creatine, vegetarians who took creatine had significantly greater increases in muscle total creatine (~35 versus ~10 mM/kg of dry mass), lean tissue mass (2.4 versus 1.9 kg), and total work performance for knee flexion and extension (~1300 versus ~600 J). For all subjects combined, the change in total muscle creatine was correlated with initial muscle creatine (greater increases occurred in those with initially lower levels) and with the changes in lean tissue mass and exercise performance (the greater the change in muscle creatine level, the greater the increase in lean mass and performance).

Together, these data suggest that vegetarian athletes who participate in sports that rely on the ATP/phosphocreatine system may experience greater benefits than their omnivorous peers from creatine supplementation. Despite good evidence of positive physiologic effects, however, the need for caution regarding creatine supplementation has been stressed.[63] Although case reports of renal dysfunction[67,68] have not been confirmed in studies conducted to date,[69–71] the most prudent conclusion is that more data on the long-term safety profile are needed before creatine supplementation can be endorsed for athletes, vegetarians, or others.

ASSESSING THE EFFECTS OF A VEGETARIAN DIET ON PERFORMANCE

In his 1999 review, Nieman cited several studies and concluded that a vegetarian diet was neither beneficial nor detrimental to endurance performance.[12] However, much of the literature available at that time was limited to cross-sectional comparisons between vegetarians and omnivores (in several cases, subjects of these studies were non-athletes), to short-term interventions in which differences would not be anticipated, or to small studies with inadequate power to detect a difference.

Since that time, few (if any) well-controlled trials have been conducted to assess the effect of a vegetarian diet on physical performance of athletes. Two studies, however, have examined the effect of a vegetarian diet on the response to resistance training.[72,73] It had been observed that older adults fed a LOV diet did not experience muscle hypertrophy with resistance training,[74,75] whereas other studies showed that those consuming a self-selected omnivorous diet responded with increased muscle mass.[76] Accordingly, Campbell et al.[72] directly compared the effects of an omnivorous or LOV diet during 12 wk of resistance training in older men. Fat-free mass and whole-body muscle mass increased in men consuming the omnivorous diet but decreased in those consuming the LOV diet. Gains in strength were observed in both diet groups, and although the percentage increases tended to be greater on the omnivorous diet, the differences between groups were not statistically significant. Although this study appeared to suggest beneficial effects of a meat-containing diet, clear conclusions cannot be drawn because the study diets were not well controlled: men assigned to consume the LOV diet tended to decrease their energy and protein intakes, which might have contributed to the loss of muscle mass observed in that group.

A subsequent study by the same research group was designed to control dietary intakes to a greater extent.[73] Twenty-one men consumed a weight-maintaining self-selected LOV diet, which was supplemented with 0.6 g of protein per kilogram of body weight per day from soy products or beef. Energy and protein intakes were similar between the soy and beef groups. Both groups responded to 12 wk of resistance training, with similar increases in muscle strength and cross-sectional area, suggesting that the protein source did not influence the response to training when dietary energy and protein intakes were similar between groups.

OTHER NUTRITIONAL ASPECTS OF VEGETARIANISM RELEVANT TO ATHLETES

The Female Athlete Triad

The female athlete triad denotes a combination of three conditions that can affect female athletes: disordered eating, amenorrhea, and osteoporosis.[77] Athletes in sports with an emphasis on leanness for optimum performance (e.g., long-distance running), appearance (e.g., synchronized swimming), or to qualify for particular weight classes (e.g., rowing) may be at particular risk for the disorders included in the triad. In addition to their intense training programs, athletes in sports with an emphasis on thinness often experience pressure to attain and maintain a particular body size. This can increase their vulnerability to disordered eating and the other conditions associated with the triad.[78,79] The consequences of the female athlete triad are serious with respect to athletic performance in the short term and to reproductive and bone health in the long term. Stress fractures and other sports-related injuries, bone loss, and infertility are possible outcomes.[79]

A recent meta-analysis of eating problems and athletic participation confirmed that athletes are more likely than non-athletes to experience disordered eating and that athletes participating at the elite level in so-called lean sports are at particular risk.[80] In their study of elite athletes, Sundgot-Borgen and Torstveit[81] reported that an average of 13.5% had clinical or subclinical eating disorders. Female athletes were affected more than males (20% versus 8%), and participants in esthetic sports were affected more than those in endurance or technical sports (e.g., 42% of elite female athletes in esthetic sports had a clinical or subclinical eating disorder versus 17% in technical sports).

VEGETARIANISM AND THE FEMALE ATHLETE TRIAD. Although few studies have specifically examined the possible association of vegetarianism with the female athlete triad, it is conceivable that all three components of the triad may be more likely in those following a vegetarian diet. For example, a vegetarian diet could be associated with disordered eating habits in some women, specifically if it is adopted as a strategy for weight control.[82–84] Vegetarian diet patterns are found more frequently in young women with anorexia nervosa,[85,86] although it is likely that the developing eating disorder leads to the adoption of a vegetarian diet, rather than vegetarianism being a causal factor in the etiology of the eating disorder.[85]

It has also been suggested that menstrual cycle disturbances (such as amenorrhea or less-pronounced subclinical disorders such as anovulatory cycles) may be more common among vegetarians. As reviewed previously,[87] there are three mechanisms by which vegetarianism could be associated with increased menstrual cycle disturbances: energy imbalance, psychosocial or cognitive factors, and components of the diet itself. However, whereas retrospective studies of vegetarian and non-vegetarian athletes have reported a greater frequency of amenorrhea among vegetarians,[88,89] our prospective study of healthy weight-stable young women who exercised no more than 7 h/wk did not find that vegetarians experienced menstrual cycle disturbances more frequently than their omnivorous peers.[90] Due to the individual variation in response to contributing factors such as negative energy balance, prolonged training, and emotional stress, it is difficult to say which factors must be present to produce menstrual dysfunction (such as amenorrhea) in a particular athlete.[91]

Osteoporosis is the third component of the female athlete triad. It results from the combined effects of disordered eating patterns (which can include prolonged energy deficits and inadequate nutrient intakes) and hormonal imbalances (reflected by amenorrhea or other menstrual cycle disturbances). A lactovegetarian diet does not appear to predispose one to osteoporosis[92,93]; however, vegan diets are typically low in calcium and may be associated with lower bone mineral density.[94–96] Although fewer concentrated sources of absorbable calcium are found among plant foods,[97] with careful planning and appropriate use of fortified products or supplements, recommended intakes could be met in vegan diets.

YOUNG VEGETARIAN ATHLETES. Approximately 2% of young people between the ages of 6 and 17 y have indicated that they are vegetarian (excluding meat, fish, and poultry) and a total of 6% have excluded meat.[98] Vegetarianism in children and adolescents has been examined with respect to whether or not a vegetarian diet is sufficient to support growth and development. Given that the energy and nutrient needs of young athletes are even higher than those of more sedentary young people, the challenge of supporting optimal growth, development, and performance in athletic youth with a vegetarian diet is particularly pertinent.

Studies of vegetarian children from the general population have indicated that a well-planned vegetarian diet can support normal growth and development. For example, a longitudinal study of growth in vegetarian and omnivorous children ages 7 to 11 y reported no significant differences in weight, upper arm skinfold thickness, or midarm circumference, although the vegetarian children were slightly taller.[99] However, as a diet becomes increasingly restrictive, problems may arise. This was illustrated by a study of 48 adolescents who had previously followed a nutritionally inadequate vegan macrobiotic diet until an average age of 6 y.[100] When compared with 24 omnivorous age-matched controls, the adolescents who had followed a macrobiotic diet had lower intakes of vitamin B12 (31 of 48 were B12 deficient) and calcium, and their serum ferritin levels were lower. Tests of cognitive functioning found reductions in performance among those who were deficient in vitamin B12.

There are several nutritional considerations for young vegetarian athletes. First, because of the potential bulk of a vegetarian diet (which may be high in fiber and low in overall caloric density compared with non-vegetarian diets), it may be challenging for young athletes to meet their energy needs. Also, vitamin B12 is present only in foods that are fortified or from animal sources. The need to ensure a source of vitamin B12 (supplements or fortified foods) is particularly important for vegetarian children to allow for appropriate neural development. Other dietary considerations that apply to adult vegetarian athletes would also apply to children (e.g., ensure diets contain sufficient protein, iron, and calcium).[18,19]

CONCLUSION

To date, well-controlled long-term studies assessing the effects of a vegetarian diet on physical performance in athletes have not been conducted. Conclusions must thus be drawn cautiously, with the caveat that future research may provide more definitive data. Nevertheless, the following observations can be made:

1. Based on limited observational data, well-planned, appropriately supplemented vegetarian diets appear to effectively support athletic performance. Convincing evidence in support of consistent beneficial or adverse effects on performance of vegetarian (versus omnivorous) diets is not available.
2. Provided protein intakes are adequate to meet needs for total nitrogen and the essential amino acids, plant and animal protein sources appear to provide equivalent support to athletic training and performance. Protein intakes of vegetarians are almost always sufficient to meet these needs.
3. As a group, vegetarian athletes may be at increased risk for non-anemic iron deficiency, which appears to limit endurance performance. This risk, however, is not confined to vegetarians. Accordingly, periodic assessment of iron status is warranted for all athletes, particularly women, irrespective of dietary pattern.
4. As a group, vegetarians have lower mean muscle creatine concentrations than do omnivores, and this may affect supramaximal exercise performance. Because the beneficial effects of creatine loading are inversely related to initial muscle creatine concentrations, vegetarians are likely to experience greater performance increments in activities that rely on the ATP/phosphocreatine system. However, initial muscle creatine concentrations vary considerably, even within groups of vegetarians and omnivores, so dietary pattern does not predict the response to supplementation on an individual basis.
5. Coaches and trainers should be aware of the possibility that a vegetarian diet may be adopted as a strategy for weight control in some athletes. If a vegetarian diet is accompanied by unwarranted weight loss, especially in female athletes, the possibility of a disordered eating pattern should be investigated.

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