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Perspectives

The Importance of Dietary Protein Quality in Mid- to High-Income Countries

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ABSTRACT

In wealthy countries, the protein intake of adults is usually considered to be adequate, and considerations of protein quality are often deemed irrelevant. The objective was to examine dietary protein intakes of adults in developed countries in the context of dietary protein quality. An analysis of NHANES population data on actual protein intakes in the United States (a developed country) demonstrated that for a dietary Digestible Indispensable Amino Acid Score (DIAAS) of 100%, 11% of the adult (19–50 y) population had habitual protein intakes below the Estimated Average Requirement (EAR) and 22% below the Recommended Dietary Allowance. The percentage of the population with utilizable protein intakes potentially falling below the EAR increased as the assumed DIAAS declined. Analysis of the NHANES data and several other datasets also indicated that total protein intakes can be limiting or close to limiting for the elderly and some vegetarians and vegans. Here, lower dietary protein quality can potentially lead to inadequate utilizable protein intakes. For many people in specific physiological states (e.g., weight loss, endurance sports, resistance exercise) attempting to meet higher dietary protein targets often with accompanying lowered energy intakes, low dietary protein quality can lead to protein calories expressed as a proportion of total calories, falling outside what may be acceptable limits (maximum of 30% protein calories from total calories). In general, individuals within the adult population may be susceptible to macronutrient imbalance (whenever total protein intakes are high, daily energy intakes low) and for diets with lower protein quality (DIAAS <100%). Our analysis shows that dietary protein quality is relevant in mid- to high-income countries.

Keywords: protein, protein quality, DIAAS, protein requirements

Introduction

Dietary proteins supply the body with amino acids, which are the building blocks used for protein synthesis to grow and maintain lean body mass. Amino acids also serve in the synthesis of a myriad of molecules with essential biological functions. Many amino acids have specific regulatory functions.

It is of critical importance, therefore, that humans of all ages and physiological states receive adequate protein in their diets, especially to meet the daily requirement for the dietary indispensable amino acids (IAAs). Different proteins supply different amounts of the IAAs, and commonly, several sources of food proteins are consumed to make up the daily diet. As different proteins vary in their capacity to supply amounts of digestible amino acids relative to the requirement, they are said to differ in their "protein quality."

Protein quality describes the potency of a food protein to supply the body with amino acids relative to requirements [1]. It is largely a function of a protein's indispensable (essential) amino acid content and profile, as well as the digestibility or availability of the amino acids. There are many measures of protein quality, the most common in practice being the Protein Digestibility-Corrected Amino Acid Score (PDCAAS). A new more accurate score designated DIAAS [2,3] has been promulgated to replace PDCAAS. DIAAS (%) is based on true ileal amino acid digestibility for individual IAAs and the true ileal digestibility of reactive lysine (lysine availability) for foods in which lysine may have been structurally altered during

Abbreviations: AMDR, acceptable macronutrient range; BW, body weight; DIAAS, Digestible Indispensable Amino Acid Score; EAR, Estimated Average Requirement; EPIC-Oxford, European Prospective Investigation into Cancer and Nutrition-Oxford; IAA, indispensable amino acid; IOM, Institute of Medicine; MEC, maintenance energy cost; PAI, physical activity index; PDCAAS, Protein Digestibility-Corrected Amino Acid Score; RDA, Recommended Dietary Allowance.

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processing [4]. DIAAS gives the estimated absorbed amount of the first limiting amino acid in the protein or diet (based on correcting the total amount of the IAA for its respective true ileal digestibility or availability), expressed per unit of the respective required amount of IAA. The lowest ratio expressed as a percentage is the DIAAS. For a food protein, mixed meal, or mixed diet with a DIAAS equal to 100%, the first limiting amino acid meets the requirement exactly, at a daily protein intake of 0.66 g/kg body weight (BW), which is the EAR for an adult. In this case, the dietary protein/proteins would be fully utilizable for protein synthesis (utilizable). If DIAAS is <100%, the first limiting amino acid is undersupplied relative to the requirement and the protein/proteins would be less than fully utilizable. DIAAS values for an individual food protein source are not truncated, but for a meal or diet, the DIAAS is capped at 100% to avoid the implication that a diet with a DIAAS value of >100% has a utilizability greater than unity. A DIAAS value >100% means that the first limiting amino acid is supplied in excess of the requirement, indicating that the protein is fully utilizable and that the protein may have value for complementing the supply of the limiting amino acid in other lower quality proteins. DIAAS itself has inherent limitations but is currently the most accurate means of describing the protein quality of standalone foods and diets [5,6].

Dietary DIAAS values (100% or <100%) can be applied to estimates of total protein intakes to derive estimates of utilizable protein intakes. By way of example, if the total dietary protein intake is 80 g/d and the DIAAS of the diet is 100%, then utilizable protein is 80 g/d (80 multiplied by 1.0), whereas if the total protein intake is 80 g/d and the diet DIAAS is 50%, then utilizable protein intake is 40 g/d (80 multiplied by 0.5).

Plant-sourced proteins, generally but not always, have lower DIAAS values than animal-sourced proteins. Nonetheless, mixed meals and diets may have high overall protein quality scores, despite an abundance of plant-sourced dietary proteins, as animal and plant proteins may be complementary sources of amino acids [7]. Equally, mixed meals and diets with less diverse combinations of proteins and particularly those slanted heavily toward plant proteins may have low protein quality scores.

The current Recommended Dietary Allowance (RDA) for protein, based in most jurisdictions on the “safe” requirement to maintain body nitrogen balance [8], is 0.83 g/kg BW/d for adults of all ages except pregnant and lactating females. The “safe” requirement is the EAR plus 2 SDs. It is important to note that the widely applied WHO, UNU, FAO [8] RDA for protein is based primarily on nitrogen balance studies and reflects the minimal protein intake to achieve body nitrogen balance [9]. More recent work using stable isotope tracers suggests that the RDA for protein in adults may be higher, more on the order of 1.1 to 1.2 g/kg BW/d [2,10].

It is often overlooked that the “safe level of intake” (RDA) for protein recommended by the WHO, UNU, FAO [8] of 0.83 g/kg BW/d, refers to high quality protein (DIAAS ≥100%), or more specifically, utilizable protein (absorbed balanced amino acids). A fundamental assumption in comparing dietary nutrient intakes with nutrient requirement levels is that the same unit of comparison is used. The EAR and RDA for protein are given in units of “utilizable” protein, and thus, for legitimate comparison, dietary protein intakes need to be described in the same way.

Daily intakes of dietary protein are often assessed for their adequacy by comparing total protein intakes of individuals or populations with the RDA or EAR. This approach ignores the potential effect of protein quality. A recent study using FAO national-level food supply data has highlighted that such an approach for low-income countries masks what may be significant protein deficiencies [11].

In contrast to the case for low-income countries, in mid- to high-income countries the overall daily total protein intake for adults is usually well in excess of the RDA for protein (e.g., 180% for United States/Canada). Because dietary protein appears to be comfortably oversupplied in such countries, it is widely assumed that differences in dietary protein quality are irrelevant.

The objective of this largely theoretically based study was to examine the dietary protein intakes of adults in mid- to high-income countries and the implications of variations in dietary protein quality to the adequacy of dietary protein intake. The study uses several approaches and evaluates the “adequacy” of dietary protein intake in different ways. Potential effects of protein quality (DIAAS <100%) were taken into account for published NHANES survey data across a well described United States population. The United States was taken as an example of a developed economy. Theoretical analyses, often based on data from specific published studies, are also presented for individuals on weight-loss diets, the elderly, people undertaking endurance sports and resistance exercise, and vegans/vegetarians to illustrate the potential importance of dietary protein quality for individuals in specific nutritional states. Many such individuals may be intentionally consuming protein to achieve dietary targets in excess of the stated requirement, making them more susceptible to the influence of lower protein quality (DIAAS). In the presently described work and for individuals, the comparison was made between daily total and utilizable dietary protein intakes and the RDA for protein, whereas with the population-based data (distributions), the comparison was made between daily dietary protein intake and both the EAR and RDA.

Study One: Population-Based (NHANES) Dietary Protein Intakes Accounting for Potential Differences in Dietary DIAAS

To assess the percentage of the adult population having utilizable protein intakes potentially less than recommended levels, we used data from the United States NHANES for 2001–2018. Subjects 19+ y of age were included; however, those with incomplete dietary records or who were pregnant/lactating were excluded from the dataset, providing an analytical sample of 44,018 (22,079 males and 21,939 females). Usual dietary protein intake in mg/kg was determined using the National Cancer Institute method [12,13], and the cut-point method was used to assess the percentage of the population below the EAR for protein of 0.66 g/kg BW [14,15] and the percentage below the RDA for protein (Table 1). Subsequently, we assessed the percentage of the population potentially falling below the EAR and RDA assuming dietary DIAAS values of 0.9, 0.8, 0.7, and 0.6 (original analyses assumed a dietary DIAAS of 1.0). The original usual total protein intakes were adjusted downward by multiplying the respective intake by the dietary DIAAS values (0.9, 0.8, 0.7, 0.6), and intakes and the percentage of the population falling below the EAR and RDA were reassessed. Analyses were stratified by age (19–50, 51–70, and 71+ y) and sex (Table 1).

TABLE 1
Proportion (%) of US adult population with usual daily utilizable protein intake falling below the EAR[1] or the RDA[2], assuming different dietary DIAAS (NHANES dataset, 2001–2018, n = 44,018[3])

Population	DIAAS	% Population potentially below EAR	% Population potentially below RDA
19–50 y (male and female)	1.0	10.64	22.43
	0.9	16.36	31.72
	0.8	24.97	43.95
	0.7	37.57	59.16
	0.6	54.59	75.53
19–50 y (male)	1.0	5.24	13.35
	0.9	8.97	20.87
	0.8	15.28	31.82
	0.7	25.91	47.00
	0.6	42.15	65.76
19–50 y (female)	1.0	16.38	31.93
	0.9	24.10	43.13
	0.8	35.15	56.78
	0.7	49.89	71.78
	0.6	67.52	85.65
51–71 y (male and female)	1.0	15.78	30.77
	0.9	23.18	41.60
	0.8	33.88	54.89
	0.7	48.06	69.71
	0.6	65.33	83.79
71+ y (male and female)	1.0	19.72	36.71
	0.9	28.09	47.95
	0.8	39.83	61.50
	0.7	54.88	75.73
	0.6	71.74	88.14

Abbreviations: BW, body weight; DIAAS, Digestible Indispensable Amino Acid Score; EAR, Estimated Average Requirement; NHANES, National Health and Nutrition Examination Survey; RDA, Recommended Dietary Allowance.
[1] US EAR for protein, 0.66 g/kg BW/d.
[2] US RDA for protein.
[3] 22,079 males and 21,939 females.

Even for a DIAAS of 1.0 (100%), some 11% of the adult population had estimated utilizable protein intakes below the EAR. Interestingly, for the 19 to 50 y-old age group, the percentage of the population consuming protein intakes below the EAR regardless of protein quality was higher for females than males (16% compared with 5%), and the percentage increased with age (e.g., 71+ y male and female = 20%).

If a person consumes protein to meet the stated requirement level, but the quality of that protein is poor, then that person would need to consume more protein to meet the actual requirement, which is given in units of "high quality" protein. The percentage of the population with utilizable protein intakes (after correction for DIAAS) potentially falling below the EAR increased considerably as DIAAS declined, with potentially 72% of the 71+ y-old population having utilizable protein intakes (DIAAS = 0.6) falling below the EAR and 88% falling below the RDA. Once again, this does not mean that these proportions of the United States adult population are actually consuming inadequate protein intakes, as it is unlikely that large numbers of individuals in this population would be receiving poor protein quality diets, but the data highlight the potential for effects of protein quality. In further work, we intend to determine the actual protein quality ratings of diets consumed by individuals in such populations and their distributions. It can be shown [11] using food supply data at a national level [16] that the overall national diet (assuming an even distribution of food) in a high-income country such as the United States has a DIAAS of 100%, but the overall national diet in a mid-income country such as China has a lower DIAAS of 85%.

Based on the NHANES survey data, a significant proportion of the United States adult population receives insufficient protein to meet minimal requirements regardless of dietary protein quality. As demonstrated by the data presented here (Table 1), such deficits in dietary protein may potentially be exacerbated by lower dietary protein quality.

Study Two: Individuals within a Population in Specific Nutritional States

Individual adults in specific nutritional and physiological states may require or desire higher daily amounts of utilizable dietary protein than recommended by the RDA [17–20]. In these states, it may be difficult to achieve such utilizable protein intakes within the boundary of daily energy intake if protein quality is low. Further, in some people in certain nutritional/physiological states, average habitual total protein intakes may be close to or below the RDA for protein, meaning that low protein quality may lead to the need for higher protein intake to meet needs. These possibilities are evaluated here for the nutritional/physiological states associated with weight loss, old age, endurance sports and resistance exercise, and veganism/vegetarianism.

In situations in which utilizable protein intakes are purposefully higher than the RDA, and particularly when the high protein intake is accompanied by a low energy intake (e.g., weight-loss dietary regimens), the scenario is different than when the RDA is inadequate to meet the optimal or desired level of consumption. In this circumstance, the concern is that for low protein quality diets the total amount of protein that must be consumed to meet the targeted amount of utilizable protein may potentially exceed the acceptable upper limit of intake.

What is a reasonable estimate for an acceptable amount of for dietary protein energy expressed as a percentage of dietary energy?

Several groups have provided estimates of the maximal values (upper threshold of an acceptable macronutrient range [AMDR]) for protein energy when expressed as a percentage of total dietary energy. The Institute of Medicine (IOM) [21] gives an upper estimate of 35% whereas an estimate of 20%, based on macronutrient recommendations, is given by a grouping of 5 global institutions and countries [22]. Bilsborough and Mann [23], after reviewing evidence on rates of amino acid uptake from the digestive tract and rates of ureagenesis, suggest a maximum protein intake of around 25% of total energy, especially at higher protein intakes (>2 g/kg BW/d). The latter authors correctly make the point, however, that to fully understand the metabolic effects of protein and amino acid intake, protein intake expressed on an energy basis needs to be viewed alongside absolute daily protein intakes and daily protein intake expressed per kg BW. In deriving a maximum amount of protein in relation to total energy, metabolic capacities affected largely by the absolute amounts of macronutrients are one consideration, but the relative proportions of protein, carbohydrate, and fat may also be important for optimal metabolism and health. By way of example, a diet with high proportions of its dietary energy supplied by fats and proteins may lead to unacceptably low intakes of dietary fiber, vitamin C, or plant secondary compounds, especially at low energy intakes. Too great a supply of any one macronutrient may also lead to metabolite imbalances. The IOM [21] found that there was insufficient evidence to set a specific tolerable upper intake level for dietary protein or the IAAs. They did, however, give an upper amount for protein for adults (35% of diet energy) based on an AMDR for protein and the other macronutrients. The AMDR was defined as follows: "a range of (macronutrient) intakes for a particular energy source that is associated with reduced risk of chronic diseases while providing adequate intakes of essential nutrients." In the present study, and with reference to the latter 3 published recommendations, a daily protein energy intake of 30% of total dietary energy was accepted as a maximum value. This value should not be seen as a strict cutoff point, but diets exceeding this value need to be carefully assessed.

Individuals undergoing weight loss

Utilizable protein intakes exceeding the RDA have been recommended to minimize the loss of lean body mass during BW loss [18,24–26], and some individuals follow a high dietary protein/low dietary energy regimen in order to lose and maintain BW (see for example the CSIRO Protein Plus Nutrition and Exercise Plan [27]). Dietary utilizable protein intakes up to or exceeding 1.5 g/kg BW/d have been recommended for weight loss [24]. These recommendations largely relate to specific findings rather than official recommendations.

The objective was not to justify higher protein requirements for weight loss and weight management, but rather to demonstrate the impact of dietary protein quality at levels of protein intake that may be targeted by individuals.

The data presented by Wycherley et al. [28] for weight loss using high protein diets were used here to estimate potential effects on macronutrient balance of ingesting lower quality proteins in meeting a daily utilizable protein target during weight loss. Table 2 [28] gives the daily utilizable protein intake expressed as a percentage of total energy for different high (all exceeding the RDA) daily protein intakes and different dietary DIAAS values, for the degree of energy restriction in the Wycherley et al. [28] study.

In the study [28], overweight and obese males aged about 50 y (BMI = 33.0 kg/m^2) consumed an energy restricted diet (7000 kJ/d) with a high daily protein intake (142 g protein, 1.34 g/kg BW/d). After 12 mo on the diet, the subjects on the high protein energy restricted diet had lost around 12 kg BW and had lost less lean body mass compared to a low protein, high carbohydrate control. The prescribed protein intake of 1.34 g/kg BW/d is in units of utilizable protein and assumes a DIAAS of 100%. At these protein and energy intakes and with an assumed DIAAS of 100%, the protein calories comprised 35% of total calories.

If protein quality is less (DIAAS <100%) then the daily amount of total protein required to meet the target of 142 g of utilizable protein increases, as does the protein energy expressed as a proportion of total energy intake. The highest daily protein intake (lowest DIAAS) of 237 g protein equates to 2.34 g/kg BW/d. Although as an absolute protein intake this amount of protein may not necessarily be harmful, in the context of the low energy intake, macronutrient balances fall well outside advised limits.

When a high protein quality diet (DIAAS 100%) was consumed at 1.34 g/kg BW/d as in the Wycherley et al. [28] study, the contribution of protein energy to total energy was 35% of energy intake. Significant decreases in protein quality at this level of protein intake lead to even greater macronutrient imbalance. Dietary protein quality, therefore, is relevant to dieters consuming low energy/high protein diets.

For lower protein intakes (1.2 and 1.3 g/kg BW/d), macronutrient imbalance can also occur (Table 2) [28]. For higher protein intakes (1.4, 1.5, and 1.6 g/kg BW/d) and for all DIAAS values, protein energy as a percentage of total energy exceeded the upper limit of 30%, and markedly so at the lower DIAAS values. When dietary energy intakes are low, and utilizable protein intakes relatively high, ignoring dietary protein quality can potentially lead to dietary protein calories as a percentage of total calories exceeding acceptable upper levels. In these situations, protein quality is important to avoid or minimize such macronutrient imbalance. This will also be the case for high protein BW maintenance diets. It needs to be recognized that an upper limit to protein energy expressed as a proportion of total dietary energy is not well established, but the present analysis raises concerns about the potential absolute amounts of protein potentially consumed if protein quality is poor. Any actual metabolic and physiological effects need to be ascertained in controlled studies.

The elderly

Aging appears to disrupt net protein balance (muscle protein synthesis equals muscle protein breakdown) in adults, blunting the muscle protein synthesis response to anabolic stimuli, including exercise and dietary protein intake. This phenomenon is known as age-related anabolic resistance [29]. Such

TABLE 2
Protein energy as % of total energy for differing utilizable protein intakes for a restricted energy diet (7000 kJ/d, 106 kg male).

Utilizable protein (g/kg BW/d)	DIAAS (%)				
	100	90	80	70	60
1.2	31 (127)[1]	34 (141)	39 (159)	44 (181)	52 (212)
1.3	34 (138)	37 (158)	42 (173)	48 (197)	56 (230)
1.34 [28]	35 (142)	38 (153)	43 (178)	49 (203)	58 (237)
1.40	36 (148)	40 (164)	45 (185)	52 (211)	60 (247)
1.50	39 (159)	43 (177)	48 (199)	55 (227)	64 (265)
1.60	41 (170)	46 (188)	52 (212)	59 (243)	69 (283)

Abbreviations: BW, body weight; DIAAS, Digestible Indispensable Amino Acid Score.
[1] Values in parentheses are actual amounts of total protein needed to meet the required amount of utilizable protein.

age-related changes can result in a loss of skeletal muscle (sarcopenia) and decreases in functionality, quality of life, and life expectancy.

Higher dietary protein intakes offer a means of overcoming age-related anabolic resistance, assisting to mitigate losses in muscle mass and associated function [30,31]. The need for greater dietary protein intakes in the elderly has been the subject of several recent studies [32–34] and reviews [17,35–39], and based on these studies, dietary utilizable protein intakes of ≤1.5 g/kg BW/d are recommended for adults to minimize muscle loss. Although this advice is not universally accepted [40,41], some authorities have increased protein recommendations for the elderly (e.g., The French Food Safety Agency, AFSSA, 2007).

The objective of the presently reported study was not to justify higher protein requirements for the elderly, though there is scientific evidence supporting this, but rather to examine the effects of variation in dietary protein quality on elderly people seeking to meet utilizable protein intake targets higher than the RDA.

Several studies have highlighted that habitual total protein intakes may be limiting for some elderly, highlighting the potential importance of effects of protein quality in practice. Sullivan et al. [42] found that 21% of hospitalized elderly had an average daily in-hospital total protein intake of <50% of the maintenance requirement. In another study, >30% of elderly patients were found to be subject to protein energy malnutrition [43]. In the Health ABC Study [44], 43% of elderly participants reported a daily total protein intake lower than the RDA, and NHANES (2003–2004) data (Fulgoni [45], also see results of Study One above) show that in the United States, 25% of older males and 50% of older females are not consuming the protein RDA. In a meta-analysis [46], ~20% of older adults were found to have a daily protein intake below 0.8 g/kg BW. Almost half of the older adults had a daily total protein intake below 1.0 g/kg BW. In a survey of dietary protein intake in the Dutch elderly, Tieland et al. [47] reported mean daily total protein intakes of 1 g/kg BW in frail elderly and 0.8 g/kg BW in institutionalized elderly, which would make these people susceptible to low dietary protein quality. A similar result was found in the National Adult Nutritional Survey in Ireland [48], where the average daily total protein intake for older adults (>65 y) was only 1.15 g/kg BW. The same pattern was again observed in the 2012 Japanese National Health and Nutrition Survey, where around 20% of middle-aged and older adults had a total protein intake of <1 g/kg BW/d [49]. Moreover, close to half of the people (>30 y) surveyed did not meet Japanese recommended levels of protein intake required for the prevention of sarcopenia. Leucine intake was also insufficient for each sex and age group, believed to likely be due to a decreased intake of animal proteins. It is interesting that in the InCHIANTI Study [50], animal protein intake (high protein quality, nutrient dense) was inversely correlated with mortality in older adults. Community dwelling older adults in the Netherlands with low total protein intakes (<0.8 g/kg BW/d) also consumed a lower proportion of animal protein than their contemporaries [51].

In all of these studies, poor dietary protein quality would potentially lead to utilizable protein intakes well below the RDA, and dietary protein quality is an important vector to consider in the nutrition and health of the elderly. This has also been highlighted by others [9,17,52–55].

The effects of dietary protein quality (DIAAS) on total protein intake and total protein energy expressed as a percentage of total energy intake, to meet utilizable protein requirements higher than the RDA, in the elderly, within a given energy intake are shown in Table 3. The calculated data presented are for a low to moderately active 70+ y-old female of 70 kg BW consuming a maintenance energy diet at different targets for utilizable dietary protein. Some elderly people will have considerably lower energy intakes than that used here due to lower BW or lower levels of activity. The latter scenarios are also included in Table 3. The equation given by Henry [56] (maintenance energy cost [MEC] = 0.0417 BW + 2.41) for a female aged >70 y was used to determine the MEC along with a physical activity index (PAI) of 1.30 for low to moderate daily energy activity or 1.1 for sedentary behavior.

For a typical 70 kg female with a PAI of 1.3, the daily energy requirement was calculated to be 6930 kJ/d or 1656 kcal/d. The calculated energy intake agreed closely with a determined daily energy intake of 1670 ± 516 kcal (mean ± SD) for a 67.4 kg female aged 69.4 y as reported by Lixandrão et al. [57]. For a sedentary female (PAI = 1.1) of 60 kg BW, the daily energy requirement was calculated to be 5403 kJ/d.

The results demonstrate that at the WHO/UNU/FAO [8] safe intake level for protein (0.83 g/kg BW/d), total daily protein energy expressed as a percentage of total energy falls within an acceptable range, though at lower protein qualities (DIAAS 60% to 70%), the macronutrient balance may be considered of concern [22]. When daily protein intake is increased to 1.5 g/kg BW/d, however, the effect of dietary protein quality (DIAAS) in increasing the amount of protein needed to meet the target amount of utilizable protein is of significance. For the low to moderately active 70 kg female, if the DIAAS of the diet falls below 90%, the diet macronutrient balance becomes of concern. Macronutrient balance appears to be broadly adequate when protein is consumed to meet the RDA, for the 60 kg sedentary female, but at the target protein intake of 1.5 g/kg BW/d, dietary protein quality becomes relevant. At this protein intake, if the DIAAS of the diet falls below 100%, the protein energy as a percentage of the total protein is high leading to potential concerns about macronutrient imbalance.

It is concluded that for elderly adults, diet protein quality may need to be considered when electing to achieve utilizable protein intakes exceeding the RDA.

Endurance sports and resistance exercise

Resistance exercise is commonly employed in both athletes and recreational exercisers and refers to the building of muscle mass and strength by undertaking resistance (resisting a force) exercises for defined periods of time. Endurance exercise usually refers to sports involving longer periods of sustained exercise, increasing overall body aerobic fitness. The daily energy intakes of those undertaking both endurance and resistance activities can vary greatly depending upon the level of activity (e.g., very low energy intakes in athletes attempting to reduce body fat or make weight, to very high energy intakes for some endurance sports such as marathon running). Also, energy intake and total energy expenditure can vary greatly over time, especially between training periods, competing periods, and recovery periods [58].

There is considerable published data making the case that those undertaking resistance exercise and endurance activities have daily dietary utilizable protein requirements in excess of the RDA. Optimal amounts of protein for those undertaking resistance exercise and sports likely vary with the mode of exercise, intensity and duration, as well as performance goals and therefore need to be individualized. This may well explain the wide range (1.2–3.0 g utilizable protein/kg BW/d) for the amounts of protein suggested as being optimal, although several of the recommendations fall around 2.0 to 2.5 g protein/kg BW/d [59–70]. Further, reported habitual protein intakes of some athletes (particularly power trainers and body builders) are high relative to the RDA for an adult, ranging from 2.0 to 3.5 g/kg BW/d [23,53,70]. Habitual protein intakes for endurance athletes appear to be lower, but still high relative to the RDA, and in the range of 1.2 to 1.6 g/kg BW/d.

Two published studies that provide realistic estimates of dietary energy and protein targets pertaining to those undertaking different types of physical activity are modeled here to estimate the potential effects on diet macronutrient balance of ingesting lower quality proteins while attempting to meet a given daily utilizable protein target at a given energy intake. A third set of similar calculations is given that relates to resistance exercise for a female and male athlete with a daily energy intake (based on PAI estimates) deemed to apply to an active person.

Our first analysis involves male endurance athletes [71]. The participants were competitive master triathletes and at the time of study had trained between 6 to 10 h/wk over a 3-y period. We modeled 8 participants on a high protein (beef) regimen undergoing a 10-wk endurance training program. At the recorded protein (1.52 or 2.50 g/kg BW/d) and energy intakes (normal dietary energy intake of the subjects, 2382 kcal/d), the participants on the beef treatment lost BW but preserved thigh muscle mass. The modeled results for this study demonstrate that at the daily utilizable protein intake of 1.52 g/kg BW/d, protein energy expressed as a proportion of total energy was not in excess except for the lowest protein quality rating (protein energy/total energy = 33%). At the higher utilizable protein intake (2.5 g/kg BW/d) protein energy expressed as a proportion of total energy exceeded the upper level of 30% of energy intake, even for the highest quality protein (DIAAS = 100%) and reached a level of 53% for DIAAS = 60%.

Our second analysis [67] investigated hypocaloric diets accompanied by resistance exercise. This is a common strategy with athletes attempting to lose BW or make weight for a specific competition. When an energy deficit is combined with intense exercise it is common to increase daily protein intake in an attempt to preserve lean body mass. This study with twenty males (average age = 23 y, average BW = 100 kg) involved a 40% reduction in energy intake (energy intake = 2409 kcal/d) combined with an increased daily utilizable protein intake (to 2.5 g/kg/d). During the 4-wk period, the males undertook resistance exercise combined with high-intensity interval training. There was a substantial weight loss with the low energy diet, but lean body mass actually increased with the high protein treatment. The modeled results for the study show that at the utilizable protein intake promoted for retention of lean body mass (2.4 g/kg BW/d) accompanied by the low energy intake and exercise regimen, dietary protein energy given as a percentage of total energy intake greatly exceeded the

TABLE 3
Effect of dietary protein quality (DIAAS) on diet protein energy expressed as a percentage of total energy for a 70+ y-old female of different body weight and level of physical activity

1. Daily energy intake[1] = 6930 kJ/d, PAI = 1.30, 70 kg BW					
Utilizable protein (g/kg BW/d)	DIAAS (%)				
	100	90	80	70	60
0.83	14 (58)	16 (65)	18 (73)	20 (83)	24 (97)
1.50	26 (105)	29 (117)	32 (131)	37 (150)	43 (175)
2. Daily energy intake[1] = 5403 kJ/d, PAI = 1.1, 60 kg BW					
Utilizable protein (g/kg BW/d)	DIAAS (%)				
	100	90	80	70	60
0.83	16 (50)	18 (56)	20 (63)	22 (71)	26 (83)
1.50	28 (90)	31 (100)	36 (113)	41 (129)	47 (150)

Abbreviations: BW, body weight; DIAAS, Digestible Indispensable Amino Acid Score; PAI, Physical Activity Index.
Values in parentheses = Actual protein intakes (g/d).
[1] Daily energy intake = PAI × (Maintenance Energy = 0.0417 × BW + 2.41).

recommended range for all of the DIAAS values (40% for DIAAS = 100% up to 66% for DIAAS = 60%), and the macronutrient distribution would be considered as unbalanced.

The third desktop study included young (aged 18–30 y) male (80 kg BW) and female (60 kg BW) athletes undertaking regular resistance or endurance exercise such that their PAI was 1.70 (e.g., 1 h/d of jogging, running, cycling, aerobic activity) [72]. This was considered to cover individuals using resistance or endurance exercise to maintain everyday muscle strength and fitness. The calculated energy intakes were within the range of actually recorded daily energy intakes (9530 kg/d for females and 12,974 kg/d for males) for athletes during training intervals [58]. Two target utilizable protein intakes (1.5 and 2.5 g/kg/d) were modeled, and at the lower protein intake and calculated habitual energy intake, the total protein intakes required (taking DIAAS into account) were not excessive as judged by protein energy as a percentage of total energy (16%–27%). However, at the higher utilizable protein intake, close to that recommended by a number of experts in the field, protein intake at all levels of DIAAS except for the highest scores (DIAAS = 90%–100%) led to unacceptably high proportions of protein energy to total energy (33%–45%).

Overall, it is concluded that, particularly at the higher daily protein intakes frequently taken up by athletes (>2.0 g/kg BW/d), dietary protein quality may need to be considered to avoid macronutrient imbalances. This has been recognized and discussed by others [68,73–75].

Veganism and Vegetarianism

Here, we refer to vegetarian and vegan adults and define vegetarians as people excluding meat and fish from their diet, regardless of whether they also exclude other animal products (e.g., dairy, eggs) from their diet. A vegan is defined as someone who consumes plant-based foods only and excludes all foods of animal origin from their diet.

Given that plant-based foods often have a relatively high energy to protein ratio, it is expected that daily food protein intakes may be lower in vegans and vegetarians, who consume relatively high amounts of plant-based foods compared to omnivores. It follows that at a given energy intake, vegans and vegetarians are likely to ingest less protein than omnivores, and given that plant proteins generally are of lower protein quality compared to animal proteins, the overall dietary protein quality may also be lower. It is important therefore to consider not only the dietary total protein intake but also the daily intakes of utilizable protein.

The European Prospective Investigation into Cancer and Nutrition-Oxford Study (EPIC-Oxford cohort study) was chosen here to compare total protein and utilizable protein intakes for adult vegetarians, vegans, and omnivores [76]. The EPIC-Oxford study included 30,251 participants (18,244 meat eaters, 4531 fish eaters, 6673 vegetarians, and 803 vegans) aged between 30 and 90 y and relied upon self-reported food intakes based on food frequency questionnaires. The reported mean total protein intakes (g/kg BW/d) for males in the study were 0.95 for vegetarians and 0.91 for vegans. Comparable mean total protein intakes for the females were 1.05 and 0.99, respectively, for vegetarians and vegans. The EPIC-Oxford dataset was chosen for modeling as it is a large study following a broadly based population, and the data were expressed taking BW into account. Several other relevant national food intake surveys have been undertaken [77–80], and these were reviewed by Mariotti and Gardner [81]. They show generally similar total protein intakes for vegans and vegetarians as found in the EPIC-Oxford study. The mean total daily protein intakes for vegans ranged from 62 to 82 g/d, with the EPIC-Oxford study reporting 64 g/d. A further study [82] reported a mean ($n = 22$) total protein intake for vegans of 74 g/d, and Knurick et al. [83] recorded mean total protein intakes for vegetarians of 68 g/d ($n = 26$) and for vegans of 69 g/d ($n = 28$). Kniskern and Johnston [84] reported mean ($n = 22$) total protein intakes of 53 g/d (0.86 g/kg BW/d) in 19- to 40-y-old vegetarian females. It would appear, therefore, that the EPIC-Oxford data fall within the range of recorded total protein intakes for vegetarians and vegans.

The total protein intakes for the EPIC-Oxford study adjusted for dietary protein quality (DIAAS) show that even at a DIAAS of 90%, the amount of utilizable protein is close to or falls below the FAO/WHO/UNU [8] RDA. For poorer quality diets (DIAAS 80% or lower), the intakes of utilizable protein generally fall below the RDA. For DIAAS <70%, the intakes of utilizable protein were well below the RDA (0.54–0.69 g/kg BW/d). The modeling demonstrates that dietary protein quality needs to be taken into account by both vegetarians and vegans, and if poorer protein quality diets are consumed, the RDA for protein may not be met. The mean protein intakes of vegans and vegetarians provide only a small total protein excess above the RDA, which means that protein quality can potentially be important.

Another study chosen for modeling here is that of Ciuris et al. [85], which relates specifically to vegetarian athletes. Thirty-eight omnivore and 22 vegetarian athletes provided 7-d food records to ascertain compliance with a recommended target utilizable protein intake of 1.2 to 1.4 g/kg BW/d. The mean recorded total protein intake for the vegetarian athletes was 78.5 g/d or 1.2 g/kg BW/d compared with 101.6 g/d and 1.4 g/kg BW/d for the omnivores. The effect of variation in dietary protein quality (DIAAS) on the amounts of utilizable protein was calculated. Only at the highest DIAAS (100%) could the lower protein target (1.2 g/kg BW/d) be met. As protein quality declined, the deficiency (against the lower protein target) increased from 0.12 g/kg BW/d at DIAAS = 90% to 0.48 g/kg BW/d at DIAAS = 60%. In the study, the actual DIAAS values of the diets consumed were calculated, with a mean DIAAS of 100% for the omnivores and 90% for the vegetarians. Given that the actual DIAAS for the vegetarians was <100%, dietary protein quality was shown to lead to utilizable protein intakes falling below the targeted intake for the athletes in this study. Poor protein quality diets have the potential to underpin protein deficiencies in relation to such target utilizable protein intakes. Consistent with the lower dietary protein quality, the vegetarian athletes had lower lean body mass compared with the omnivores.

Others, recognizing the generally lower total protein intakes of vegans and vegetarians, have also raised potential issues regarding dietary protein quality [84,86,87]. In their study with vegetarians, Kniskern and Johnston [84] noted lower than expected intakes of animal proteins for vegetarians and calculated the overall digestibility of protein and the PDCAAS for the vegetarian diet. Protein digestibility was found to be 82% and the PDCAAS 80%. Based on this, they concluded that the dietary reference intake for protein for vegetarians may be too low. At least for this group of vegetarians, the low actual protein quality of the diet (PDCAAS <100%) led to low predicted intakes of utilizable protein.

There is little doubt, however, that with careful planning, vegans and vegetarians are able to meet their amino acid needs [55,81,88,89], though at least in some countries, this may be more expensive than the omnivorous option [90,91].

General Observations

An analysis of actual dietary total protein intakes in the United States (NHANES dataset) showed that quantitatively significant proportions of subgroups of the adult population have habitual total protein intakes below the EAR/RDA, and for these people, low dietary protein quality would exacerbate the protein shortfall. Dietary protein quality is important whenever dietary protein intakes are marginal. Moreover, when different dietary protein quality ratings were assumed at the population level, meaning that in some cases higher total protein intakes would be needed to meet the EAR or RDA (given as utilizable protein), the estimated proportions of the population potentially consuming utilizable protein below the EAR or RDA increased greatly. When it was assumed that dietary protein quality was poor (DIAAS = 60%) some 55% of the population (19–50 y) would fail to meet the EAR, whereas when assuming a more moderate dietary protein quality rating (DIAAS = 80%), an estimated 25% of the population failed to meet the EAR and 44% fell below the RDA. Although the percentage of the population below the RDA also increased dramatically as DIAAS decreased, we do not suggest this represents the percentage of the population with inadequate intakes (that comes from percentage of the population below the EAR), but we do suggest that percentages of the population below the RDA might be useful for dieticians as this is the percentage of the population they may be counseling that may need more protein in their diets.

The actual quality ratings of diets consumed by individuals in the United States are not well known, and this study gives potential scenarios only. It is likely, however, that there is variation in the quality of dietary protein ingested by different individuals and that some people may be ingesting less utilizable protein than is indicated by their total protein intakes. That individuals within an overall population whose mean total protein intake appears to be adequate may be receiving utilizable protein intakes below the RDA for protein, could help to explain the correlations reported for developed countries between male height and dietary protein quality [92], especially if the findings given here for adults also hold for young adults and children.

For members of the adult population whose dietary total protein intakes are relatively low (at, below, or marginally above the RDA for protein) due to specific states, low dietary protein quality can mean that utilizable protein intakes fall below the RDA for protein. This concern is highlighted in the present analysis by examples for vegetarians and vegans as well as for the elderly.

Moreover, it should not be assumed that a high total protein intake necessarily avoids potentially negative outcomes consequent to low dietary protein quality. Some members of the population ingesting relatively high amounts of total protein may be susceptible to macronutrient imbalance (excessive protein energy as a proportion of total energy), especially when dietary protein intake is high, daily energy intake is low, and dietary protein quality is low. This is exemplified here by the calculations relevant to people on weight-loss dietary regimens, the elderly, and for endurance athletes. In these cases, dietary protein quality is important for achieving the targeted high utilizable protein intake without exceeding suggested upper limits for protein energy as a percent of total energy. Also, in practice, such high protein intakes can be difficult to achieve within the envelope of lower energy intakes, given the relatively low protein to energy ratios of many common foods. In these cases, protein-rich foods, which are normally of high protein quality, need to form part of the diet.

Calculated dietary protein energy intakes expressed as a percentage of total dietary energy for a relatively broad combination of dietary protein and energy intakes for adult females and males are given in Supplementary Tables 1 and 2. The results allow some generalizations to be made. A utilizable protein intake of 0.8 g/kg BW/d, which is close to the RDA, can be achieved (over the energy range 86–146 kJ/kg/d) without the total protein energy per unit total energy exceeding an acceptable maximum, regardless of the quality of the dietary protein (DIAAS). Lower dietary protein quality, however, can lead to unacceptably high amounts of total protein required to meet a target for utilizable protein, at energy intakes below ~122 kJ/kg/d and utilizable protein target intakes above ~1.2 g/kg BW/d.

Population-based mean dietary total protein intakes usually exceed the RDA for protein in mid- to high-income countries and, based on this, it is often concluded that dietary protein quality is of limited significance in these countries. Such conclusions can be misleading; however, as such data mask the situation for many individuals within the population. Even in industrialized nations, protein quality may need to be accounted for to ensure that targeted utilizable protein intakes are met and that diets are adequately balanced for macronutrients. More work is needed to assess the actual effects of subjects with utilizable protein intakes below the RDA and for people consuming high amounts of protein calories. Given the recent trend toward plant-based diets, whether for health and nutrition reasons or for supposed environmental concerns, as these diets are adopted, protein quality is likely to be an even more important consideration.

Author contributions

The authors' responsibilities were as follows – PJM, VLF, RRW: jointly conceived and designed the work; PJM wrote the article with section on Study One written by VLF; and all authors: read and approved the final manuscript.

Conflict of interest

PJM, VLF III (co-author), RRW (co-author) report that financial support was provided by Dairy Management Inc. VLF III reports a relationship with Dairy Management Inc that includes: consulting or advisory and funding grants. VLF III is Senior Vice President of Nutrition Impact, LLC, a food and nutrition consulting firm that analyses NHANES data for numerous food and beverage companies and related entities. RRW has received research grants from the National Cattleman's Beef Association and is a founder and co-owner of The Amino Company. RRW holds several patents for essential amino acid -based compositions. The work was conducted independently of any company or Industry body.

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Appendix A. Supplementary data

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