Plant proteins in relation to human protein and amino acid nutrition[1,2]

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ABSTRACT Plant protein foods contribute ≈65% of the per capita supply of protein on a worldwide basis and ≈32% in the North American region. These sources of protein are discussed in relation to their amino acid content, human amino acid requirements, and dietary protein quality. Mixtures of plant proteins can serve as a complete and well-balanced source of amino acids for meeting human physiological requirements. This short review ends with a list of a series of myths and realities concerning the relationship between plant protein and human nutrition and a list of some nutritional issues of concern to the health professional and informed consumer. *Am J Clin Nutr* 1994;59(suppl):1203S–12S.

KEY WORDS Amino acids, requirements, protein, complementation, nutritional quality, nitrogen, balance, amino acid score, timing, digestibility, limiting amino acid, lysine

Introduction

Plants are the predominant harvesters of solar energy and they constitute a primary resource of carbon, vitamins, minerals, protein, essential fatty acids, and utilizable energy for human food production. It is not surprising, therefore, that plant foods have always supplied the global household with the bulk of its food energy intake and most of its protein needs. Indeed, plants have been major players in shaping the course of human history (1). Furthermore, it is anticipated that before the turn of the next century we will be using, directly or indirectly, crop products that have been tailored to market specifications by the addition, deletion, or modification of genes (2, 3). With an increased understanding of the genetic organization and regulation of genes responsible for encoding seed storage proteins it is likely that the nutritional value of grains, for example, will be amenable to effective manipulation (4). Additionally, an increased contribution of plant foods in Western-type diets has been recommended as a way to reduce the risk of chronic diseases (5). For these reasons it is pertinent to consider, in brief, the role of plant food proteins in human nutrition.

Quantitative importance of major plant crops

Throughout history, humans have used some 3000 plant species for food and at least 150 species have been cultivated for commercial purposes. However, most of the world's population depends on approximately 20 different plant crops, which are generally divided into cereals, vegetables (including legumes), fruits, and nuts. In the context of human protein nutrition, the most important groups are cereal grains and food legumes, including oil-seed legumes.

The world supplies of protein that are derived from either plant or animal sources are difficult to estimate, but their approximate amounts are given in **Table 1.** On a global basis, plants provide ≈65% of the world supply of edible protein. The cereal grains, in particular, account for a substantial portion of the world's food protein (**Table 2**) and energy. On the other hand, animal products contribute ≈35% of the per capita availability of food protein. However, there are marked discrepancies in per capita protein supplies from animal and protein sources between the developed and developing regions (Table 1; ref 6). For example, in North America animal products supply ≈70% of the food protein, whereas the equivalent figure is ≈20% for the populations of the Far East, and may approach much lower levels for many individuals in rural areas of India and Indonesia. In the United States, food consumption survey data (**Table 3**) show that the contribution made by plant protein to the estimated daily protein intake is ≈30% for all age groups and for the population as a whole. Also shown in Table 3 is the pattern of intake of the indispensable (essential) amino acids lysine, sulfur amino acids, threonine, and tryptophan, which is constant across all age groups.

In part because livestock production involves a potential loss of the energy and available protein of plants that could otherwise be used to meet human needs, it has been a popular view, and one that was echoed at the Second International Congress on Vegetarian Nutrition, to recommend significant reductions in the amounts of cereals and legumes used for feed and to increase their direct use as foods for humans. Furthermore, the potential health benefits of this shift in the composition of human diets have received considerable attention in recent years and this topic was also a major focus of interest at the Congress. Therefore, the nutritional aspects of plant foods and the protein nutritional adequacy of diets based mainly on plant sources deserve our consideration.

To assess the nutritional role of plant proteins in meeting the needs of human subjects under various conditions we should first

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TABLE 1
Energy and protein supplies per capita per day for selected geographic and economic regions for 1989[1]

	Energy	Carbohydrate	Animal protein	Total protein	Plant protein
	kcal (MJ)	*%*	*g*	*g*	*%*
Region					
Developing	2846 (11.91)	73	14	61	77
Far East	2450 (10.25)	75	11	59	81
Middle East	2954 (12.34)	67	17	78	78
Africa	2363 (9.89)	72	12	58	79
Latin America	2732 (11.43)	65	29	68	57
Economic class					
Least developed	2058 (8.61)	76	9	52	83
Low income	2409 (10.08)	74	11	58	81
Developed	3417 (14.30)	53	61	104	42
Western Europe	3457 (14.46)	51	60	103	42
North America	3650 (15.27)	48	73	110	34
Oceania	3240 (13.56)	50	66	98	33
World	2710 (11.34)	67	25	71	65

[1] Based on FAO/Agrostat data (reference 6).

turn our attention to the estimates of requirements for total protein (nitrogen) and for the specific indispensable amino acids. This subject has been reviewed by us (8, 9) and others (10, 11) and so an abbreviated account of some of the more important issues relevant to plant proteins will be presented here.

Protein and amino acid requirements and protein quality considerations

The requirements for total protein, at various stages during the life cycle of humans, were reviewed and evaluated recently by a joint panel of the Food and Agriculture Organization, the World Health Organization, and the United Nations University (FAO/WHO/UNO) (11). In **Table 4,** the safe intakes of high quality proteins, defined in the FAO/WHO/UNU (11) report as those from eggs, meat, and milk, are given for different age groups. These data were derived largely from growth and metabolic nitrogen balance studies and, when expressed per kg body weight, they reveal an age-related decline in dietary protein needs for maintenance of adequate protein nutritional status.

TABLE 2
Relative importance of various food groups in average world daily per capita intake for 1989[1]

	Energy	Percent of energy	Protein	Percent of protein
	kcal (kJ)	*%*	*g*	*%*
Total plant	2277 (9 526)	84	46.1	65
Cereals	1385 (5 794)	51	33.7	47
Pulses, nuts, oil crops	109 (456)	4	6.0	8
Starchy roots	141 (590)	5	2.0	3
Other vegetables	46 (192)	2	2.5	4
Fruits	65 (272)	2	0.8	1
Total animal	433 (1 811)	16	25.0	35
Total	2710 (11 339)	100	71.1	100

[1] Based on FAO/Agrostat data (reference 6).

TABLE 3
Protein consumption and amino acid pattern for various age groups (female) in the United States[1]

		Proteins			Amino acids[2]			
Age group	Total protein	Plant	Meat, poultry, fish	Grain products	Ly	Saa	Thr	Try
	g/d		*g/d*			*mg/g protein*		
<1 y	42	27	55	59	69	31	40	12
6–8 y	68	33	154	227	69	35	40	12
19–22 y	65	30	183	184	72	35	39	12
35–50 y	65	29	191	169	71	34	39	12
>75 y	59	32	148	190	68	34	38	12

[1] Based on US Department of Agriculture Food Consumption Data (reference 7).
[2] Ly, lysine; Saa, sulfur amino acids; Thr, threonine; Try, tryptophan.

The requirement for dietary protein consists of two components: *1*) the requirement for the nutritionally indispensable amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine) under all conditions and for conditionally indispensable amino acids (cystine, tyrosine, taurine, glycine, arginine, glutamine, proline) under specific physiological and pathological conditions and *2*) the requirement for nonspecific nitrogen for the synthesis of the nutritionally dispensable amino acids (aspartic acid, asparagine, glutamic acid, alanine, serine) and other physiologically important nitrogen-containing compounds such as nucleic acids, creatine, and porphyrins. With respect to the first component, it is usually accepted that the nutritive values of various food protein sources are to a large extent determined by the concentration and availability of the individual indispensable amino acids. Hence, the efficiency with which a given source of food protein is utilized in support of an adequate state of nutritional health depends both

TABLE 4
Safe protein intakes as proposed in 1985 by FAO/WHO/UNU[1]

Age group	Males	Females[2]
	g protein · kg^{-1} · d^{-1}	
3–6 mo	1.85	1.85
6–9 mo	1.65	1.65
9–12 mo	1.50	1.50
1–2 y	1.20	1.20
2–3 y	1.15	1.15
3–5 y	1.10	1.10
5–7 y	1.00	1.00
7–10 y	1.00	1.00
10–12 y	1.00	1.00
12–14 y	1.00	0.95
14–16 y	0.94	0.90
16–18 y	0.88	0.80
Adults	0.75	0.75

[1] Adapted from reference 11. Values are uncorrected for nutritional value (amino acid scores) of mixed dietary proteins for infants and children and digestibility for all groups.
[2] Safe protein intakes for pregnant females, intakes in table + 6g; for lactating females (0–6 mo), intakes in table + 17.5 g; and for lactating females (6 mo), intakes in table + 13 g.

on the physiological requirements for the indispensable amino acids and total nitrogen and on the concentration of specific amino acids in the source of interest.

This raises the question of the content and balance of indispensable amino acids in plant and animal protein foods. There are extensive data on the amino acid composition of foods (12, 13). For present summary purposes, **Table 5** gives the amounts in different food sources of those indispensable amino acids that are likely to be the most limiting in plant protein foods. As shown, the indispensable amino acid lysine is consistently at a much lower concentration in all major plant-food protein groups than in animal foods. In addition, the sulfur-containing amino acids are distinctly lower in legumes and fruits and threonine is lower in cereals compared with amounts found in proteins of animal origin. A more extensive survey of the limiting amino acid and the amino acid score for various plant protein foods is presented in **Table 6.**

Given these comparisons of amino acid content among plant and animal proteins, it is now relevant to ask about their nutritional significance in reference to meeting the needs of human protein nutrition. Hence, we introduce the topic of protein nutritional quality. Various approaches have been used to assess the comparative nutritional value of food proteins (*see* ref 15 for review). One example is the rat bioassay procedure termed the protein efficiency ratio (PER), which has been in widespread and official use since first proposed in 1919 (16). However, this procedure does not necessarily predict satisfactorily the nutritional value of all plant protein foods intended for direct human consumption (17, 18). This is particularly so for legume and oil-seed proteins. Alternative procedures that would be more directly applicable to human protein and amino acid nutrition have been proposed and developed.

The procedure that was adopted by a recent FAO/WHO Expert Consultation (19) on protein quality evaluation is based on the concept of an amino acid score. This concept was first introduced in 1946 by Block and Mitchell (20), who observed a linear relationship between the biological value of proteins and the content of their limiting amino acid. The amino acid score is defined as the concentration of the limiting amino acid in the food protein and is expressed as a proportion or percentage of the concentration of the same limiting amino acid in a standard or reference amino acid pattern (15). Hence, a particularly critical and important issue becomes the choice of the amino acid reference pattern to be used for assessing nutritional quality or for calculating an amino acid score for a food protein or mixture of proteins of interest. When Block and Mitchell (20) proposed this scoring procedure, the amino acid composition of egg proteins was used as a standard. It was later determined that the relatively high amounts of indispensable amino acids in egg proteins undervalued many proteins for human nutrition, which led to the use of estimates of human amino acid requirements as a basis for subsequent scoring systems (11, 21, 22).

A common feature of most of the amino acid scoring systems proposed before 1985, when the FAO/WHO/UNU report on energy and protein requirements was published, was that a single reference amino acid pattern was used for studies on all ages, despite published amino acid requirement data that generally showed that infants needed ≈35% of their total amino acids in the form of indispensable amino acids whereas adults apparently needed only 15% or less (11, 22).

TABLE 5
Survey of the amino acid content of different food protein sources[1]

Food source	Lysine	Sulfur amino acids	Threonine	Tryptophan
	mg/g protein			
Legumes	64 ± 10	25 ± 3	38 ± 3	12 ± 4
Cereals	31 ± 10	37 ± 5	32 ± 4	12 ± 2
Nuts, seeds	45 ± 14	46 ± 17	36 ± 3	17 ± 3
Fruits	45 ± 12	27 ± 6	29 ± 7	11 ± 2
Animal foods	85 ± 9	38	44	12

[1] $\bar{x}$ ± SD. Based on data from FAO (reference 12) and US Department of Agriculture (reference 13).

The 1985 FAO/WHO/UNU estimates of the amino acid requirements in various age groups and the estimates proposed by US authorities (10) are shown in **Table 7.** For amino acid scoring purposes, if the values given in Table 7 for the concentration of essential amino acids in relation to the total protein needs of adults were adopted, the nutritional value of a protein for children would be overestimated. In contrast, adoption of the child pattern would underestimate the value of a protein for adults.

When the FAO/WHO/UNU (11) amino acid requirement estimates for the adult, which are expressed per unit of protein need, are compared (*see* Tables 5 and 7) with the amino acid pattern of various plant and animal protein sources, it should be evident that the amounts of amino acids in these food sources is much higher (per unit of protein) than required. As a result, all of the indispensable amino acids, including the sulfur amino acids, in soy proteins and lysine in cereal proteins are predicted to be in considerable excess of adult needs. Thus, all usual food proteins would readily meet and even exceed the requirement for the indispensable amino acids, providing that the dietary protein supply was equal to or above the safe protein intakes (Table 4).

On the above basis it would be concluded that there is little reason to be further concerned with an assessment of the nutritional quality of plant proteins in adults. It could also be concluded that our attention should be focused on children and infants, particularly because they might be given diets containing a single food protein source or a limited number of protein sources, for example, infants fed a diet of a proprietary formula, possibly supplemented with strained foods. However, there is increasing evidence that the current international FAO/WHO/UNU (11) and national (10) requirement estimates for most indispensable amino acids in adults are far too low (9, 23, 24). Several groups (25–27) are seeking to further substantiate this evidence, which would strengthen the case for the inadequacy of the international recommendations and would have important implications for the approaches to be taken to comprehensively assess the roles of both plant and animal food protein sources in human nutrition.

The specifics of this new research on human amino acid requirements were previously reviewed by us (9, 23, 24). However, from more recent data we have arrived at a new, tentative set of estimates for the amino acid needs of adults. These values are shown in **Table 8,** and are compared with the 1985 estimates made by FAO/WHO/UNU for the children aged 2–5 y.

It can be seen that, except for a lower threonine and slightly lower lysine content, our proposed adult pattern is quite similar

TABLE 6
Protein concentration, limiting amino acid (LAA) score and lysine score for selected plant foods[1]

	Protein	LAA score (amino acid)	Lysine score
	%		
Cereals			
Amaranth	14.5	89 (Lys)	89
Barley	12.5	64 (Lys)	64
Buckwheat	13.3	87 (Lys)	87
Bulgur	12.2	48 (Lys)	48
Corn	9.4	49 (Lys)	49
Millet	11.0	33 (Lys)	33
Oats	16.9	72 (Lys)	72
Rice brown	7.9	66 (Lys)	66
Rice white	7.1	62 (Lys)	62
Rye	14.8	71 (Lys)	62
Sorghum	11.3	35 (Lys)	35
Triticale	13.2	48 (Lys)	48
Wheat hard	12.6	46 (Lys)	46
Wheat durum	13.7	38 (Lys)	38
Wheat flour	10.3	38 (Lys)	38
Spaghetti	12.8	33 (Lys)	33
Legumes			
Bean white	21.9	100	118
Bean kidney	23.6	100	118
Chick peak	19.3	100	115
Cow pea	23.5	100	117
Lentil	28.1	86 (Saa)	120
Lima bean	21.5	95 (Saa)	116
Lupine	36.2	78 (Saa)	92
Mungbean	23.9	83 (Saa)	120
Peanut	25.8	62 (Lys)	62
Pigeon pea	21.7	91 (Saa)	121
Soybean	36.5	100	115
Wing bean	29.7	100	124
Nuts and Seeds			
Almond	20.4	58 (Lys)	58
Brazil	14.3	65 (Lys)	65
Cashew	15.3	92 (Lys)	92
Coconut	3.3	76 (Lys)	76
Pecan	8.0	65 (Lys)	65
Pistachio	14.9	100	107
Walnut	14.3	47 (Lys)	47
Cottonseed	41.0	88 (Lys)	88
Pumpkin seed	24.5	100	129
Sesame seed	17.7	55 (Lys)	55
Sunflower seed	22.8	71 (Lys)	71
Vegetables			
Bean (green)	1.8	83 (Lys)	83
Broccoli	3.0	67 (Leu)	82
Cabbage	1.2	73 (Saa)	81
Carrots	1.0	58 (Saa)	67
Cassava	1.3	44 (Leu)	56
Okra	2.0	70 (Lys)	70
Onion	1.2	53 (Leu)	82
Peas (green)	5.4	85 (Saa)	101
Pepper sweet	0.9	77 (Lys, Leu)	77
Potato	2.1	91 (Leu)	105
Spinach	2.9	100	105
Squash	1.2	70 (Thr)	95
Sweet potato	1.7	85 (Lys)	85
Taro	1.5	77 (Lys)	77
Tomato	0.9	56 (Leu)	64
Vegetables (continued)			
Turnip	0.9	53 (Aaa)	69
Yam	1.5	66 (Lys)	66
Fruits			
Apples	0.2	75 (Aaa)	109
Avocados	2.0	82 (Lys)	82
Bananas	1.0	80 (Lys)	80
Figs	0.8	67 (Leu, Lys)	69
Orange	0.9	37 (Leu)	86
Peach	0.7	57 (Lys)	57
Pear	0.4	62 (Lys)	62
Pineapple	0.4	74 (Leu)	111
Plantain	1.3	69 (Leu)	80
Plum	0.8	37 (Lys)	37

[1] Lys, lysine; Saa, sulfur amino acids; Leu, leucine; Aaa, aromatic amino acids. Based on FAO/WHO/UNU data (reference 11) and references 12, 13, and 14.

to the pattern recommended by FAO/WHO/UNU (11) for preschool and early school-age children (2–5 y). If these revised estimates of amino acid requirements in adults are rational, as we believe they are for reasons discussed elsewhere (9, 23, 24), the nutritional value of different protein sources would not be affected as markedly by the age of the consumer. This is in contrast to the position adopted in the 1985 FAO/WHO/UNU report. Based on the revised estimations of amino acid requirements that are given in Table 8, it follows that for evaluation of dietary protein quality in human nutrition it is only necessary to recommend use of two amino acid requirement, or scoring, patterns. The first pattern would be that for the infant, which according to FAO/WHO/UNU (11) should be based on the amino acid composition of breast milk; the second, as shown in Table 8, would be the amino acid requirement pattern for ages 2–5 y, which would be applied to all groups above 2 y of age. This view is now reflected in the recommendations made by the expert group convened by FAO/WHO (19), which proposed that the 1985 FAO/WHO/UNU amino acid requirement for the group aged 2–5 y be used to assess the protein quality of foods in reference to young children, older children, and also adults.

FAO/WHO (19) proposed, for scoring purposes, the so-called protein digestibility–corrected amino acid score (PDCAAS), which can be defined as follows:

$$\text{PDCAAS} = \frac{\text{Amino acid content (mg/g protein) in food protein} \times \text{digestibility}}{\text{Amino acid content in 1985 FAO/WHO/UNU pattern for ages 2–5 y}}$$

It should be noted that digestibility is included in this amino acid scoring procedure, to allow for differences in the digestibility of the different food-protein sources. We will refer specifically to the digestibility of plant protein foods below.

Amino acid score and plant protein quality

The amino acid scoring procedure appears likely to be adopted by the US government as the official procedure for food protein

TABLE 7
Estimates of amino acid requirements of preschool children, older children, and adults

Amino acid	Intake for wt			Intake by protein		
	Preschool[1] (2–5 y)	Schoolchildren[2] (10–12 y)	Adults[1] (≥ 18 y)	Preschool[1] (2–5 y)	Schoolchildren[2] (10–12 y)	Adults[1] (≥ 18 y)
	mg · kg body wt⁻¹ · d			*mg/g protein*		
Histidine	—	—	8–12	—	—	16
Isoleucine	31.0	28.0	10.0	28	28	13
Leucine	73.0	44.0	14.0	66	44	19
Lysine	64.0	44.0	12.0	58	44	16
Methionine and cystine	27.0	22.0	13.0	25	22	17
Phenylalanine and tyrosine	69.0	22.0	14.0	63	22	19
Threonine	37.0	28.0	7.0	34	28	9
Tryptophan	12.5	3.3	3.5	11	9	5
Valine	38.0	25.0	10.0	35	25	13
Total (−histidine)	352.0	216.0	84.0	320	216	111

[1] Adapted from reference 11.
[2] Based on NRC data (reference 10).

quality evaluation and quality control of protein foods. Because we have argued in favor of this policy (28) it might be worthwhile to briefly compare some human metabolic data with predictions based on the PDCAAS.

In **Table 9** we compare the amino acid composition of common hybrid and high-lysine maize and have calculated the PDCAAS for these different cultivars. The prediction is that the nutritional value of the high-lysine variety is superior to that of the hybrid maize and this has been confirmed in metabolic studies in children, as summarized by Bressani (29). A lower biological value for normal maize compared with two varieties of high-lysine maize was also reported (29). However, whether any significance should be given to the difference between the value for the score of 0.63 (Table 9) and the numerical estimates for the biological value of the high-lysine maize as derived from the metabolic studies is difficult to judge. The relative differences between the scores and the metabolically derived, biological values for the hybrid and high-lysine maizes are small. If the lysine content of the FAO/WHO/UNU (11) amino acid reference pattern for children aged 2–5 y is set too high then this would give the protein a lower numerical value for the score than would be obtained via a feeding-metabolic study. Because lysine is most likely to be the first limiting amino acid in diets that are based predominantly on cereal grains (30) it is important to determine more accurately the lysine content of the reference amino acid requirement pattern.

The reference amino acid pattern used to arrive at the PDCAAS predicts that in addition to cereals, well-processed soy protein products, such as isolated soy proteins (18), would have a high nutritional value. We have reviewed this topic in detail and have concluded that soy flour and soy isolates, when they are the sole or major source of protein in diets containing adequate energy and other essential nutrients, are fully capable of promoting adequate growth in young infants (17, 18). For example, Torun (31) gave graded amounts of one of two soy-pro-

TABLE 8
New, tentative amino acid requirement estimates for adults and corresponding requirement pattern for preschool children

Amino acid	Adult tentative requirement[1]	Adult amino acid pattern[2]	Preschool child amino acid pattern[2]
	mg·kg⁻¹·d⁻¹	*mg/g protein*	*mg/g protein*
Isoleucine	23	35	28
Leucine	40	65	66
Lysine	30	50	58
Sulfur amino acids	13	25	25
Aromatic amino acids	39	65	63
Threonine	15	25	34
Tryptophan	6	10	11
Valine	20	35	35

[1] Based on data from reference 23.
[2] Adapted from reference 11.

TABLE 9
Indispensable amino acid content and amino acid score of normal and high-lysine maize

Amino acid	Maize[1] Normal	Maize[1] High-lysine	1991 FAO/WHO pattern[2]	Amino acid score[3] Normal	Amino acid score[3] High-lysine
	mg/g N		*mg/g N*		
Lysine	177	256	363	0.44	0.63
Isoleucine	206	193	175	>2.00	0.98
Leucine	827	507	413	>1.00	>1.00
Sulfur amino acids	188	188	156	>1.00	>1.00
Aromatic amino acids	505	502	394	>1.00	>1.00
Threonine	213	199	213	0.89	0.83
Tryptophan	35	78	68	>1.00	>1.00
Valine	292	298	219	>1.00	>1.00
Leucine-Isoleucine	4.01	2.63	2.36	>1.00	>1.00

[1] Adapted from reference 29.
[2] Adapted from reference 19.
[3] Corrected for digestibility, assuming a value of 0.89 relative to reference proteins.

tein isolates to children who had recovered from earlier protein-energy malnutrition and compared nitrogen-balance responses with those obtained using milk as the reference protein. Interpretation of the nitrogen-balance data showed that the nutritive value of the isolated soy protein tested was ≈86–107% that of milk, depending on the specific criterion used for comparison. Hence, the protein nutritional value of the well-processed isolated soy proteins so far examined in young children is essentially equivalent to that of milk protein.

Results of studies on the nutritional quality of specific soy-protein products in adults have also been reviewed previously (17, 18). In summary, the nutritional value of an isolated soy protein (Supro-620, Ralston Purina Co, St. Louis, MO), based on an analysis of the nitrogen-balance data, was high for healthy adults, > 80% of the nutritional value of egg protein. The true digestibility of the soy isolate was also high (≈97%) and was comparable with that for egg proteins.

Of particular importance from the findings in these various metabolic studies, was the observation that the protein value of this soy isolate when tested in children and adults was considerably higher than what would be predicted from the PER assay carried out in rapidly growing rats. The latter assay seriously underestimates the nutritional quality of the soy isolate for children and adults. Perhaps the discrepancy between "rat" and "human" data also explains why there appears to be a lingering view held by some professionals as well as consumers that soy proteins are of poor quality. Clearly the more recent, direct human metabolic data reveal that they can be and are of high nutritional value.

Parenthetically, the question of the need for methionine supplementation emerges here. From our own studies and those of others (17, 18), methionine supplementation of soy proteins is clearly unnecessary in adults. Soy proteins, consumed as isolates or concentrates, are excellent sole sources for meeting nitrogen and all amino acid needs when consumed at physiologically important intakes of total protein. Methionine supplementation of soy-based infant formulas may, however, be desirable, although the methionine addition required to achieve high utilization of soy protein appears modest (18, 32) and is considerably lower than would have been predicted from rat PER assay data.

More than 30 y have passed since the 1957 report of the first FAO protein requirements committee (21), who selected protein, or amino acid, scoring as an official basis for assessing the nutritional value of proteins for meeting human nutritional requirements. Provided that an adjustment is made for the digestibility of ingested proteins (or the availability of the indispensable amino acids in the protein), the conclusion made by this group "that the concept of a desirable pattern of essential amino acid has a great advantage and by comparison, with such a pattern, data on the amino acid content of individual foods and food combinations can be appraised for a wide range of situations, with respect to evaluation of the nutritional quality of the diet and of methods of improving it" remains valid. In addition, the recent recommendations made by FAO/WHO (19) are entirely consistent with this view.

Additional issues

Complementation and timing of ingestion of proteins

Important differences among and between food products of vegetable and animal origin are the concentrations of proteins and indispensable amino acids that they contain. The concentration of protein and the quality of the protein in some foods of vegetable origin may be too low to make them adequate, sole sources of proteins when consumed in their traditional manner, particularly for infants and children. However, children can thrive on as well as recover from severe malnutrition if given well-formulated diets based entirely on plant food sources. Thus, plant foods, in appropriate amounts and combinations are able to supply the essential nutrients required for maintenance of adequate health and function.

Mixtures of plant protein foods may be of potentially high nutritional quality. For example, although the soybean is low in sulfur-containing amino acids, cottonseed, peanut and sesame flour, and cereal grains are deficient mainly in lysine. This indicates that oil-seed proteins, in particular, soy protein, can be used effectively in combination with most cereal grains to improve the overall quality of the total protein intake. A combination of soy protein, which is high in lysine, with a cereal that contains a relatively good concentration of S-amino acids results in a nutritional complementation; the protein quality of the mixture is greater than that for either protein source alone.

This concept of protein, or amino acid, complementation is pertinent to a discussion of plant foods. Various nutritional responses are observed when two dietary proteins are combined. These have been classified by Bressani et al (33) into one of four types (Types I, II, III, and IV) as shown in **Figure 1.**

Type I is an example where no protein complementary effect is achieved. For example, this occurs with combinations of pea-

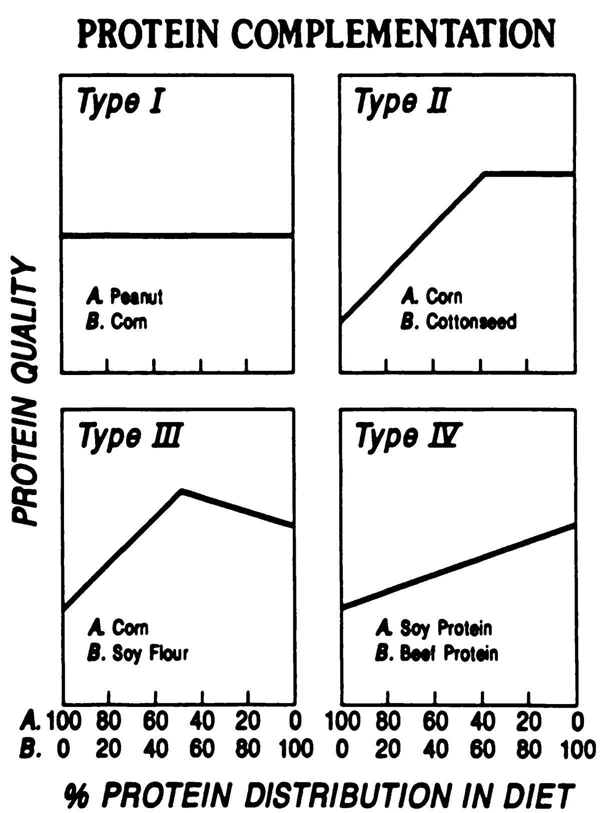

FIG 1. Four types of response, assessed in terms of an index of biological value or protein quality, arising from mixing of two food protein sources. Adapted from reference 33.

TABLE 10
Digestibilities of different sources of food protein in humans[1]

	True digestibility	Digestibility relative to reference proteins
	%	%
Reference proteins		
Egg	97 ± 3[2]	100
Milk, cheese	95 ± 3	100
Meat, fish	94 ± 3	100
Plant proteins		
Maize	85 ± 6	89
Polished rice	88 ± 4	93
Whole wheat	86 ± 5	90
Oatmeal	86 ± 7	90
Beans	78	82
Maize, beans	78	82
Indian rice diet	77	81
Brazilian mixed diet	78	82
Filipino mixed diet	88	93
US mixed diet	96	100

[1] Adapted from reference 11.
[2] $\bar{x}$ ± SD.

nut and corn, where each of the protein sources have a common and quantitatively similar lysine deficiency and are both also deficient in other amino acids. Type II response is observed when combinations are made of two protein sources that have the same limiting amino acid, but in quantitatively different amounts. Corn and cottonseed flour, for example, are both limiting in lysine but cottonseed is relatively less inadequate than is corn.

The third type of response (Type III) demonstrates a true complementary effect because there is a synergistic effect on the overall nutritive value of the protein mixture; the protein quality of the best mix exceeds that of each component alone. This type of response occurs when one of the protein sources has a considerably higher concentration of the most limiting amino acid in the other protein. An example of this response, based on studies in children (33), is observed when corn and soy flour are mixed so that 60% of the protein intake comes from corn and the remainder from soya protein.

Finally, the Type IV response occurs when both protein sources have a common amino acid deficiency. The protein component giving the highest value is the one containing a higher concentration of the deficient amino acid. Combinations of some textured soy proteins and beef protein follow this type of response (34).

These nutritional relationships have been determined from rat bioassay studies. However, the more limited results available from human studies with soy and other legumes confirm the applicability of this general concept in human nutrition. This knowledge helps us to understand and evaluate how nutritionally effective combinations of plant protein foods can be achieved.

Our reason for discussing amino acid complementation is to introduce the question of timing of ingestion of complementary proteins. There is some concern, at least at the consumer level, about the need to ingest different plant proteins at the same time, or within the same meal, to achieve maximum benefit and nutritional value from proteins with different, but complementary, amino acid patterns. This concern may also extend to the question of the need to ingest a significant amount of protein at each meal, or whether it is sufficient to consume protein in variable amounts at different meals as long as the average daily intake meets or exceeds the recommended or safe protein intakes.

According to FAO/WHO/UNU (11), estimates of protein requirements refer to metabolic needs that persist over moderate periods of time. Although protein and amino acid requirements are conventionally expressed as daily rates (of intake) there is no implication that these amounts must be consumed each and every day. Therefore, it is not essential, at least in adults, that daily intakes of protein, or presumably of each indispensable amino acid, must equal or exceed the physiological requirement; it is apparently sufficient for the average intake over a number of days to achieve this level. This pattern of intake would allow maintenance of an adequate protein nutritional state.

There is a limited database that we can consult to make a definitive conclusion on the timing of consumption of complementary proteins or of specific L-amino acid supplements for proteins that are deficient in one or more amino acids. Earlier work in rapidly growing rats suggested that delaying the supplementation of a protein with its limiting amino acid reduces the value of the supplement (35–38). Similarly, the frequency of feeding of diets supplemented with lysine in growing pigs affects the overall efficiency of utilization of dietary protein (39, 40). There are few data available from human studies to assess the significance of these findings. However, the relevance of rat and pig studies can be questioned in view of the profoundly different qualitative and quantative characteristics of protein metabolism in rats and pigs compared with human subjects (41). Our studies in human adults showed that overall dietary protein utilization was similar whether the daily protein intake was distributed among two or three meals (42). However, the supplementary effect in children of the addition of *Phaseolus vulgaris* to a maize-bean diet was somewhat less when the supplement was given at intervals of > 6 h (R Bressani and D Wilson, personal communication, 1992).

We believe that for usual conditions of healthy living it is not necessary to consume complementary proteins at the same time and that separation of the proteins among meals over the course of a day would still permit the nutritional benefits of complementation. There are also physiological data to support this contention.

Because lysine is most likely to be the limiting amino acid in a diet based predominantly on cereal grains (30), it is of interest and relevance that in the skeletal musculature there is a sizeable pool in the intracellular space of free amino acids, particularly of lysine. The size of this pool responds to changes, both acute and chronic, in the amount of lysine ingested (43). Based on the data of Bergstrom et al (44), we calculate that after a protein-rich meal (providing 50 g bovine serum albumin) 60% of the adult daily requirement for lysine may be deposited in this intracellular pool within 3 h. Hence, a protein with a relatively low lysine content (maize) could be ingested some hours later than a complementary, higher lysine-containing protein (eg, soy protein) and the free-lysine pool in the muscle would buffer the low lysine content of the amino acid mixture derived from the digestion of maize. Overall, the nutritional quality of the combined meals would be high.

We conclude that it is not necessary to balance the amino acid profile at each meal, especially under conditions where intakes of total protein substantially exceed minimum physiological re-

TABLE 11
Plant proteins in human nutrition: myths and realities

Myth	Reality
1) Plant proteins are "incomplete" (ie lack specific amino acids)	*1*) Usual dietary combinations of proteins are complete; specific food proteins may be low in specific amino acids
2) Plant proteins are not as "good" as animal proteins	*2*) Quality depends on the source and dietary mixture of plant proteins; can be equivalent to high-quality animal proteins
3) Proteins from different plant foods must be consumed together in the same meal to achieve high nutritional value	*3*) Proteins do not need to be consumed at the same time, the balance over a day is of greater importance
4) Animal bioassay procedures are satisfactory indexes of the human nutritional value of food proteins	*4*) Animal bioassay procedures can be useful but they may underestimate plant protein nutritional quality for humans
5) Plant proteins are not well digested	*5*) Digestibility can vary according to source and food preparation; digestibility can be high
6) Plant proteins alone are not sufficient to achieve an adequate diet (protein intake)	*6*) The intakes and balance of intakes of indispensable amino acids and nitrogen are crucial and can be adequately met from plant or plant and animal sources
7) Plant proteins are "imbalanced" and this limits their nutritional value	*7*) There is no evidence that amino acid imbalances per se are important; possible imbalances can be created by inappropriate amino acid supplementation, but this is not a practical problem

quirements. Consumption of complementary proteins at different meals over the course of the day should assure the achievement of an adequate state of nitrogen (protein) retention and utilization. Therefore, an undue emphasis on amino acid balance at each meal is inappropriate in the context of usual diets in healthy populations.

Protein digestibility and amino acid availability

The nutritional value of a dietary protein source may not be predicted with precision from a determination of its amino acid content alone; several other factors can affect the utilization of proteins. An important factor, which is frequently critical in the feeding of simple-stomached farm livestock, is the digestibility and availability of the protein and individual amino acids.

In general, the digestibility of vegetable proteins in their natural form is lower than that of animal proteins. **Table 10** summarizes results for the digestibility in human subjects of various plant sources and of diets based on mixed plant-food sources. Plant proteins are often consumed only after undergoing some degree of preparation or processing. Although the effects of processing on protein quality and availability will not be reviewed here, this factor deserves attention in an overall assessment of plant foods for humans. For example, oil-seed flours may be products of processes designed to economically recover the oil from the seed. Such processes do not necessarily favor the efficient recovery of high-quality protein. Cereals and legumes intended for human feeding are cooked or processed to enhance their palatability and acceptance. For example, wheat is used primarily in bread, pasta, and breakfast-cereal-type foods. Thermal processing methods that use high-temperature, short-time processing conditions, such as extrusion, microwave heating, puffing, and spray drying, have been widely adopted. However, as a result of such treatments, the nutritive value of the protein may be either enhanced or reduced to an extent that depends on the protein components in the food and factors such as the temperature, duration of heating, and the presence or absence of moisture. Boiling in water generally improves protein quality, whereas toasting or dry heating reduces protein quality. Hence, it is difficult to draw broad generalizations concerning the effects of various processing and preparation conditions on the proteins and the individual amino acids of plant foods. More basic work is needed on the chemical and physical changes that occur in proteins under these conditions and their nutritional effects to develop, in the long-term, optimum procedures for the utilization of plant food proteins.

Many plants contain numerous compounds that may cause unfavorable physiological and clinical responses when eaten, including diminished digestibility. Man has learned to avoid those foods that produce immediate ill effects or has devised means of eliminating the undesirable compounds from others. Often processing, or cooking, results in the destruction, inactivation, or lessening of these toxic compounds (antinutritional factors), but they may not be sufficiently reduced to eliminate the health problem entirely, particularly if novel plant foods are eaten more frequently and over longer periods of time. Examples of some of the factors present in various legume-seed protein sources and their possible metabolic and physiologic significance are: amylase inhibitors, which are found in most legumes and may interfere with starch digestion; cyanogen, which is found in lima beans and may cause respiratory failure; and tannins, which are phenolic compounds found in most legumes and may form less digestible complexes (45). In products that are commercially available these factors do not pose any nutritional or clinical problems. Nevertheless, they are important to consider in the course of developing new and improved sources of plant protein, for example, as in the case of new varieties and uses of sorghum (46).

Summary and conclusions

In this brief review we have highlighted the value of plant proteins in relation to human protein nutrition. We began with a brief consideration of the contribution made by plant proteins to the protein component of diets on a worldwide basis and also within the United States. We then discussed the requirements for protein and for indispensable amino acids in humans at various ages, together with a short survey of the amino acid composition of different plant-food protein sources. There is a large variation in the contribution made by plant proteins to the availability and intake of total dietary protein among populations both within the technically advanced regions of the world and between these and developing regions. It can be shown from considerations of the amino acid composition of the major food protein sources that plant proteins are a major determinant of the lysine content of diets worldwide (29, 30). This indispensable amino acid might well be limiting, or marginal, in diets of some countries where cereals, for example, wheat, are the predominant source of the total dietary energy supply. However, modest amounts of higher-lysine protein foods such as legumes or animal proteins, can have a major and favorable impact on the protein nutritional quality of such diets (30). Overall it can be concluded that mixtures of plant proteins can serve as a complete and well-balanced source of amino acids that effectively meet human physiological requirements.

We present in **Table 11** a list of myths and realities concerning plant proteins in human nutrition. We have included in this list a reference to amino acid imbalance (no. 7) that we did not consider in any detail earlier, largely because we do not consider this issue to be an important problem in practice (47). Considerable and interesting experimental data have defined the nature and mechanisms of dietary amino acid imbalances (48) and the untoward physiological consequences of an imbalance have been observed in children during amino acid supplementation trials of dietary protein (49). However, the suggestion that high leucine intakes, as supplied by sorghum in regions of India, might be etiologically significant in the pellagra that exists in these areas (50) has not been substantiated by considerable additional investigation (47). Thus, we conclude that consumers do not need to be at all concerned about amino acid imbalances when the dietary amino acid supply is from the plant-food proteins that make up our usual diets. Mixtures of plant proteins can be fully adequate for meeting human requirements. From the standpoint of the composition of a healthful diet, they serve as a desirable vehicle for carrying nitrogen and indispensable amino acids to meet both our needs and wants (Table 11, reality no. 6).

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