Nutritional Role of Soya Protein for Humans[1]

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ABSTRACT

This paper reviews the role played by soya protein in human nutrition on the basis of protein quality, energy and protein densities, and availability of trace minerals. The importance of supplementation with methionine was analyzed and it was concluded that there is little nutritional or public health justification for such supplementation when the intake of protein is adequate. The use of refatted soy products has good potential to increase the dietary concentrations of protein and energy, which may be particularly important for children in developing countries and for the elderly or other persons with limited dietary intakes and digestive capacity. Investigations based on chemical balance and on the use of stable isotopes indicate that the iron from soybean is well absorbed by humans, as are inorganic iron and zinc in the presence of soy protein. Soybeans and properly processed soy products have a good protein quality, and when fed in adequate amounts, they can satisfy the total nitrogen and essential amino acid needs of children and adults. Further research related to soy products should be directed mainly toward establishing their overall nutritional value as part of mixed diets or food systems, and not just assess their protein quality. Assessing the protein quality of soy products may be required when major processing modifications are made in the manufacture of soy products for human consumption.

INTRODUCTION

Soybean protein has played an increasing role in human nutrition over the last two decades in both developing and industrialized regions of the world. The production of soybeans has increased in many countries, notably the U.S., Brazil and China (1). Technological advances leading to the development of soy concentrates, isolates and textured extended-expanded products have increased soy consumption by humans. The functionality of these products and their mixtures with other foods have increased their acceptance by persons of all ages and of different cultural backgrounds. Major applications of soy protein products include infant formulas; hypoallergenic foods; vegetable protein mixtures; protein supplements; bakery products; traditional food items; snacks; food analogs, replacers and extenders, such as dairy products, processed fish and meat products; and a variety of formulated or fabricated food products (2,3).

The primary nutritional function of dietary protein is to furnish the essential amino acids and the nitrogen required for the synthesis of tissue proteins and other compounds necessary for normal function and growth of the organism. Therefore, the different food proteins and protein sources are considered in relation to their capacity to meet the amino acid and total nitrogen requirements of the host. This so-called "protein quality" of soybean products is the main issue addressed in this short review. However, a comprehensive assessment of the potential role of soy proteins in the human diet requires consideration of the impact of increased soy consumption on the overall nutritional health of individuals and population groups. The effects of soy protein or of soy-based foods on the utilization and requirements for other nutrients are addressed elsewhere in this conference. We will, however, refer briefly to some such aspects, based mainly on recent investigations carried out in our laboratories and on selected examples of the results obtained by other investigators. We intend to emphasize the complexity of the relationship between food proteins and overall nutritional health, including the utilization and requirements for other nutrients. We also intend to stress the importance of such factors in the evaluation of the nutritional role of soybean and other protein sources, which transcends merely assessing that the essential amino acid and total nitrogen requirements have been satisfied.

SOY PROTEIN QUALITY EVALUATED IN HUMANS

General Considerations

The criteria to evaluate the nutritional quality of a protein for humans have been the subject of numerous reviews and conferences (e.g., 4,5). The following considerations can be derived from them.

There are discrepancies between protein quality evaluations in animals and in humans, especially in the case of vegetable proteins, in which methionine is the limiting

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TABLE I

Comparison of Isolated Soybean Protein Quality Using the PER Method in Rats and the N Balance Method in Humans

Method	Protein quality[a]	Age of subjects	References
PER	62-72% (casein)	Young rats	6,7
N balance	Similar to milk	Infants	8
N balance	81-98% (milk)	Preschool children	9,10
N balance	74-87% (egg, beef, fish)	Adult men	11-13

[a]Reference protein in parenthesis.

amino acid. For example, Table I shows the nutritional quality of isolated soybean protein, relative to a reference protein, with a rat protein efficiency ratio (PER) and a human (multilevel nitrogen balance) assay. Clearly, the rat assay underestimates the protein quality for humans.

Protein quality in humans is usually assessed by relatively short-term methods (i.e., lasting a few days or weeks). Table II shows some measures that are or can be used in the evaluation. The majority of studies conducted in humans have been based on measurements of weight gain, on nitrogen retention in infants and children, and on indexes of nitrogen balance in adolescents and adults. Changes in body composition and the measures listed as "physiological and metabolic functions" are the most relevant, but they must be used in longer-term studies, and a series of other interfering variables must be accounted for.

It is not always practical to measure the value of a protein by direct human bioassays. Therefore, several laboratory indexes of protein quality have been developed. Some are based on the growth of microorganisms with known requirements for essential amino acids, such as *Streptococcus faecalis* and *Leuconostoe mesenteroides* (14,15), *Streptococcus zymogenes* (16,17), *Tetrabymena pyriformis* (18-20) and *Tetrabymena thermophila* (21). Others are based on the protein's essential amino acid composition and the concentration of its first limiting amino acid compared to that of a reference (22,23). The latter must be corrected for protein digestibility (24), which can be assessed directly in humans or indirectly by the in vitro use of proteolytic enzymes such as pepsin, trypsin, chymotrypsin, pancreatin, papain and peptidase (25,26).

TABLE II

Some Measures That Are or Can Be Used to Evaluate Protein Quality in Human Subjects

- Growth and body composition
  - Weight changes
  - Height growth
  - Changes in body composition
- Metabolic balance
  - Nitrogen balance
  - Short-term nitrogen balance index
  - Nitrogen digestibility
- Blood constituents
  - Serum protein and albumin concentrations
  - Aminotransferase and other enzyme activities
  - Plasma-free amino acid concentrations
  - Urea nitrogen concentration
- Urine constituents
  - Changes in urea nitrogen
  - Excretion of hydroxyproline, creatinine, 3-methyl-histidine or sulphur compounds
- Physiological and metabolic functions
  - Growth rates
  - Physical fitness
  - Incidence of morbidity
  - Pregnancy performance
  - Lactation characteristics

Protein quality is expressed in relation to that of a reference. There is not unanimous agreement as to which should be the reference, and whereas most investigators have used human or cow's milk protein for infants, cow's milk and hen's eggs have been used as the standard of comparison for older children, and milk, egg, beef or fish have been used for adults. The FAO/WHO Expert Committee on Protein and Energy Requirements (23) suggested a theoretical essential amino acid pattern as a better alternative than the use of any natural protein for the "chemical score" method. The adequacy of that pattern is also subject to discussion in the light of recent experimental evidence on the essential amino acid requirements of preschool children (27,28).

Soy As the Only Protein Source

We recently presented an overview of the studies conducted by various investigators on the nutritional quality of processed soybean protein for humans (12). It was concluded that when well-processed soy products serve as the major or sole source of the protein intake, their protein value approaches or equals that of foods of animal origin and they are capable of meeting the essential amino acid and protein needs of children and adults.

The results of other recent studies support that conclusion. An isolated soy protein (Purina Protein 220) was used in one of a series of studies performed at the Institute of Nutrition of Central America and Panama (INCAP) to assess the protein requirements of preschool-aged children (10). Nitrogen balance techniques were used with four sequential levels of protein intake, ranging from 0.50 to 1.25 g/kg/day, at 9-day intervals. The ten children who participated were 17-31 months old. They drank a cow's milk formula also at the same levels of protein intake. The children's mean nitrogen requirements were found to correspond to an intake of 0.75 g soy protein/kg/day, and the safe level of intake was calculated as 0.98 g/kg/day, which is 15% less than the FAO/WHO 1973 estimates for milk or egg protein (23).

Table III shows the amounts of essential amino acids provided by 0.98 g of the soybean protein isolate corrected for its "true" digestibility of 93%. Those results are in agreement with the findings in INCAP's investigations on the essential amino acid recommendations for preschool children (28; Torún et al., unpublished data). Compared with milk, the soybean isolate had a protein quality of 82% based on N balance techniques. Based on its essential amino acid composition and digestibility and on our recommendations for such amino acids, it had an amino acid quality index of 0.90 and a relative nutritive quality of 80% compared with cow's milk (28).

Another recent study was conducted on 8 young men at the Massachusetts Institute of Technology (MIT) to assess the nutritional value of a soy protein concentrate (Stapro 3200) using N balance techniques with four levels of protein intake ranging from 0.35 to 0.65 g/kg/day at 14-day intervals (Young et al., unpublished data). The soy

TABLE III

Essential Amino Acid Recommendations for Preschool Children (INCAP) and Amounts of Amino Acids Provided by the Safe Level of Intake of an Isolated Soy Protein

Amino acid	Recommendation, mg/kg/day[a]	Amt provided by 0.98 g soybean protein (mg)
Isoleucine	31	51 (47)[b]
Leucine	73	77 (72)
Lysine	64	61 (57)
Methionine + cystine	27	26 (24)
Phenylalanine + tyrosine	68	88 (81)
Threonine	37	36 (34)
Tryptophan	13	16 (15)
Valine	38	52 (48)

[a]From Torún et al. (28; and unpublished data).

[b]Purina Protein 220. Figures in parenthesis were corrected for 93% "true" nitrogen digestibility (10).

TABLE IV

Relative Protein Value (RPV) of Different Soy Products Evaluated by a Short-Term Nitrogen Balance Index[a]

	Regression coefficient of N balance (Y) on N intake (X)	RPV[b] (%)
Preschool children		
Cow's milk	0.91	
Soy protein isolate (Supro 710)	0.80	88
Soy protein isolate (PP 220)	0.78	85
Young men		
Lean beef	0.88	
Soy protein isolate (Supro 620)	0.84	95
Textured soy protein (Protemas)	0.69	78
Protemas: beef (50:50)	0.87	99

[a]Calculated from Navarrate et al. (30) and unpublished data of Torún et al.

[b]Relative to milk for children and to beef for adults.

protein concentrate was well tolerated at all levels of intake and its protein nutritional quality was very good: the relative protein value (RPV) and relative nitrogen requirement (RNR) (11) were 102 and 74, respectively, and they did not differ significantly from those of egg as the reference protein.

The protein quality of several soy products have been assessed at INCAP in preschool children (29; Torún, unpublished data) and in adults (29-31), using the short-term nitrogen balance indexes devised by Bressani and coworkers (29,32) and modified by Torún (unpublished data) for their use with young children. The RPV of the soy products were calculated from the regression coefficients of nitrogen balance (Y) on nitrogen intake (X) relative to the regression coefficient of cow's milk for children and lean beef for adults. The results, summarized in Table IV, confirm the good quality of the isolated soybean proteins. The texturized soy product used in one of those studies (Protemas, Alimentos, S.A.) had a low RVP that increased markedly when it was mixed as a 50:50 blend with lean beef.

The protein and overall nutritional quality of soybeans and soy products as foods for children are discussed in more detail in another section of this conference (33).

Supplementation with Methionine

In terms of essential amino acid requirements, soy protein is limited by the sulfur amino acids (28). Therefore, the effects of methionine supplementation on soy protein quality has been investigated in humans of different ages by various groups of researchers.

Fomon and coworkers have studied in infants the effect of supplementing soybean with 5 mg of L-methionine per g of protein (8,34). Intakes were of the order of 2.4 g protein/kg/day. Methionine supplementation did not influence retention of nitrogen, growth rate (weight and length), or serum concentration of albumin (Fig. 1). However, serum concentration of urea nitrogen was lower, which may suggest an improvement in protein quality through supplementation (35), although it is difficult to judge the health significance of that finding.

Graham (36) reported the results of studies in eight children between 6 and 23 months of age, who had recently recovered or were in the process of recovering from acute, severe malnutrition. Daily protein and energy intakes were 1.25-2 g and 100-150 kcal/kg/day, respectively, with 4-7% of the total energy derived from protein. Protein sources were a soy milk based on toasted soy flour with and without a supplement of 11-22 mg DL-methionine/kg body weight/day (three children), a soy protein isolate with and without 16-20 mg DL-methionine/kg/day (four children), and a full-fat soy flour with and without 20 mg DL-methionine/kg/day (one child). The supplementation increased nitrogen retention in all children.

Parthasarathy et al. (37), working with girls 8-9 years old, studied the effect of supplementing full-fat soy flour with DL-methionine or a DL-methionine hydroxy analog (MHA) (Monsanto Chemical Co.). The eight girls weighed between 17.7 and 23.8 kg and their heights ranged from 114 to 128 cm. Most of them had a weight-for-height 10-12% below the 50th centile of U.S. standards. They ate a low-protein (about 0.12 g/kg/day) diet based on tapioca flour, corn starch and vegetable oil, to which the soy flour

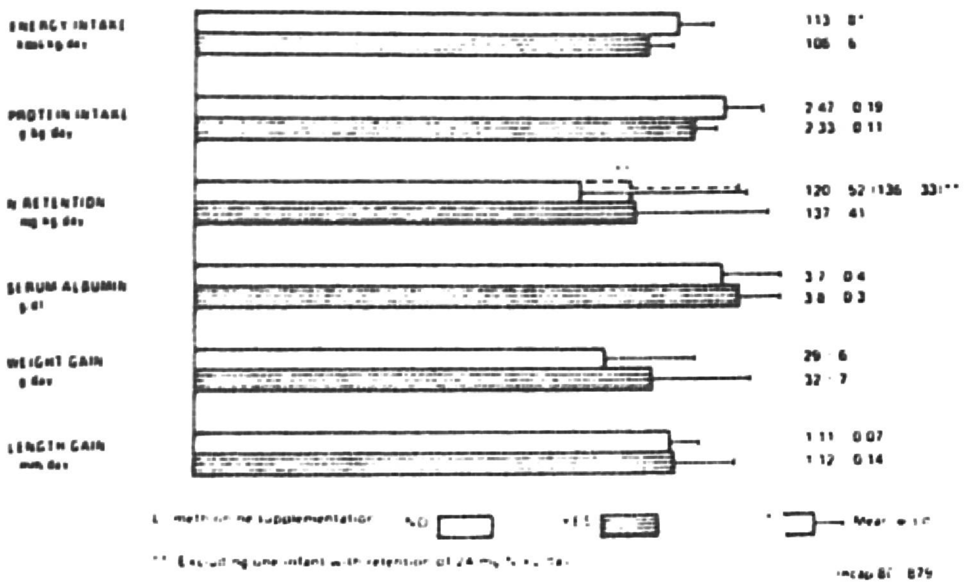

FIG. 1. Supplementation of soy protein with L-methionine. Nutrient intake, N balance, serum albumin concentration and growth of 7-10 infants between 8 and 112 days of age fed a formula based on a soy protein isolate (8).

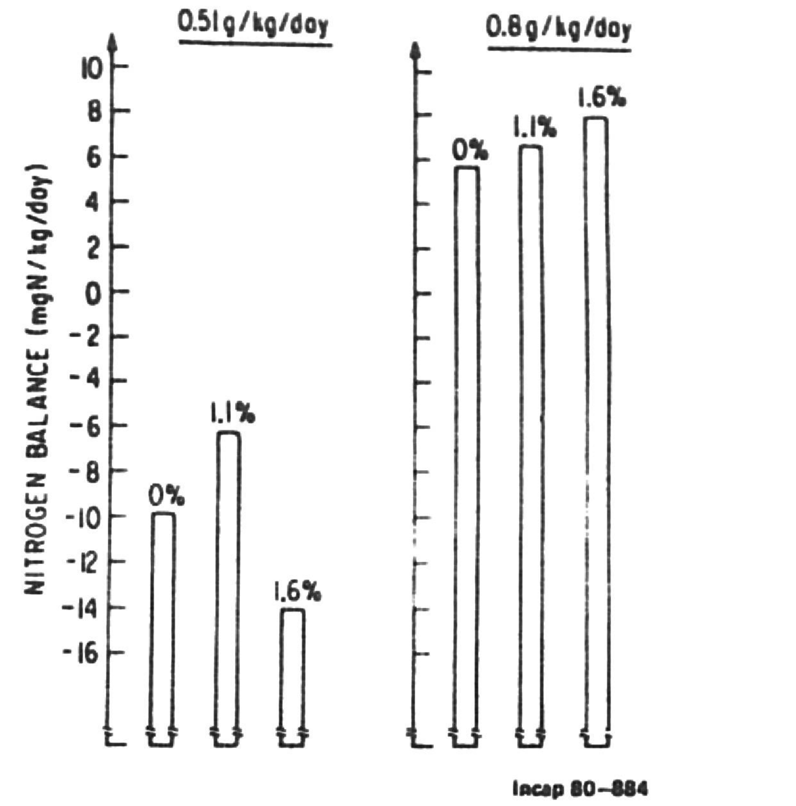

FIG. 2. Mean nitrogen balances in eight young men given two levels of soy protein isolate with and without methionine supplementation (11).

was added alone or with one of the supplements. Total protein intake was around 1.2 g/kg/day and the additional DL-methionine or MHA was 13.3 mg/kg/day. The diets had apparent and true nitrogen digestibilities of 68 and 86%, respectively. The supplementation with either DL-methionine or its hydroxy analog increased the dietary N retention.

To compare the metabolic implications of the levels of supplementation used by Graham (36) and Parthasarathy et al. (37) with those used in the studies described below and by Fomon et al. (8,34), it is important to remember that only amino acids with the L-configuration are involved in human protein synthesis.

Other investigations in adolescents (38) and in adults (11,12,39-41) indicate that supplementation with L-methionine improves N retention and, therefore, protein quality when low levels of soy protein intake are used. Supplementation, however, seems undesirable when the amino acid is added in large amounts to soy-based diets that provide marginal levels of total nitrogen intake. This was illustrated by studies performed at MIT with young men (11). As Figure 2 shows, supplementation at a level of 1.1% of protein intake improved N balance with a diet which provided 0.51 g isolated soy protein/kg/day. This level of supplementation (5.6 mg/kg/day), similar to that used by Fomon and coworkers in infant formulas (8), increased the total sulphur-amino acid content of the diet to the amount suggested by FAO/WHO experts (23) in the pattern for amino acid scoring (i.e., 35 mg/g protein). When the supplementation level with L-methionine was increased to 1.6%, there was a deterioration in nitrogen balance. This indicates that healthy young men with marginal or deficient levels of protein intake may have a negative reaction to an imbalance of the dietary essential amino acids. As Figure 2 shows, such reaction did not occur when the diet provided 0.8 g soy protein/kg/day and the addition of methionine did not influence N retention.

The absence of a methionine supplementation effect with higher soy protein intakes coincides with the results of investigations by Kies and Fox (39) and by Zezulka and Calloway (40) in young men. Kies and Fox (39) showed that supplementation of texturized soy protein (TVP, Archer Daniels Midland Co.) fed at a level of 4 g N/day improved N balance, but at a level of 8 g N/day, there were no differences between beef protein, unsupplemented TVP and TVP with methionine. Therefore, it can be concluded that if sufficient amounts of soy products are fed, they can satisfy the protein needs of adults. In their studies with isolated soy proteins, Zezulka and Calloway (40) showed that the effects of methionine supplementation on nitrogen retention decreased as soy protein intakes increased from 3 to 7.5 g N/day. They also showed that the methionine requirements of young men seemed to be satisfied with soy intakes of 6.5 g N/day.

In conclusion, a case may be made for a small level of methionine supplementation in soy-based diets for children and adults with marginal dietary protein intakes, and for infants. Nevertheless, there is little nutritional or public health justification for supplementing soy protein with methionine when the soy products are consumed as part of a mixed diet and the sulphur-amino acid content is not likely to be a limiting factor, especially when total protein ingestion is above the recommended safe levels of intake (23).

Combination of Soy with Other Protein Sources

The use of soy as part of a food system has great importance because, except for metabolic and nutritional studies, soy is currently used as the sole source of protein in only one area–formulas fed to newborns and young infants. The nutritional role of soy protein is important not just for infants and for those population groups who might consume soybeans as their major staple food, but for virtually all humans who eat vegetable-based diets or processed foods of animal origin, which are liable to be partially replaced with soy products for reasons of economics or food supply.

Many studies have been conducted on humans, either under metabolic ward conditions or as part of population feeding programs, which have demonstrated the good nutritional impact of soybean protein as a component of a mixed diet or as a food supplement. These are reviewed in detail by Bressani (42) elsewhere in this conference. We wish to emphasize the advantages of using soybeans (a) as part of a diet when it is combined with cereal grains, mainly because of the amino acid complementation that is achieved, and (b) when full-fat soy products are used to feed children, mainly because the provision of a good-quality protein is accompanied by an increase in energy density.

PROTEIN AND ENERGY DENSITY OF DIETS BASED ON VEGETABLE FOODS

Dietary protein sources have marked differences not only in the concentration of protein per unit weight of food, but

TABLE V

Protein and Energy Densities of Some Cooked Foods and Commercially Available Soy Flours

Foods and flours	Protein (g/100 g)	Energy (kcal/100 g)
Boiled rice	2.2	120
Broiled semi-lean beef	24	250
Dry soy flours[a]		
full fat (20%)	40	460
refatted, high fat (15%)	45	435

[a]Calculated from data of Waggle and Kolar (3).

also in the concentration of other constituents, including carbohydrate, fat and fiber. These differences result in a wide variety of nutrient concentrations or densities. The spectrum of nutrient densities is even wider when foods are analyzed after they are prepared in the traditional manner in which they are consumed. For example, the protein and energy densities of boiled rice are about 70% lower than the densities of the dry grains, resulting in around 2.2 g protein and 120 kcal/100 g boiled rice, in contrast to an increase in the concentrations of those nutrients in beef to around 24 g protein and 250 kcal/100 g when it is broiled or cooked. These compositional differences have important consequences for nutritional requirements, particularly for children in developing countries who find it difficult to satisfy their relatively high nutritional needs with predominantly vegetable-based diets, which usually have a low-protein content, low energy density and high bulkiness. Two recent FAO/WHO meetings of experts on fats (43) and carbohydrates (44) in human nutrition have indicated the importance of these dietary constraints. These considerations also apply to the design of adequate diets for the elderly or other groups whose intake levels and digestive capacity may be more limited in comparison to those of healthy young adults.

Soybeans may play an important role in overcoming those dietary limitations because of their high fat content and the good nutritional quality and high concentration of their protein. The use of full-fat or refatted soy products has good potential to increase a diet's protein and energy concentrations (Table V).

SOY PROTEIN AND TRACE MINERAL NUTRITION

It may be concluded that soy can partially replace protein foods of animal origin without loss of the protein nutritive value of the diet. But since animal protein foods contribute many minerals in forms that are highly available for meeting human needs (45,46), it is necessary to consider the significance that soy, as a dietary ingredient, may have on the availability of trace elements.

The extent to which the dietary intake of a mineral is absorbed from the lumen of the intestinal tract and subsequently made available for meeting the metabolic needs of cells and organs depends upon many factors. Some are related to the diet itself, such as the amount and chemical form in which the mineral is ingested or the presence of other elements or substances that may enhance or inhibit its absorption; others depend on the host, such as his or her nutritional and physiological state and health conditions; other factors can be loosely termed "environmental," such as the roles played by infectious agents and the dietary or personal habits of the host's social group. Some of these factors are more relevant than others in relation to dietary soy protein. The effects of soy protein on mineral availability are discussed in more detail by Erdman and Forbes (47) in another section of this conference. We will make some brief comments on soy protein and trace element absorption in humans and refer to recent studies at MIT and INCAP. More details of some of those studies have been presented elsewhere (48).

Van Stratum and Rudrum (49) studied the effects of including about 23 g of soy protein/day, mostly from concentrates, to provide one-quarter of the total protein in the diets of a large group of adult volunteers over a 4-week period. Table VI shows a partial summary of their chemical balance and serum concentration data. There were no unfavorable trends in calcium, magnesium, zinc and iron nutriture. These findings were consistent with balance studies performed by Greger et al. (50) in adolescent girls, which indicated that zinc absorption was similar with meat and soy and that zinc nutriture was maintained with a soy-based diet.

Because of the limitations of the chemical balance techniques for measuring trace element absorption (51), as well as safety and ethical issues related to the use of radioactive tracers, we began to use diets enriched with stable isotopes by extrinsic tagging and measurements by neutron activation analysis (52,53) to study the absorption of iron, zinc and selenium from soy protein-based diets fed to children at INCAP and adults at MIT. In one of the adult studies, five healthy young men ate isoenergetic, isonitrogenous diets that provided 0.8 g protein/kg/day based on cow's milk, a soy protein isolate (Supro 620, Ralston Purina) or a 50:50 mixture of both, during three consecutive 14-day periods. The diets supplied a constant, known intake of about 15 mg Fe and 15 mg Zn/day. On days 6 and 7 of each period, part of the minerals were substituted with ^{58}Fe and ^{70}Zn. Determinations of iron and zinc absorption were made by a fecal monitoring method

TABLE VI

Effect of a High-Soy Protein Diet on Mineral Metabolism in Adult Subjects[a,b]

	Soy diet	Control	p[c]
Calcium			
Urine	4.9	5.2	NS
Feces	23.4	23.5	NS
Magnesium			
Urine	5.24	5.27	NS
Feces	11.7	10.1	0.02
Zinc			
Serum	17	16	NS
Feces	192	216	0.02
Iron-Serum	17.9	20.0	NS
Iron-binding capacity	62.3	61.8	NS

[a]Summarized and adapted from Van Stratum and Rudrum (45).
[b]Urinary and fecal data are mmol/24 hr; serum data are μmol/ℓ.
[c]Comparison of the two diets, Student's "t" test; NS = not significant.

TABLE VII

Determination of Iron and Zinc Absorption in Young Men Using ^{58}Fe, ^{70}Zn and a Fecal Monitoring Method[a]

	Diet		
	Supro 620	Supro 620/milk	Milk
Total iron intake (mg/day)			
Iron from protein	9	4.8	0.5
Iron from $FeCl_3$	6	10.5	15.0
Iron absorption (%)[b]	21 ± 6	17 ± 7	22 ± 6
Total zinc intake (mg/day)			
Iron from protein	3.3	4.9	6.5
Iron from $ZnCl_2$	12	10.5	9
Zinc absorption (%)[b]	40 ± 41	46 ± 7	47 ± 4

[a]Diets were based on milk, a soy isolate (Supro 620) or a 50:50 mixture (unpublished MIT data).

[b]Mean ± SEM for five subjects. No significant difference among diets.

(52-54). The results are summarized in Table VII. There were no differences in absorption of either element, albeit most of the iron in the Supro diet came from the soy protein whereas almost all the iron in the milk diet came from the inorganic iron supplement. It should be noted, however, that factors known to inhibit iron absorption, such as dietary fibers and high calcium contents, were absent from the experimental diets, whereas an enhancer-like ascorbic acid was provided in generous amounts. Nevertheless, the results coincide with those of Steinke and Hopkins in rats (55) and the conclusions reached from other investigations in humans (56,57) in the sense that the iron from soybean is well absorbed by humans. The same is true of zinc, based on the MIT study and others (49,50).

In a separate but similar human metabolic study (Young et al., unpublished data), the availability of dietary zinc and iron were compared when young men received a diet supplying the entire protein (0.65 g/kg/day) from a soy concentrate (Stapro 3200) or dried skim milk. Again, the overall absorption of these elements did not differ between the two diets. These preliminary data suggest that well-processed soy products can constitute a significant or sole source of protein without unfavorable effects on zinc and iron nutriture, providing the intakes of these nutrients are adequate. However, more research is obviously needed under other experimental conditions, especially such as when soybeans or soy proteins are part of mixed diets in different population groups, to fully evaluate the impact of new soy products on human mineral nutrition.

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