	FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS	ESN: FAO/WHO/UNU EPR/81/41 August 1981
	WORLD HEALTH ORGANIZATION	
	THE UNITED NATIONS UNIVERSITY	

Provisional Agenda Item 4.1.3

Joint FAO/WHO/UNU Expert Consultation on Energy and Protein Requirements

Rome, 5 to 17 October 1981

THE RELATIONSHIP BETWEEN FOOD COMPOSITION AND AVAILABLE ENERGY

by

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1. This paper examines two conventions that are important in the relationship between food composition and available energy. The first concerns the calculation of 'protein' values for foods from total nitrogen values, and the second the calculation of the energy value of foods. The second part incorporates the conclusions drawn in the two accompanying working papers on Energy Absorption and Protein Digestion and Absorption.

2.1 The Calculation of the Protein Content of Foods

The convention used in food composition where the total nitrogen in a food (usually based on a Kjeldahl-type of measurement) is multiplied by a factor to calculate 'protein' has a long history. It dates from the earliest studies of the composition of foods (McCollum, 1957) when the nature of food components was poorly understood.

It has been retained as a convention based on the fact that most proteins contain around 16% of nitrogen, and that therefore total N × 6.25 will give a reasonable estimate of protein content. In strict terms this should always be cited as 'Crude Protein' and ideally accompanied by the actual factor used.

The fact that some proteins contain more or less nitrogen has also been known for some time

(Widdowson, 1955), and Jones (1941) measured the nitrogen content of a range of isolated proteins and calculated the most appropriate conversion factors. This approach has been extended at various times since Jones' original work, and the range of nitrogen conversion factors for specific foods has been used in US Department of Agriculture Publications and FAO/WHO publications (FAO/WHO, 1973) and the British Food Composition Tables (McCance and Widdowson, 1960, Paul and Southgate, 1978) in a slightly simplified way. The conversion factors used in Paul and Southgate (1978) are shown in Table 1. (based on FAO/WHO, 1973).

Table 1

Factors for converting total nitrogen in foods to protein

	Factor per g N		**Factor per g N**
Cerals		Nuts	
Wheat :		Peanuts, Brazil nuts	5.41
Wholemeal	5.83	Almonds	5.18
Flours (except wholemeal)	5.70	All other nuts	5.30
Macaroni	5.70	Milk and milk products	6.38
Bran	6.31	Gelatin	5.55
Rice	5.95	All other foods	6.25
Barley, oats rye	5.83		
Soya	5.71		

2.2 Calculation from Non-protein Nitrogen

It is known that many, if not all foods contain non-protein nitrogen (noteably meat, fish and vegetables), and it has been suggested that the protein value of foods should be calculated from a value for non-protein nitrogen. As such of this non-protein nitrogen is often amino-acids, it seemed more logical in the context of food composition tables to calculate 'protein' content from amino-acid nitrogen (including protein and free amino acids and peptides). This approach has much to recommend it (Southgate, 1974), but data on food composition which gives the required information is not at all complete and could not be applied at the present time.

2.3 Calculation from Amino-acid Composition

This has led to a further suggestion that the conversion factors used to convert the total nitrogen values to 'protein' should be derived from amino-acid composition values. This also has much to recommend it on theoretical grounds.

At the present time there is sufficient amino-acid data to attempt these calculations, but the apparent improvement in the accuracy of 'protein' values in foods would, I think, be spurious for a number of reasons which relate primarily to the technical problems still associated with the measurement of amino-acids in foods. These relate to hydrolytic losses (and incomplete hydrolysis) of some amino-acids, the need to measure tryptohan, problems in measuring and assigning the ammonia produced on hydrolysis, the proportion of asparagine and glutamine present in the protein and the recovery of nitrogen over the whole process of analysis. In our review of the literature of amino-acid values (Paul and Southgate, 1978), we frequently found the literature reporting these analyses to be deficient in the detail required to calculate nitrogen conversion factors from amino-acid composition data that would be intrinsically more accurate than the present system.

2.4 'Protein' in Studies of Digestibility and Biological Value

Most studies of this kind are based on total-nitrogen measurements in foods, faeces, urine and carcases, and it is very rare for these studies to be interpretable in any other way than by calculating protein in the conventional way. If better, that is, specific procedures for protein became available, then future studies could be based on this system.

2.5 Conclusions

2.5.1 The convention of calculating protein by multiplying total-N values by a factor should be retained. It must however be emphasised that this is a convention and does not give values for protein in the biochemical sense. [There is at present no method that is specific for protein in general; conventional colorimetric procedures depend on specific amino-acid residues, and dye-binding methods do not give identical binding with different proteins - all procedures are calibrated against a specific protein]

2.5.2 The calculation can be improved by calculating from protein-nitrogen values [it is however difficult to define procedures for measuring these values] or preferably from a nutritional viewpoint, from amino-acid nitrogen (protein amino-acids + free amino acids and peptides).

2.5.3 Where sound amino-acid composition values are available, amino-acid nitrogen to protein conversion factors could be used in the future.

2.5.4 At present all digestibility and biological value studies are based on this convention and no radical misinterpretation of the data available is likely to arise because of the use of the convention.

Recommendations

2.6.1 The conversion factors used in the 1973 report are still valid.

2.6.2 Compilers of Food Composition Tables and Data Bases should include total-nitrogen values and state very precisely which conversion factors have been used to calculate 'protein'.

2.6.3 Non-protein nitrogen values for foodstuffs would be a useful addition in food compositional compilations.

2.6.4 In the future it is possible that calculation from amino-acid data would be a better approach to measuring protein in the biochemical sense in foods.

3. Calculation of the Available Energy of Foods

Most calculations of energy value are based on the Atwater system (Merrill and Watt, 1955) or derivatives of this system (Widdowson, 1955; Southgate and Durnin, 1970; Paul and Southgate, 1978). The system was developed largely from the experimental studies of Atwater and his colleagues in the later part of the last century and the early years of the present one. Its use has frequently been the cause of dispute (Maynard, 1944; FAO, 1947; Hollingsworth, 1955; Widdowson, 1955), but no real alternatives have been proposed. As with the calculation of protein from total nitrogen, the Atwater system is a convention and its limitations can be seen in its derivation.

3.1 Derivation of the Atwater System

Available energy (as used by Atwater) is equivalent to the modern usage of the term Metabolisable Energy (ME).

Metabolisable Energy = (Gross Energy in Food) - (Energy lost in Foods,Secretions and Gases) Urine

In most human work losses in secretions and gases are ignored. The Gross Energy of a food, as measured by bomb calorimetry is equal to the sum of the heats of combustion of the components - protein (GE_p), fat (GE_F) and carbohydrate (GE_{CHO}) (by difference) in the proximate system.

$$GE = \sum GE_P + GE_F + GE_{CHO}$$

Atwater considered the energy value of faeces in the same way.

$$GE^F = \sum GE^F_P + GE^F_F + GE^F_{CHO}$$

By measuring ‘coefficients of availability’ or in modern terminology ‘apparent digestibility’, Atwater derived a system for calculating faecal energy losses.

Digestible energy = $GE_P\ (D_P) + GE_F(D_F) + GE_{CHO}(D_{CHO})$ where D_P D_F D_{CHO} are respectively the digestibility coefficients of protein, fat and carbohydrate calculated as $\frac{\text{Intake-faecal excretion}}{\text{Intake}}$ for the constituent in question.

Urinary losses were calculated from the energy to nitrogen ratio in urine. Experimentally this was 7.9 kcals/g urinary N and thus his equation for metabolisable energy became

$$ME = (GE_P - \frac{7.9}{6.25})\ D_P + GE_F\ D_F + GE_{CHO}\ D_{CHO}$$

3.1.1 Gross Energy Values

Atwater collected values from the literature and also measured the heat of combustion of proteins, fats and carbohydrates. These vary slightly depending on sources and Atwater derived weighted values for the gross heat of combustion of the protein, fat and carbohydrate in the typical mixed diet of his time. It has been argued that these weighted values are invalid for individual foods and for diets whose composition in terms of foodstuffs is different from those eaten in the USA in the early 20th century (Maynard, 1944).

3.1.2 Apparent Digestibility Coefficients

Atwater measured a large number of digestibility coefficients for simple mixtures, and in substitution experiments derived values for individual foods.

These he combined in a weighted fashion to derive values for mixed diets. When these were tested experimentally with mixed diets they did not give a good prediction, and Atwater adjusted the coefficients for mixed diets (Merrill & Watt, 1955).

3.1.3 Urinary Correction

The energy/nitrogen ratio in urine shows considerable variation and the energy/organic matter is less variable (Benedict, cited by Merrill and Watt, 1955), but the energy/nitrogen value provided Atwater with a workable approach although this has caused some confusion (Widdowson, 1955) and only applies for subjects in nitrogen balance (Southgate & Barrett, 1966).

3.2 Specific Conversion System

Following Maynard's (1944) objection, Merrill and Watt (1955) returned to Atwater's original approach and derived a system whereby specific calorie conversion factors for different foods were proposed. This takes cognisance of the fact that first the gross energy values of the protein, fats and carbohydrates from different food sources are different, and second, that the apparent digestibility of the components of different foods is different.

This system relies on having measured heats of combustion of a wide range of isolated proteins, fats and carbohydrates. It also depends on data from digestibility studies, where individual foods have been substituted for basal diets in order to measure the apparent digestibility coefficients for those foods. This approach is based on the assumption that there are no interactions between foods in a mixture in the intestine, and from a practical view point, such studies with humans are difficult to control with the required accuracy.

3.3 Assumptions Based on the Use of Carbohydrates by Difference and the Effects of Dietary Fibre

These have been discussed in the earlier paper. In summary, the carbohydrate by difference approach presents several problems. Firstly, it does not distinguish between sugars, starch and the unavailable carbohydrates (dietary fibre).

This affects firstly the gross energy that is assigned to carbohydrate - sucrose has a heat of combustion of 3.95 (Kcal/g) (16.53 KJ/g) and starch 4.15 (Kcal/g) (17.36 KJ/g).

Secondly it does not provide for the fact that sugars and starch are virtually completely digested and absorbed, and thus provide metabolisable energy equivalent to their heat of combustion.

The unavailable carbohydrates (dietary fibre) are degraded to a variable extent in the large bowel. The products of this microbial digestion are fatty acids, CO_2, methane and hydrogen. The fatty acids (acetate, butyrate and proprionate) are absorbed in the large intestine and provide some metabolisable energy. The extent of degradation depends on the source of the dietary fibre (its composition and state of division), and the individual consuming the dietary fibre. There is insufficient data to give firm guidance on the energy available from this source.

Finally dietary fibre affects faecal losses of nitrogen and fat as discussed earlier. Whether the increased fat loss is due to an effect on small intestinal absorption is not clear. The increased faecal nitrogen losses on high fibre diets are probably due to an increased bacterial nitrogen content of the faeces. Both these effects however lead to reductions in apparent digestibility, and therefore in the Atwater system produce small changes in the proper energy conversion factors for those diets (Southgate & Durnin, 1970).

3.4 Theoretical and Practical Considerations Relating to the Calculation of Energy Values

3.4.1 Variations in Heats of Combustion of Food Constituents Proteins

The experimental evidence for the magnitude of this variation is very limited, but as the heats of combustion of the individual amino-acids are different it is reasonable to expect variations between different proteins. Sands (1974) reported an observed range of from 5.48 for conglutin (from blue lupin) to 5.92 for Hordein (barley), which compares with Atwaters' range of 5.27 for gelatin to 5.95 for wheat gluten. It is difficult to calculate expected values for a protein from amino-acid data, as some of the heats of combustion are not known accurately. Preliminary calculations on cows milk suggest a value of around 5.5 Kcal/g (23.0 kJ/g).

Fats

Analagously the experimental evidence is limited, but since the fatty acids differ in their heats of combustion one should expect fats to vary in heats of combustion. These differences are however relatively small - for example, breast milk fat has a calculated heat of combustion of 9.37 Kcal/g compared with that of cows milk fat of 9.19 Kcal/g.

Carbohydrates

Monosaccharides have heats of combustion of around 3.75 Kcal/g, disaccharides 3.95 and polysaccharides 4.15 – 4.20 Kcal/g. The heat of hydrolysis is very small and these values are essentially equivalent when calculated on a monosaccharide basis. Thus 100g sucrose gives on hydrolysis 105.6 g monosaccharide and 100g starch gives on hydrolysis 110g glucose.

3.4.2 Apparent Digestibility Coefficients

The human digestive tract is a very efficient organ, and the faecal excretion of nitrogenous material and fats is a small proportion (usually less than 10%) of the intake (Southgate and Durnin, 1970). Atwater recognised that the faecal excretion was a complex mixture of unabsorbed intestinal secretions, bacterial material and metabolites, sloughed mucosal cells, mucus, and only to a small extent, unabsorbed dietary components. This may be one reason why he chose to use 'availability' rather than digestibility. His view was that these faecal constituents were truly unavailable and that his apparent disregard of the nature of faecal excretion was justifiable in a practical context.

The relationship 'Intake minus Faecal Excretion divided by Intake,' wherever faecal excretion is small, will approximate to unity and thus these 'coefficients' have a low variance and have the appearance of constants. This is spurious since faecal excretion is variable even on a constant diet (Southgate and Durnin, (1970) Cummings et al, (1978)), and there is no evidence to suggest that faecal excretion is in fact related to intake in the way implied by these coefficients.

3.4.3 Practical Considerations in Calculations of Energy Value of Foods and Diets

The calculation of energy values must be regarded as an alternative to direct measurement, and therefore is likely to be associated with some inaccuracy when compared with direct assessment. These inaccuracies arise for a number of reasons:-

a. Variations in Food Composition: Foods are biological mixtures and as such show considerable variation in composition, particularly in respect of water and fat content. This means that compositional values quoted for representative samples of foods in food composition tables do not necessarily apply to individual samples of foods (Paul and

Southgate, 1978). In studies where great accuracy is required, samples of the food consumed must be analysed.

b. Measurements of Food Intake: In estimating energy intakes, measurements of food intake are made, and these are known to be subject to considerable uncertainty. Even in studies under very close supervision the errors in weighing individual food items are rarely less than ± 5%. A certain degree of pragmatism must therefore be used when assessing procedures for calculating energy intakes, and many authors impute greater accuracy to quoted calculated energy intakes than is justifiable.

c. Individual Variation: Variations in individuals are seen in all human studies, and these variations are not allowed for in most calculations.

The theorectical and physiological objections to the assumptions inherent in the Atwater system are likely to result in errors much smaller than these practical matters. Southgate and Barratt, (1966) derived conversion factors from experimental studies with young infants, but these produced values for metabolisable energy intake that were insignificantly different from those obtained by direct application of the modified Atwater factors (Southgate and Durnin, 1970).

3.5 Alternatives to the Atwater System

At the present time there seem to be two possible approaches to the calculation of energy values.

3.5.1 Empirical

The studies of Macy, (1942) Levy et al, (1958) and Southgate and Durnin, (1970) could provide an emperical system which would not involve the theoretical objections to the Atwater system. This would possibly be preferable on grounds of scientific aesthetics. The equation derived from the Southgate and Durnin (1970) observations and applicable to the Macy (1942) data has the following form:-

Metabolisable Energy = 0.977 Gross Energy -6.6N - 4UC where N = total nitrogen intake and UC is the intake of unavailable carbohydrates.

The data of Levy et al, (1958) produced an equation of a similar kind:-

ME = 0.976 GE - 7.959 N - 59.8

The residual constant possibly reflects the intake of unavailable carbohydrates in the diets studied by Levy et al (1958).

Gross energy values (if this was adopted) could be determined directly from food composition tables, or could be calculated from compositional data. Since these calculations do not involve physiological variables one would expect greater accuracy. Southgate and Durnin (1970) found that the accuracy of the Atwater system was limited by the accuracy with which the system predicted gross energy intake.

3.5.2 Biochemical Approach

The pathways of energy transduction in the mammalian system are well established and it is intuitively possible to derive a system for calculating energy value for foods and diets which would take account of the metabolic fate of ingested nutrients. Such a system would move away from the 'black box' view of the animal which is inherent in the Atwater system, and would meet the suggestion of Keys, (1945).

This approach should also take into account the current views of dietary induced thermogenesis, and provide a better indication of the metabolisable energy that would be available for storage in tissues and maintenance. It would be premature to advocate this approach at the present time until the factors controlling thermogenesis are better understood.

3.6 Conclusions

3.6.1 At the present time the conventional use of energy conversion factors provides a method for estimating the available energy intake which is more accurate than estimates of food intake, although there are real theoretical and practical objections to the derivation of such a system of factors.

3.6.2 The accuracy of the system is improved if measurements of sugars and starch are used instead of carbohydrate (by difference).

3.6.3 The unavailable carbohydrates, non-starch polysaccharides, or dietary fibre components of a diet contribute a small amount of energy by virtue of the fatty acids produced from them by the intestinal microflora. In normal Western diets this is negligible, but where the intake of these components is high (say 100g per day), the contibution may be important where energy intakes are marginal. Detailed studies are required to measure this potential contribution. However, high intakes of dietary fibre are associated with increased losses of faecal energy, and for most practical purposes the contribution of dietary fibre to energy intakes can be discounted in calculations.

3.6.4 Organic acids contribute to the energy intake, and where intakes of these are known they should be included.

3.7 Recommendations

3.7.1 For practical use in the estimation of the energy value of foods, the factors used by Paul and Southgate (1978) (Table 2) are suggested. However it must be recognised that the calculation of energy values is largely a convention, and other aspects produce greater inaccuracies in the estimates than the factors themselves.

3.7.2 In all studies of energy metabolism where great accuracy is required there is no substitute for direct measurements.

Table 2

Energy Conversion Factors

	Kcal/g	**kJ/g**
Protein	4	17
Fat	9	37
Carbohydrate (available (sugars + starch) expressed as monosaccharides)	3.75	16
Ethanol	7	29

Glycerol [(a)]	4.31	18.0
Acetic [(a)]	3.49	14.6
Citric [(a)]	2.47	10.3
Lactic [(a)]	3.62	15.1
Malic [(a)]	2.39	10.0

(a) These have been assumed to be completely absorbed and metabolised.

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