A PERSPECTIVE ON THE APPLICATION OF
THE ATWATER SYSTEM OF FOOD ENERGY ASSESSMENT

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FOREWORD

The Life Sciences Research Office (LSRO), Federation of American Societies for Experimental Biology (FASEB), provides scientific assessments of topics in the biomedical sciences. Reports are based upon comprehensive literature reviews and the scientific opinions of knowledgeable investigators engaged in work in specific areas of biology and medicine.

This technical report was developed for the U.S. Department of Agriculture (USDA) in accordance with the provisions of USDA Grant Agreement No. 59-3198-2-45. It was prepared and edited by Richard G. Allison, Ph.D., Senior Staff Scientist, and Frederic R. Senti, Ph.D., Associate Director, LSRO, FASEB.

The LSRO acknowledges the contributions of the investigators and consultants who assisted with this study. This report is based on the opinions expressed by an ad hoc study group that met at the Federation on January 17-18, 1983. Study group members and reviewing consultants reviewed a draft of the report and provided additional documentation and viewpoints on the various conclusions. In addition, they delineated research suggestions for incorporation into the final report. The study participants and LSRO accept responsibility for the accuracy of the report; however, the listing of individuals as study participants does not imply that they specifically endorse each study conclusion.

The final report was reviewed and approved by the LSRO Advisory Committee (which consists of representatives of each constituent Society of FASEB) under authority delegated by the Executive Committee of the Federation Board. Upon completion of these review procedures, the report was approved and transmitted to USDA by the Executive Director, FASEB.

While this is a report of the Federation of American Societies for Experimental Biology, it does not necessarily reflect the opinion of each individual member of the FASEB constituent Societies.

November 27, 1983
(date)

Kenneth D. Fisher, Ph.D.
Director
Life Sciences Research Office
SUMMARY

This report provides an assessment of the accuracy and utility of the Atwater system of food energy evaluation as it is currently used. Members of an ad hoc group contributing to the study focused discussions on food energy values determined by the Atwater system as published in Agriculture Handbook No. 8 and on methodology for measuring food energy values. A feature that distinguishes the Atwater system from other systems that estimate metabolizable energy is the measurement of carbohydrate by difference, a procedure that includes dietary fiber within the carbohydrate fraction. Available data are reviewed that compare tabulated metabolizable energy values with those calculated using the Atwater system from actual analysis of the proximate composition of foods and mixed diets. No evidence indicates a substantial problem in applying the Atwater system. It was concluded that the Atwater system provides estimates of metabolizable energy within the limits of accuracy for measuring food intake and also within the predictive limits of food composition tables. The Atwater system represents a practical approach to assigning energy values that can be measured or calculated to represent energy values relating to healthy humans consuming "normal" diets.

Opportunities for improvements in the application of the Atwater system lie principally in refinement of food composition data and acquisition of coefficients of digestibility on additional food products. Changes in the methods of fat extraction may require adjustment of Atwater's specific factors for both the lipid fraction and the lipid-free residues. An important issue to resolve in order to improve calculation of the energy value of foods is the energy value of dietary fiber. Among other recommendations for research were compiling gross energy values for individual foods, ascertaining the need for further dissemination of information to dietitians and physicians on the appropriate use of food energy values, and investigating the influence of modern diets containing a range of complex carbohydrates on the efficiency of food energy utilization.
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I. INTRODUCTION

A. BACKGROUND

Food energy values and other nutrient composition values are published in Agriculture Handbook No. 8 (Watt and Merrill, 1963) and its revised sections (U.S. Department of Agriculture, 1976; 1977; 1978; 1979a,b; 1980a,b; 1982a,b; 1983) by the Nutrient Data Research Branch, Consumer Nutrition Division, Human Nutrition Information Service, USDA. This is part of a continuing responsibility in food resource information. The information in the handbook series (Agriculture Handbook No. 8) is used by health professionals in many countries and the procedures employed to derive the reported values have been adopted by regulatory agencies of certain other nations. Establishing and maintaining internationally useful information on nutritional values of foods would be aided by adopting conventions based on the best available methodology to determine food energy values of physiological relevance.

The U.S. Department of Agriculture (USDA) has determined a need to reassess the accuracy and utility of the Atwater system as currently used for calculating energy values of foods. Contributing to this need are changes in food composition, analytical methodology, and definitions of food components such as fat and fiber that have occurred since the system was developed. If there is evidence that the method of calculating the energy content of food can be improved by modifying the Atwater system, then the recommendations of knowledgeable scientists are needed to determine the best corrective measures and appropriate research.

The Consumer Nutrition Division, Human Nutrition Information Service, USDA, requested that the Life Sciences Research Office (LSRO) of the Federation of American Societies for Experimental Biology (FASEB) undertake the reassessment. LSRO selected an ad hoc study group of knowledgeable scientists with appropriate expertise in relevant areas, including the areas of food analysis and composition, calorimetry, energy metabolism, and clinical nutrition to conduct a review of the Atwater system of food energy assessment. These investigators provided their opinions and recommendations on the Atwater system through discussions at a meeting held on the FASEB campus, January 17-18, 1983, and through suggestions offered during the drafting of this report. The information and opinions provided by members of the ad hoc group, other interested investigators, and a review of relevant scientific literature are the basis of this report. Possible changes in the analysis and reporting of food energy values are discussed, and research opportunities to validate and/or improve the current system are identified.
B. SCOPE OF THE STUDY

The purpose of this study was to assess the accuracy and utility of the Atwater system as it is currently used and to identify possible needs for changes or for research to improve that system. The report focuses on food energy values as published in Agriculture Handbook No. 8 and on methodology for measuring food energy values. An attempt was made to assess how accurately tabulated metabolizable energy values of foods or values calculated from their proximate composition by using the Atwater system of analysis predict the ability of individual foods or diets to meet physiological demand. An in-depth review of energy metabolism, energy transformations, and the efficiency of energy utilization directed at describing energy requirements of human beings was beyond the scope of this study. However, the problems of measuring food energy values and of measuring metabolic energy requirements are not completely separable when food energy values are expressed in physiological terms such as digestibility and metabolizable energy rather than gross energy as measured by complete oxidation in a bomb calorimeter.

The following questions were among those that guided the discussions of the working group. Many of the issues that arose in the discussions are highlighted in an effort to identify gaps in knowledge concerning assessment of food energy values. No attempt was made, however, to develop a comprehensive answer to each question.

- What is the effect of complex diets on digestibilities of protein, fat, and carbohydrate components of foods?
- What variation in efficiency of digestion is to be expected among the U.S. population and within various subgroups?
- What is the effect on digestibility of the level of fat, protein, carbohydrate, and fiber in the diet?
- Have the composition and energy value of foods changed significantly since Atwater derived factors for mixed diets and specific foods?
- What is the normal percentage variation in proximate composition of various plant and animal products? What factors contribute to this variation?
- How is the fat or lipid content of foods determined now as compared with methods used by Atwater and are these differences reflected in recent revisions of Agriculture Handbook No. 8?
Is the available information on heats of combustion and digestibility of the lipid fraction in foods, as determined by various methods, sufficient for the selection of the best method for lipid analysis?

To what extent do differences in analytical methodology affect estimates of the caloric value of individual foods and mixed diets?

Could the accuracy of energy values be improved significantly by better identification and quantitation of nitrogen-containing compounds present in individual foods?

Does the practice of calculating protein content from the determination of nitrogen (nitrogen to protein conversion factors), as used in the Atwater system and attributed to D.B. Jones, adequately reflect the protein of a whole grain and its various fractions?

To what extent is the Atwater system correlated with other systems employed by various countries for analysis of food energy?

Does analysis for specific sugars and starch offer significant advantages or disadvantages over determining carbohydrate by difference in regard to energy assessment?

Will changes in the methods of analysis for dietary fiber and studies on digestibility of certain types of non-starch polysaccharides present the opportunity of assigning caloric values to such fractions in individual foods or mixed diets?
II. CONCEPT OF FOOD ENERGY

The amount of energy available from food depends upon the composition of the food and the extent to which food components are oxidized through metabolic processes in the body. In their transformation from one state to another, foods yield energy. The amount of energy released is not dependent upon the pathway of metabolism, the formation of intermediary compounds, or the rate of the transition or metabolic oxidation. The amount of energy available to the body depends on the composition of the food, the extent of digestion and absorption of the food, and the extent of oxidation by metabolic processes. In theory, the energy yield could be calculated "exactly" given the complete chemical description of a food and its final metabolic products; however, such information is unavailable for individual foods and mixed diets. In practice, metabolizable energy values are assigned to foods and mixed diets by various systems that employ certain assumptions concerning composition of foods and their metabolic products as well as digestion, absorption, and the amount of energy available via metabolic conversions.

The caloric value of food and animal feeds has been expressed in terms of gross, digestible, metabolizable, and net energy depending on the intended use of the data. Utilizing nomenclature proposed by the Subcommittee on Biological Energy, Committee on Animal Nutrition of the National Research Council (1981), Figure 1 depicts the energy flow through an animal. Many of the terms in Figure 1 are either not used or are of lesser importance in energy metabolism of humans. Since 1900, nomenclature concerning energy metabolism of animals and humans has evolved and has been modified by workers in a range of disciplines. The multiplicity of definitions and specific uses have created difficulties in communicating among disciplines. Efforts to consolidate the nomenclatures currently employed in various specialties such as clinical nutrition, thermal physiology, thermodynamics, animal husbandry, and others should be encouraged. The usual constructs and conventions differ in important ways among these fields, and in special situations, problems of interpretation may arise.

The complete oxidation of organic substances, such as carbohydrates, to carbon dioxide and water releases an amount of energy called the gross energy or heat of combustion. Foods can be oxidized completely in an oxygen bomb calorimeter and the energy released measured to obtain the maximum potentially available energy. This value after appropriate correction for the oxides of N and S formed in the oxygen bomb and for their heats of solution is the gross energy value of the food (Miller and Payne, 1959). As depicted in Figure 1, the gross energy intake (IE) provides for total heat production (HE), fecal energy (FE), gaseous energy (GE), waste energy [including urine (UE) and surface energy (SE) losses], and retained or recovered energy.
Figure 1. Idealized flow of energy through an animal (modified from National Research Council, 1981). Total Heat Production (HE) = \( H_E + H_J + H_C + H_d + H_f + H_W + H_P \).
(RE). Thus, gross energy is a basic descriptive compositional value that represents a valuable supplement to estimates of physiologically available energy, e.g., metabolizable or net energy. If available for individual food items, gross energy could provide a reference value for food analysts and researchers and assist in detecting changes in the composition of foods. Several investigators have proposed using empirically determined relationships between gross energy and metabolizable energy to predict metabolizable energy from measurements of gross energy (Bernstein et al., 1955; Levy et al., 1958; Miller and Payne, 1959; Southgate, 1975). This would eliminate the need for measuring digestibility coefficients through human or animal feeding studies. Equations for these relationships are discussed in a later section. The ad hoc group concluded that compilation of data on gross energy values for individual food items should be encouraged.

In the study of animal energetics, most energy assessment systems relate to net energy (∆RE/∆IE) either directly by assigning a series of net energy values to feeds, or indirectly by adjusting estimates of metabolizable energy through the use of empirically determined factors toward an energy value that would have been obtained if a net energy system were employed (National Research Council, 1981). In many ME-based animal feed evaluation systems, a set of efficiency factors, defined by diet and physiological function, convert metabolic to net energy available for a particular function such as weight gain or lactation. For predicting ruminant growth and lactation, systems based on a net energy concept are almost universally the methods of choice. A net energy-based system offers some advantages when evaluating the efficiency with which the energy of foods or feeds can be partitioned to support several different physiological functions such as maintenance, lactation, growth, and muscle activity. A single net energy value is not assigned to a feed or food for all of these functions because various energy-yielding components are used with different efficiencies, depending on the function. If a net energy system were used to evaluate foods for human use, the net energy for maintenance would be the most relevant. Beyond infancy, humans retain only a small percentage of ingested energy for purposes of growth. Excluding lactation and pregnancy, human adults eat for maintenance. The net energy of a food for maintenance is frequently thought of as ME minus the heat increment of maintenance (see Figure 2). In other words, a certain amount of the energy obtained by eating food provides for the retention of energy present in body tissues, and this represents the net energy value of food for maintenance. The ad hoc group noted that such net energy values are difficult to obtain for individual foods and that the traditional metabolizable energy system is preferable when evaluating the caloric value of foods eaten by humans.

In studies of energy metabolism in animals, such as dairy cattle, metabolizable energy is an expression of the amount of energy available for metabolism. Although as measured (IE - PE - UE),
<table>
<thead>
<tr>
<th>GROSS ENERGY INTAKE (IE)</th>
<th>(\text{PE})</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIGESTIBLE ENERGY (DE)</td>
<td></td>
</tr>
<tr>
<td>METABOLIZABLE ENERGY (ME)</td>
<td>(\text{UE})</td>
</tr>
<tr>
<td>BASAL METABOLISM ((H_eE))</td>
<td>MUSCLE ACTIVITY ((H_JE))</td>
</tr>
</tbody>
</table>

**TOTAL HEAT PRODUCTION (HE)**

Figure 2. Schematic representation of the disposition of food energy by a person in energy equilibrium (RE=0), i.e., neither changing body mass nor body composition. Nomenclature as in Figure 1. The heat increment of maintenance, \(H_{1}E\), equals \(HE - H_eE - H_JE\) when the environmental temperature is within the thermal neutral zone (see page 36).
it includes the heat of fermentation which is not available for metabolism and does not include the energy content of urine, some of which is a product of metabolism, e.g., the energy used to convert ammoniation to urea (Blaxter, 1971; Moe, 1981). However, this distinction is not commonly made and the energy values measured and reported for human foods are commonly referred to as physiological or metabolizable energy. The metabolizable energy (ME) value of a food represents the amount of energy available for total heat production and for body gains such as growth and fat deposition \( (ME = RE + HE) \). Figure 2 illustrates the situation in which there is no change in the energy content of the body \( (RE = 0) \), then \( ME = HE \), and ME represents energy available for basal metabolism, muscular activity, and the heat increment of maintenance \( (H_1E) \). \( H_1E \) is also referred to as thermic effect or calorigenic effect and, in older literature, as the specific dynamic effect of foods. Energy losses in hair, skin, nails, and secretions other than urine and feces are usually assumed to be small and thus negligible in energy balance studies and in calculating ME. Thus, excluding pregnancy, lactation, and rapid growth,

\[
ME = IE - FE - UE.
\]

These assumptions appear to be acceptable even for the intermediate and longer time periods employed for energy balance studies (Buskirk and Mendez, 1980).
III. CALCULATION OF METABOLIZABLE ENERGY

A. THE ATWATER SYSTEM

Assigning a metabolizable energy value to specific foods requires some assumptions concerning the extent to which food is digested and absorbed rather than excreted, as well as the uniformity with which individuals metabolize energy present in different complex diets. Several different approaches have been taken in developing systems for food energy analysis for both single foods and mixed diets. Each system has inherent limitations in the relevance of the derived food energy values to individual consumers and population groups. The most widely utilized system for estimating metabolizable energy of foods is based on the work of Atwater carried out at the turn of the century (Atwater and Bryant, 1900). This system of calculations has evolved with newer knowledge and methodology, but is still referred to as the Atwater system. Reviews of the Atwater system are available (Maynard, 1944; Merrill and Watt, 1973; Widdowson, 1955). Other systems of measuring the metabolizable energy of foods were not discussed in depth by the ad hoc group; however, some of the major similarities and differences of the U.K. system were addressed.

Atwater called the energy measured by his system physical energy rather than physiological energy because the energy value of a gram of fat, for example, might be different depending on the physiological function it supported (Merrill and Watt, 1973). However, the term physiological rather than physical has been applied to these values, and, in the context of this report, the terms physiological and metabolizable energy value of a food are used synonymously. This represents a practical approach to assigning energy values that can be measured or calculated to represent average values relating to healthy humans consuming "normal" diets.

In general, the Atwater system for estimating physiological energy of a specific food consists of combining a series of factors: (a) proximate composition of a food; (b) values for the heats of combustion of protein, fat, and carbohydrate; (c) coefficients of digestibility; and, (d) energy lost in urine. The methodology used and assumptions made in deriving each of these factors offer the chance of introducing errors (Atwater and Bryant, 1900). In proximate analysis, fat or lipid is usually determined gravimetrically after extraction by procedures dependent on the nature of the food, protein is calculated by applying a conversion factor to the measured nitrogen content, and carbohydrate is calculated by difference (subtracting the percentage of protein, fat, moisture, and ash from 100). At the turn of the century, methodology was inadequate to analyze for all specific components of these major nutrient fractions.
Atwater examined data from digestion experiments involving single foods or very simple mixed diets and estimated coefficients of digestibility for the protein, fat, and carbohydrate components of individual foods (Atwater and Bryant, 1900). From these preliminary estimates, digestibility coefficients were assigned to protein, fat, and carbohydrate in major food groups and were used in calculating the digestibility of the components in normal mixed diets. Based on comparisons with experimental data obtained from subjects consuming these diets, coefficients were altered slightly to bring results into close agreement, recognizing "there is more or less guess work in the method of estimating the coefficients of availability" (Atwater and Bryant, 1900). In 93 digestion experiments with ordinary mixed diets, the calculated and measured coefficients of digestibility (apparent digestibility) were for protein 93.6 and 93.3, fat 94.5 and 95.0, and carbohydrate 98.1 and 97.7, respectively. Adjustment can be made in average digestibility coefficients on the basis of proportion of various food sources represented in a diet (Bernstein et al., 1955). Most changes in Atwater's digestibility coefficients have been small, but the digestibility of vegetable protein assumed to be 83% by Atwater and Bryant (1900) was later reported as 70% (Merrill and Watt, 1973).

Heats of combustion of some 276 foods were calculated from their proximate compositions and heats of combustion that Atwater had derived for the protein, fat, and carbohydrate components of specific foods or food groups, e.g., cereals, legumes, vegetables, and fruits (Atwater and Bryant, 1900). Bomb calorimetry measurements confirmed the ability to predict closely from proximate composition the gross energy value of foods in most categories. Fresh fruits presented some problems; predicted values were about 6% lower (on a water-free basis) than the heats of combustion measured by bomb calorimetry. Predicted heats of combustion of cooked vegetables were a little higher than measured values. Atwater had analyzed fewer samples of fruits and vegetables than of other food categories, e.g., cereals.

Atwater adjusted gross energy values to available energy by taking into account all energy losses from the digestive tract and the energy content of urinary nitrogen-containing compounds (Atwater and Bryant, 1900). An average value of 7.9 kcal/g of urinary nitrogen was determined, which corresponds to about 1.25 kcal/g of protein absorbed (ingested less digestive loss). Rubner's value of 7.45 kcal/g (Rubner, 1885a,b; 1901) and Bernstein's (Bernstein et al., 1955) of 8.57 ± 0.22 kcal/g are intermediate between the heats of combustion of the two major nitrogen-containing substances in urine, urea (5.62 kcal/g) and creatinine (12.31 kcal/g) (Bernstein et al., 1955). The level of nitrogen balance can be expected to alter this calorie/urinary nitrogen ratio, but the Atwater system makes no allowance to correct for nitrogen balance.
Atwater and Bryant (1900) reported the average heats of combustion of 1 g of protein, fat, and carbohydrate in the average mixed diet (determined by survey) as approximately 5.65, 9.40, and 4.15 kcal, respectively. Applying the coefficient of digestibility (then termed "coefficients of availability" derived from digestion experiments) to these values, Atwater and his co-workers concluded that carbohydrate, fat, and total protein of a mixed diet would yield 4.05, 8.93, and 4.03 kcal/g, respectively. These factors have been rounded to 4, 9, and 4 kcal/g and used as "general factors" for calculating energy values of average mixed diets in the U.S. (Merrill and Watt, 1973). Use of these general factors for analysis of specific foods has the potential of introducing significant errors and the limitations of their use are carefully considered. For example, unavailable energy in dietary fiber is attributed to the carbohydrate fraction by the general factor.

The estimation of the energy value of foods using specific heats of combustion and digestibility factors in combination with proximate analysis of carbohydrate "by difference" characterizes the Atwater system. The correct usage and limitations of general energy factors as well as the need for specific energy and digestibility factors when considering individual foods have been repeatedly emphasized (e.g., Maynard, 1944, 1946; Merrill and Watt, 1973). Additivity of energy values of foods is assumed for mixed diets. However, when addressing efficiency with which fats, carbohydrates, and proteins deliver energy to support work or other physiological function, differences are expected due to physiological status, biochemical considerations, and diet composition. For most consumers, concern for these sources of variance in the average mixed diet are small, but in diets of "extreme" composition such as those very high in dietary fiber, physiological energy values may not be additive for all foods.

B. OTHER SYSTEMS

Other countries have evolved slightly different systems for calculating food energy by making alternative assumptions while working with similar theoretical bases. For example, the British or U.K. system employs different energy factors and determines "available carbohydrate" by direct analyses (Paul and Southgate, 1978).

Domestic rationing of food and related international concerns during World War II provided incentive for the preparation of more accurate food energy tabulations. Chatfield and Adams (1940) had compiled tables of proximate composition of foods and applied the general energy values of 4, 9, and 4 kcal/g to protein, fat, and carbohydrate fraction of individual foods, respectively. Maynard (1946) focused attention on differences in the Atwater system and the U.K. system when calculating the nutritive value
of wheat. There were differences in assumed moisture content (12 vs. 15%, respectively), carbohydrate determination and caloric factors, and adjustments for digestibility or availability of energy-yielding food components (Hollingsworth, 1955).

A detailed account of the evolution and application of the methods used to calculate the caloric value of foods for the U.K. tables is given by Paul and Southgate (1978). Analysis of available carbohydrates in the U.K. system has utilized newer methodology as it has evolved from colorimetric methods to high performance liquid chromatography. Available carbohydrates are those which are digested and absorbed, including sugars (glucose, fructose, sucrose, lactose, and maltose and its oligomers), dextrans, starch, and glycogen. Measurement of starch by enzymatic hydrolysis has been employed since about 1935. Thus, the U.K. system measures available carbohydrates by a series of direct analyses, while in the U.S. system an intermediate value of 4.0 kcal/g is assigned to carbohydrate by difference before digestibility is taken into account. However, many factors appear to reduce any potential differences in energy value assigned to the carbohydrate fraction by the two systems. Factors for digestibility may either reduce or increase the difference depending on the proportions of available polysaccharides (including starch and dextrans) and unavailable carbohydrate (dietary fiber). However, Atwater's specific factors for foods incorporate an adjustment for the composition of the carbohydrate when known (Merrill and Watt, 1973). The U.K. system reports available carbohydrates as monosaccharide equivalents and uses the caloric conversion factor 3.75 kcal/g. This method of calculation assigns to starch a value of 4.13 kcal/g because 100 g of starch yields 110 g of monosaccharides on hydrolysis (110 x 3.75 = 100 = 4.13) (Paul and Southgate, 1978). Disaccharides, by a similar calculation (105 x 3.75 = 100 = 3.94), are assigned 3.94 kcal/g. In the U.K. system, the caloric factor for protein used in early editions of the U.K. food tables was 4.1 kcal/g based on the work of Rubner (1885a,b). The current edition of the U.K. food composition tables calculates protein content from nitrogen content, using specific factors where available, and assigns 4.0 kcal/g of protein. The U.K. system does adjust this factor for differences in digestibility among different proteins as is done in the U.S. food tables (Périssé, 1983). The average physiological energy value for the protein component of an average U.S. diet was calculated by Merrill and Watt (1973) as 4.0 kcal/g, but this represented the weighted average of 4.28 kcal/g for protein of animal origin and 3.58 kcal/g for protein of plant origin which comprised 63 and 37% of the protein in the diet, respectively. Ethyl alcohol, acetic acid, citric acid, lactic acid, and malic acid are determined routinely in the U.K. system and assigned appropriate caloric values. Similar calculations are employed in the U.S. for foods containing appreciable amounts of these substances.
Any of several factors, broadly classified as either "conceptual" or "technical" by Périsse (1983), may cause the caloric value of a particular food to be reported differently. For example, in the U.K. table (Paul and Southgate, 1978) 100 g of raw gooseberries is reported as 17 kcal while Agriculture Handbook No. 8-9 (U.S. Department of Agriculture, 1982b) reports 44 kcal. The sources of such discrepancies may be difficult to identify. Technical discrepancies arising from the identity of the food, natural variation, method of sampling, and analytical methodology are more difficult to identify from the information provided with different food composition tables than are discrepancies among the concepts utilized for calculating caloric values such as outlined in Table 1 (Périsse, 1983). In the majority of national and regional food tables that have adopted the use of specific factors, carbohydrate content is determined by difference and includes dietary fiber. Most of those adopting general factors exclude dietary fiber from the carbohydrate content. Périsse (1983) concluded that any risk of overestimating the caloric value of foods by including dietary fiber in the estimate of carbohydrate is largely mitigated by the specific factors because the coefficient of apparent digestibility is less at higher fiber contents. One advantage of estimating the caloric value of a food on the basis of analytical values of available carbohydrate (U.K. system) is that new foods or combinations of foods can be assigned caloric values in the absence of additional digestibility experiments.

In the experience of the ad hoc group, the values in Agriculture Handbook No. 8 tend to overpredict the energy value of a food when food composition differences between the food that is fed and the average values reported in the handbook are not taken into account. In the study of Webb et al. (1980), gross energy values (measured by bomb calorimetry) of 45 individual foods indicated that the values in tables may be overstated by as much as 10%. The handbook values predicted 94% availability of gross energy and balance measurements indicated about 10% less availability (bomb values of food minus bomb values of wastes). Undereating or overeating in addition to diet composition influences these observations. The ad hoc group considered the sampling problem very difficult, particularly for items which vary greatly in moisture and fat content, e.g., hamburger. The analysis of the mixed diets fed by Marshall and Judd (1982) showed lower levels of fat, protein, and carbohydrate than the tables predicted. Food composition tables report "representative" values and exact correspondence with selected food items should not be expected. These and other factors severely restrict the utility of food composition tables for purposes such as metabolic experiments requiring precise data.

Attempts at quantitating the energy content of diets consumed by individuals are also limited by the methodology chosen to estimate food intake and errors in these methods are ± 5% or greater (Southgate, 1983). Additionally, if there is a consistent overestimation or underestimation of food energy intake on the
Table 1. Summary of Factors Used in Selected Food Composition Tables for Estimating Amount of Protein and Carbohydrate and Calculating Caloric Values*

<table>
<thead>
<tr>
<th>National Table</th>
<th>Protein Content</th>
<th>Carbohydrate Content</th>
<th>Conversion to Calories</th>
</tr>
</thead>
<tbody>
<tr>
<td>1959 Colombia</td>
<td>N x S</td>
<td>+F</td>
<td>S</td>
</tr>
<tr>
<td>1968 Ethiopia</td>
<td>AA</td>
<td>+F</td>
<td>S</td>
</tr>
<tr>
<td>1961 France</td>
<td>N x 6.25</td>
<td>-F</td>
<td>4</td>
</tr>
<tr>
<td>1969 Germany</td>
<td>N x S</td>
<td>+F</td>
<td>S</td>
</tr>
<tr>
<td>1978 Germany</td>
<td>N x 6.25</td>
<td>-F</td>
<td>4.1</td>
</tr>
<tr>
<td>1974 India</td>
<td>N x 6.25</td>
<td>-F</td>
<td>4</td>
</tr>
<tr>
<td>1980 Iran</td>
<td>N x S</td>
<td>-F</td>
<td>4</td>
</tr>
<tr>
<td>1974 Italy</td>
<td>N x S</td>
<td>AC</td>
<td>4</td>
</tr>
<tr>
<td>1981 Netherlands</td>
<td>N x 6.25</td>
<td>-F</td>
<td>4</td>
</tr>
<tr>
<td>1977 Norway</td>
<td>N x S</td>
<td>-F</td>
<td>4</td>
</tr>
<tr>
<td>1974 Peru</td>
<td>N x S</td>
<td>+F</td>
<td>S</td>
</tr>
<tr>
<td>1964 Philippines</td>
<td>N x S</td>
<td>+F</td>
<td>S</td>
</tr>
<tr>
<td>1961 Portugal</td>
<td>N x S</td>
<td>+F</td>
<td>4</td>
</tr>
<tr>
<td>1976 U.K.</td>
<td>N x S</td>
<td>AC</td>
<td>4</td>
</tr>
<tr>
<td>1963 U.S.</td>
<td>N x S</td>
<td>+F</td>
<td>S</td>
</tr>
<tr>
<td>1978 Venezuela</td>
<td>N x S</td>
<td>+F</td>
<td>S</td>
</tr>
</tbody>
</table>

* Adapted from Périsé (1983). General conversion factors are indicated by value.

Abbreviations:  
- **S** = specific conversion factor appropriate to the individual food or food category  
- **N** = nitrogen  
- **AA** = factor derived from amino acid composition  
- **+F** = carbohydrate by difference, including fiber  
- **-F** = carbohydrate by difference, excluding fiber  
- **AC** = available carbohydrate, starch and sugars reported as monosaccharides (see text)
basis of food composition tables, then calculated metabolizable energy intakes will have limited value in the study of free-living populations (Durnin and Ferro-Luzzi, 1982). If food energy values were published with values for variance, a confidence limit could be placed on the interpretation of data.

Jansen and Harper (1980) carried out an analysis of school lunches for energy, sugar, fat, and salt. This study compared the energy and nutrient values in Agriculture Handbook No. 8 with values determined by chemical analysis. Applying the general Atwater factors to chemical analysis values of lunch composites, Jansen and Harper found close correspondence to the energy content calculated from Agriculture Handbook No. 8 values for individual foods. The fat, carbohydrate, and protein data calculated from Agriculture Handbook No. 8 agreed remarkably well with the analyzed values considering all potential sources of error.

Clinical applications. For patients with malabsorption, the fecal losses of nitrogen, fat, and associated energy indicate that the average digestibility values derived by Atwater for normal individuals do not apply to many hospitalized patients (Heymsfield et al., 1981). Use of food composition tables when calculating energy values of foods fed patients with malabsorption syndromes may greatly overestimate the metabolizable energy value of foods for these patients. Patients who most often have malabsorption problems are those who have had gastric resections with vagotomies and postoperative diarrhea (which may last for a lifetime), diseases such as Crohn's disease, pancreatitis, obstructive liver disease in which bile salts do not enter the intestine in proper quantities, short bowel syndrome, radiation enteritis, and surgical resection of the ileum and the ileal-cesal valve. Digestibilities in the range of 48 to 91% were reported in hospitalized patients with a history of malabsorption in which values for fat digestibility were sometimes below 10% (Heymsfield et al., 1981).

In a clinical setting, an error of 10% in the energy value of a meal may be significant for certain patients. For example, burn patients may be particularly sensitive to adverse effects of receiving fewer calories than required for an extended period (Kinney, 1980). Similar problems might be associated with large urine losses of glucose in poorly controlled diabetics and with suspected uncoupling of oxidative phosphorylation sometimes seen in sepsisemia. In the opinion of the ad hoc group, the metabolizable energy values derived for purposes of food tables and labeling are being widely used without adequate consideration of their limitations. This is not limited to clinical situations. For example, the metabolizable energy value of food may be reduced for healthy, aged individuals because of impaired absorptive capacity (Peibusch and Holt, 1982). Recognition of the limitations of assigned energy values is incumbent upon persons using these energy values in attempts to meet human energy needs, be it for an individual or group, healthy or ill.
IV. ANALYSIS OF ENERGY-YIELDING COMPONENTS

A. LIPID COMPOSITION

Kinsella et al. (1975) summarized the analytical factors that affect total lipid determinations and provided an analysis of the problem associated with collating data on lipids in foods. Few of the more polar structural lipids such as the phospholipids and the glycolipids were included in Atwater's "total fat" fraction. Modern procedures obtain a more complete extraction of lipid-type components (Miles et al., 1984). Solvents include petroleum ether, chloroform, acetone, butanol, and chloroform-methanol mixtures. In the 1963 and earlier editions of food tables compiled by USDA (Watt and Merrill, 1963), fats were determined by ether extraction; current editions are being updated with data obtained using a more complete extraction of lipid-containing fractions. Values reported for the energy contributed by the fat or total lipid fraction of a food may be difficult to interpret if food composition tables provide insufficient information on the extraction methodology. The heats of combustion of the fat-free residue and of the extracted lipid as currently determined are not exactly comparable to those reported by Atwater.

The current trend of adding vegetable oils from different sources in processing of foods introduces an additional uncertainty in attempting to describe lipid composition of certain foods. For example, the energy values of coconut oil and other oils high in lauric acid are overestimated if current specific factors for vegetable oils are applied because these values were estimated on the basis of longer chain fatty acids. Atwater's heat of combustion for coconut oil was considerably lower than that of other common vegetable oils, (8.07 vs. 9.5 kcal/g) (Merrill and Watt, 1973). He also used a lower factor for milk fat (9.25 kcal/g), the heat of combustion of which is also lower than other oils.

Differences in the composition of the lipid fraction resulting from the extraction procedure employed will generally affect the heat of combustion of this fraction. In an effort to compensate for incomplete extraction of fat from meat, Atwater and Bryant (1900) assigned to the ether extraction fraction the heat of combustion value of a triglyceride, 9.5 kcal/g. This triglyceride value has, in most instances, been retained for the lipid fraction even though the heat of combustion of a pure triglyceride is higher than that of total lipids using modern extraction methodology. The structural lipids, mostly phospholipids, have a heat of combustion nearer 7 kcal/g (Kinsella et al., 1975). The effect of Atwater's assignment of 9 kcal/g to the total fat will vary with the proportion of structural lipids and other extractable materials present in a food as well as with the completeness of the extraction.
Currently, chloroform-methanol and chloroform-butanol extractions which were developed for fish are being used for meats, fruits, and vegetables. If foods such as lean meats, cereal grains, legumes, vegetables, and fruits are extracted with a solvent more polar than ether, lipid extraction will be more complete. In certain low fat items the amount of total lipid extracted can double that extracted by ether when more polar solvents are used. For items that exceed 10% fat content, the difference is probably small because the proportion of phospholipid is less. Atwater found a heat of combustion of 4.27 for ether-extracted residue of beef ("fat free"), but this residue would have contained the unextracted phospholipids. The factor of 4.27 was also applied to the fat-free residue of meats from other animals.

Miles et al. (1981, 1984) determined the lipid content of 33 different foods including cereal products, vegetable oils, margarine, poultry, beef, and pork products. Chloroform-methanol extraction of meat, fish, chicken, and eggs was the method chosen. For cereals, butanol extraction preceded chloroform extraction and the extracts were reextracted with chloroform. In each case, an aliquot of the extracted lipid was subjected to bomb calorimetry to obtain a heat of combustion. That figure was multiplied by Atwater's coefficient of digestibility to obtain metabolizable energy per g of lipid. Values found were lower than those reported by Atwater for the fat fractions of similar products. For example, the gross energy value for the total lipids from chicken light meat was 8.08 kcal/g which when multiplied by Atwater's coefficient of digestibility gives a metabolizable energy value of 7.68 kcal/g, 14.9% lower than Atwater's value of 9.02 kcal/g. Metabolizable energy values for wheat germ oil, corn oil, soybean oil, safflower oil, rice oil, lard, beef tallow, chicken fat, corn oil margarine, and soy bean oil margarine were within 2% of Atwater's values. Coconut oil was 3.4% lower. Of the four cereal products analyzed by Miles et al. (1984), corn flour, wheat bran, whole kernel corn, and brown rice, two had significantly lower metabolizable energy values per g of lipid than reported by Atwater: wheat bran, 8.6% and brown rice, 3.5%. Metabolizable energy values per g of fat-free residues from meats, poultry, and fish were between 4 and 8% lower than Atwater values.

Preliminary data presented to the ad hoc group demonstrated the effect of utilizing the lower heats of combustion (CHCl₃/MeOH) determined by Miles et al. (1984) in calculation of metabolizable energy using proximate analysis data (not obtained on the same samples) for several foods and Atwater's coefficients of availability. These preliminary data indicated that the decrease in reported metabolizable energy value for certain foods could exceed 5%; however, careful consideration must be given to corresponding changes in proximate composition and appropriate digestibility factors. Without additional data it was not possible to
predict potential effects on food composition data as currently published in Agriculture Handbook No. 8. In revising the British food tables, for example, Paul and Southgate (1978) used a lower factor for fat, 9 rather than 9.3 kcal/g fat that had been applied in the third edition (Widdowson, 1960). The change reduced the reported energy value of most foods by less than 1% (Paul and Southgate, 1978). Despite the lower heat of combustion of lipid fractions as extracted by current techniques, the greater quantity of lipid extracted may result in a greater total energy value. In fact, the caloric value for a total lipid extract may be several-fold that of an ether extract for cereals, their milled fractions, shellfish, or lean finfish (Miles et al., 1981). The proportion of total lipid contributed by phospholipid is appreciable in many foods: 28% in egg yolk, 70% in chicken white meat, and 15% in lean pork. Assignment of heat of combustion of 9 kcal/g to the total lipid fraction, as is currently practiced, can therefore result in a substantial overestimation of the metabolizable energy value of the lipid if applied to the total lipid extract. Additionally, the assignment of a heat of combustion originally determined on the "fat-free residue" of lean meat to the protein fraction will similarly result in an overestimation of caloric value for that fraction. These errors are additive, positive, and are noncompensating. Hence, employment of more complete lipid extraction techniques should be accompanied by determination of gross energy values (bomb calorimetry) and digestibility factors for both the extracted lipid and the lipid free residue.

Efforts for more completely defining the lipid components of foods arise from improvement in methodology such as gas-liquid chromatographic procedures, public health concerns regarding the polyunsaturated fatty acid content and ratio to saturated fatty acids, content of trans and positional isomers of unsaturated fatty acids, and economic incentives for utilizing less expensive sources of edible oils. Given sufficient detail in the analysis of fatty acid components, it may be possible to assign heat of combustion values to these components and calculate a more accurate estimate of the caloric contribution of the lipid fraction to metabolizable energy.

B. CARBOHYDRATE EVALUATION

As already discussed (see pages 11-13), the Atwater system determines carbohydrate by difference. The carbohydrate content is the difference between 100 and the sum of the percentages of water, protein, fat, and ash. Fiber, if present, is included in the total carbohydrate content. Direct analysis of carbohydrate is not required in order to calculate ME by the Atwater system. Carbohydrate by difference provides certain advantages in that under- or overestimations of protein are compensated by inverse changes in the content of carbohydrate, a component assigned approximately the same ME value. Similarly,
errors in fat content are partially compensated. Members of the ad hoc group suggested that this compensating feature was an asset of the Atwater system, conferring it with a certain robustness. However, information on the carbohydrate content of foods such as obtained by direct analysis in the U.K. system has applications beyond the calculation of ME. For example, it would probably be useful for health professionals including dietitians, researchers, and physicians to have values for individual carbohydrate components: starch, sugars, and dietary fiber (unavailable carbohydrate). Of these components, dietary fiber is most likely to present problems to the Atwater system of energy assessment.

Some foods provide unique problems when attempting to express the content of individual sugars. For example, a variable proportion of potato starch is converted to simple sugar depending on storage conditions (Merrill and Watt, 1973). Of the cereal grains, oats have a particularly high proportion of soluble dietary fiber (Chen and Anderson, 1981). Classes of foods for which carbohydrate composition data are severely limited, but for which such data would be particularly valuable, include tubers, roots, vegetables, fruits and berries, and legumes. Such data for meats and dairy products would have less utility. The ad hoc group suggested that individual carbohydrates be specified in food composition tables, but not necessarily utilized in calculating energy values.

1. Definition and analysis of dietary fiber

Three problems related to dietary fiber analyses were discussed by the ad hoc group: (1) The definition of dietary fiber and the best method to measure dietary fiber as defined. (2) The possible digestibility or fermentation of certain dietary fiber components to energy-yielding compounds and their availability for absorption. (3) The ability of dietary fiber to affect digestibility of other energy-yielding dietary components. Each of the problems relates to assessing the caloric value of foods and mixed diets. The ability of food components classified as dietary fiber to yield energy to humans is an unsettled question of current scientific investigation.

It is frequently stated that the lack of a universally accepted definition of dietary fiber impedes the assessment of the role of dietary fiber in digestive processes (Southgate, 1982a; Spiller et al., 1976; Talbot, 1980). An acceptable definition of dietary fiber will probably relate primarily to health aspects of the physiological properties associated with ingesting plant cell wall materials and secondarily to analytical methodologies that stress digestibility.

Plant components that are resistant to hydrolysis by the endogenous enzymes of the digestive system include both soluble and insoluble components of dietary fiber (Schaller, 1978; Southgate, 1969). Cellulose, hemicellulose, lignin, as well as plant
waxes, sterols, nondigestible products of browning reactions, and certain proteins and lipids are among the insoluble components included as dietary fiber by some methodologies. Pectins, gums, and mucilages are soluble components of dietary fiber. Many methodologies for the measurement of dietary fiber have been developed, but none has been shown to be applicable, routinely, to all food (Chen and Anderson, 1981). For example, a widely used method of the American Association of Cereal Chemists (1978), an enzyme-modified neutral detergent fiber (NDF) method, detects the insoluble components, but does not include the soluble components. At the time of its discussions, the ad hoc group was aware of several collaborative studies in progress to validate methods of analysis for dietary fiber. The results of one of these has since been submitted to the Association of Official Analytical Chemists, Arlington, Virginia for approval as an official method of the Association (Prosky et al., 1983). Briefly, this method involves heating the sample to gelatinize the starch in the presence of heat-stable alpha-amylase (after preliminary lipid extraction if necessary), protease and amyloglucosidase hydrolysis of residual protein and starch, and ethanol precipitation of water-soluble dietary fiber. The insoluble residue minus the ash and residual protein is a measure of total dietary fiber. Each of the methods mentioned above included methods to eliminate digestible, known energy-yielding components, such as starch. To this extent, it was recognized that correction of "carbohydrate-by-difference" by subtracting noncaloric dietary fiber might more accurately reflect available energy of certain food products, e.g., vegetables.

Varying amounts of starch and nitrogen-containing substances may be isolated with dietary fiber by methodology designed to quantify dietary fiber and its components (Marlett et al., 1982; Neilson and Marlett, 1983; Saunders and Betschart, 1980). The NDF (Goering and Van Soest, 1970) and the enzyme-modified NDF methods (American Association of Cereal Chemists, 1978) are gravimetric methods that measure dietary fiber as an insoluble residue. Gravimetric methods may include significant amounts of nitrogen-containing substances and starch and thus introduce errors in estimates of dietary fiber. For these methods and for methods that quantitate dietary fiber by analysis of carbohydrate (e.g., Southgate, 1969; Theander and Aman, 1982), complete gelatinization of starch to remove it from fiber is required. For example, a small amount of starch that was resistant to enzymatic hydrolysis was probably recovered as dietary fiber by the analytical procedures employed in constructing the British food composition tables (Theander, 1981).

A primary objective in analyzing the dietary fiber content of foods is to identify and quantify those components which may be associated with physiological functions as well as provide a value that is reproducible. Efforts to develop and standardize this methodology may not be optimally suited to adjusting metabolizable energy value of foods.
2. **Digestibility of dietary fiber**

Satisfactory procedures for calculating a metabolizable energy value for dietary fiber and for predicting the effect of fiber on the availability of energy from other energy-yielding components will be dependent on the methods eventually adopted for analysis of dietary fiber. One view is that the digestibility of a diet is adequately represented by the weighted average of the digestibility of its components. However, the validity of such estimates has not been shown for diets containing high levels of fiber.

Soluble fiber components such as alginates, carboxymethyl cellulose, and plant gums may make a significant energy contribution to individual foods but only a small contribution to an average diet. However, the proportion of the total dietary fiber contributed by processed fibrous components added to foods will likely increase in the future. A correct energy value for foods containing these materials will require methodology for their quantitation and for assessment of digestibility and metabolism.

Changing from a diet of low dietary fiber to one of high dietary fiber produces changes in microbial growth in the bowel (Ehle et al., 1982; Marthinsen and Fleming, 1982). The composition and source of dietary fiber, e.g., legumes vs. cereal bran, can have differential effects on intestinal flora (Hillman et al., 1983; Kurzer and Calloway, 1981). Additionally, attempting to determine the metabolizable energy value of dietary fiber components as part of a diet presents problems in the ability to detect relatively small increments of energy. If a component is tolerated in the diet only at a low level (less than 5% of potential total calories), as is the case for pectin (Cummings et al., 1979), and the error in digestion studies is ± 2%, then the metabolizable energy of that dietary component could not be reliably measured.

The apparent digestibility based on disappearance of carbohydrate in diets containing the same level of dietary fiber varied from 72 to 85% for pentosans, and from 15 to 55% for cellulose (Milton-Thompson and Lewis, 1971; Southgate and Durnin, 1970). However, pectin is apparently nearly completely digested (Holloway et al., 1983). The breakdown of dietary fiber via fermentation (anaerobic breakdown of carbohydrates) in the colon produces potentially energy-yielding volatile fatty acids including, acetic, propionic, and butyric acids (Cummings, 1983). Thus, when deriving correction factors for the estimated caloric value of the carbohydrate fraction of a food based on the amount of dietary fiber present, consideration must be given to the potential for contributions of metabolizable energy by dietary fiber and recognition that this potential will vary with fiber composition.
To study the ability of any component of dietary fiber to contribute energy, it would be preferable to use foods in which a particular fiber component predominates rather than to isolate a component of fiber and add it back to a formulated food or diet. The separation of components alters their properties and they may not produce the same physiological response in the two situations. The digestibility of the fiber may also be altered.

Carreyer et al. (1982) quantitated the fate of dietary fiber in humans by a newly developed radiolabeled fiber marker. In this instance, α-cellulose was labeled with 131I. When consumed by human subjects, about 2% of the ingested label was excreted in the urine; an additional 87% was found unbound in the feces. However, α-cellulose undergoes little fermentation and its degradation during transit through the gut would not be representative of typically consumed fiber (Slavin et al., 1981). Pectin, on the other hand, is a highly fermentable fiber source that has been labeled in vitro (Baig and Cerda, 1979) and in vivo (Baig and Cerda, 1980). Neither of these radiolabeled materials has been tested in human subjects. If such studies are done, it will be necessary to distinguish the label in any undigested fiber from the label which conceivably would be incorporated into bacterial exopolysaccharides as the bacteria degrade the pectin.

The feeding of labeled fiber has involved feeding of isolated fiber. Labeling by chemical treatment is likely to alter digestibility. In the case of cellulose, crystallinity may be reduced. Amorphous cellulose is digested by ruminant fermentation and also, at least in part, by monogastric animals including humans (Slavin et al., 1981). Crystalline cellulose is largely resistant to such digestion. The introduction of labels specifically into fiber components in an intact food requires unusual protocols such as using immediate precursors. The ad hoc group was aware of few instances in which such lines of investigation have been pursued. Questions on the digestibility of dietary fiber need to be pursued.

The magnitude of the possible error introduced by considering all soluble fiber as providing no energy even though it may be completely converted to volatile fatty acids that are utilized, appears to be small. Some rational estimates can be made for some cases, but not for all. Some variation in fermentability of various fibers among individuals is known to occur, but volatile fatty acids may represent 70% of the potential energy available from fermentation of dietary fiber that on a typical western diet (15–20 g dietary fiber) would represent 2–3% of energy (Cummings, 1983). Additional studies are needed to establish the fate of volatile fatty acids produced by fermentation in humans.
3. Effects of dietary fiber on fat and protein digestibility

Although additional intake of certain types of dietary fiber may contribute metabolizable energy, it may also cause energy losses by increased excretion of fat and protein (Kay and Strasberg, 1978; Stasse-Wolthuis et al., 1980). In one study (Slavin and Marlett, 1980) in which dietary fiber was increased by adding a powdered α-cellulose, there was no significant change in fat or nitrogen excretion. In the study of Kay and Truswell (1977), pectin (15 g) effected a pathological fat loss of about 8 g in a 24-h period. In another study by Kelsay et al. (1981), a diet having a high content of natural dietary fiber in the form of fruits and vegetables increased the amount (but not the concentration) of fecal fatty acids which the authors believe were formed in the digestion of fiber by bacteria. Nitrogen in the feces increased by 15-20%. There was no estimate of the availability of the nitrogen compounds supplied by the fruits and vegetables as compared to those compounds provided by other foods in the diet. Some evidence suggests the additional nitrogen and fat recovered in feces after feeding high levels simply reflects that amount unavailable due to association with dietary fiber in food (Southgate, 1982b). For example, Eggum et al. (1983) reported that the protein in cocoa powder was completely indigestible.

Pentosans, celluloses, and hemicelluloses are not available to the same degree and would not necessarily change the digestibility of fat and protein in the same way. Atwater's coefficients of digestibility of the nitrogen and fat components of a specific food do not take into account the wide diversity of fiber contents of the diets with which they may be eaten. Therapeutic diets may call for as much as 40 to 50 g of dietary fiber daily (Anderson, 1980). As the amount of dietary fiber goes up, nitrogen loss also increases (Eggum et al., 1982; Southgate, 1982b).

Southgate and Durnin (1970) found a 7% decrease in apparent digestibility of protein in some subjects fed a diet containing added fruits and vegetables (about 15 g of fiber, pentosans plus cellulose). This decrease of over 1 g of nitrogen exceeds the amount that could come from dietary fiber.

Kelsay et al. (1981) studied 12 men consuming four diets providing 1.9, 10.1, 19.4, or 25.6 g NDF per day. Energy, nitrogen, and fat excretion increased and apparent digestibilities decreased as fiber increased. The apparent digestibility of energy decreased from about 96% to 91%. Calloway and Yates-Zeuzulka (1980) noted that the metabolizable energy value of a high-fiber (90 g/d) Guatemalan diet was 94% of that calculated by applying Atwater's specific energy values to the proximate composition of the diet components. Longer term adaptation may occur on vegetarian diets. Dose response curves for such effects have not been determined for various dietary fibers. There is a need to describe the effect of various levels of different dietary fibers on the utilization of fats and proteins in mixed diets.
C. PROTEIN CONTENT

Atwater referred to one of the three energy-yielding fractions in food as "protein" (Atwater and Bryant, 1900). He determined the nitrogen content of food and then applied a factor, e.g., 6.25 for legumes and foods of animal origin, to convert nitrogen to grams of "protein". This "protein" fraction included total nitrogenous matter, both proteids (termed proteins in modern nomenclature) and non-proteids (nonprotein nitrogen-containing compounds other than nitrogen-containing fats). Two errors were recognized in using the conversion factor 6.25: (1) non-proteids usually contain more than 16% nitrogen and (2) their energy value is less than that of proteins. Both errors tend to overestimate the contribution of protein to the caloric value of food. Chemical methodology that would exclude non-proteids from the protein fraction had yet to be developed (Atwater and Bryant, 1900).

1. Nitrogen to protein conversion factors

The method that is nearly universally used in determining protein content is to determine nitrogen content and apply a factor to convert this value to protein. The factor that is most frequently utilized is 6.25 which assumes proteins contain 16% nitrogen. In practice, nitrogen content in proteins of most foods ranges from 13 to 19% (Jones, 1931). In addition, nitrogenous compounds such as choline, purines, pyrimidines, nitrites, and other nitrogen-containing compounds, which may have a lower or higher heat of combustion, may be included as protein. It is considered more accurate to utilize a specific factor based on the percent nitrogen in the protein of individual foods; however, many of the factors currently in use, referred to as Jones factors, were derived by isolating the predominant protein of a food rather than the entire protein fraction. Thus, in some cases, a substantial error could result. Many experts question whether sufficient scientific basis exists for the different factors for nitrogen to protein conversion reported for various foods (Baker, 1979; Morr, 1981). Additional studies are needed to establish valid conversion factors for expressing protein content.

In the Atwater system, unless otherwise noted, total nitrogen is treated as protein nitrogen and no correction is made for different nitrogen-containing components in the calculation of heats of combustion entered into modern food tables. Merrill and Watt (1973) noted that the error in total energy caused by such a calculation is small because those foods, mostly fruits and vegetables, having a large proportion of nitrogen as nonprotein nitrogen usually contain small amounts of total nitrogen. In the case of certain vegetables that have a large proportion of nonprotein nitrogen-containing substances such as potatoes and other tuber or root crops, the caloric factor is weighted to compensate for the lower caloric yield per gram of nitrogen rather than to account separately for protein and nonprotein nitrogen.
Since the identification of individual amino acids, increased emphasis has been placed on evaluating proteins as sources of nitrogen or essential amino acids rather than as energy sources. Knowledge of amino acid composition permits identification of the nutritionally limiting amino acids and derivation of chemical scores which correlate with nutritive value (growth promotion). Much of the concern for a refined conversion factor results from considerations of the efficiency of nitrogen utilization. For many uses of nitrogen to protein conversion factors, it is desirable to exclude nonprotein nitrogen other than amino acids from estimates of protein content. Heidebaugh et al. (1975) compared three methods of calculating protein content of 68 foods and six menus representing average diets of American males. The protein calculation methods were: (a) 6.25 times Kjeldahl nitrogen; (b) specific factors ranging from 5.30 to 6.38 (Jones, 1931) times Kjeldahl nitrogen; and, (c) summation of amino acid content from chemical analyses. The apparent protein content of certain foods varied by as much as 20 to 40% depending on the calculation method; however, these differences tended to cancel out in the calculation of the protein content of mixed diets and the three methods differed by less than 3%. The authors concluded that a factor based on amino acid composition would provide a more reliable conversion factor for individual foods than one based on total nitrogen content.

Amino acids may contribute significantly to the energy value of diets composed of single sources of nutrients such as infant formulas, breast milk, or other liquid diets (Talbot, 1979). However, for most foods, the nonprotein nitrogen fraction is small and this is certainly true for most mixed diets. In assessing the overall effect on the estimated energy value of a food, the Atwater system compensates to a large extent by assigning any underestimate of the protein content to carbohydrate because carbohydrate is calculated by difference. Since both fractions are assigned similar physiological energy values, the error is small.

2. Metabolism of proteins

When deriving specific factors for the physiological energy value of proteins, a series of factors is combined, and some uncertainty exists in each. The protein content is estimated by nitrogen to protein conversion factors. Next, a heat of combustion is determined for an isolated protein fraction. As measured by Atwater, this value probably included the contribution of some residual lipids (Kinsella et al., 1975). A third factor, the digestibility coefficient, was determined by Atwater from the relative proportion of nitrogen excreted by individuals consuming single foods or simple diets rather than as a component of commonly ingested mixed diets. The energy content of components of excreta was based on proximate analyses assigning the gross energy values as determined for the fat, carbohydrate, and protein fractions of the food to the corresponding fraction of feces. Little error
resulted from the assumption that all energy in urine comes from products of incompletely oxidized protein (Levy et al., 1958). Separation of the nitrogenous components of urine including urea, uric acid, creatinine, and 3-methyl histidine is possible, but the relationship of these to dietary composition has not been extensively studied. The ad hoc group noted that each of the factors contributing to Atwater’s specific factors was derived from separate experiments, but any resultant error appears small, particularly when considering average mixed diets.

It has been recognized for some time that it is physiologically inaccurate to assume all energy-yielding nutrients and dietary combinations can be treated as equivalent by correcting their heats of combustion for fecal and urinary losses as is done in the Atwater system. Hill (1971) suggested considering ATP yields and associated metabolic costs as a potentially more functional frame of reference for measurement of physiological energy. Livesey (1984) has examined the heats of combustion and caloric equivalents of cytoplasmic ATP for a variety of food proteins and fats based on amino and fatty acid composition. Heats of combustion of food proteins and fats derived from compositional data were within 1% of published values obtained by calorimetry. He concluded, however, that knowledge of biochemical energy transduction is sufficient to permit only a crude estimate of the caloric equivalence of cytoplasmic ATP; this equivalent varies by less than 5% between both different food proteins and different food fats. Modification of the Atwater calorie conversion factors on this basis requires both an accurate quantification of the caloric equivalence of cytoplasmic ATP for glucose in vivo, and an indication that oxidative phosphorylation is similarly efficient in different individuals (Livesey, 1984).

Young (1981) has suggested assessment of the effect of various food protein sources on the utilization of energy-yielding substrates and other essential nutrients. The composition of the diet can have a large influence on the efficiency of total metabolizable energy utilization. The studies of Dauncey and Bingham (1983) suggest that the efficiency of total energy utilization for protein over glucose is about 12%. In experimental animals, the variation in efficiency with which ATP is produced and used for the maintenance of body protein may be as much as 25% (Reeds et al., 1980). This is in addition to the heat increment of maintenance which varies from a low value for the assimilation and storage of fat, to an intermediate value for carbohydrate, and to a much higher value for amino acids. The thermogenic response as affected by food intake, diet composition, and physiological condition remains a topic of intense investigation (Blaza and Garrow, 1983; Bogardus et al., 1981a, b; Dauncey and Bingham, 1983; Schutz et al., 1982; Webb and Abrams, 1983; Webb and Annis, 1983). Some members of the ad hoc group believe a reexamination of the basic assumptions currently held with respect to physiological energy transformations and utilization may disclose sources of variability significant to human nutritional assessment.
MacLean and Graham (1979) studied the effect of protein level in the diet of infants and found an increase in the efficiency of energy utilization as energy provided by protein increased from 4 to 6.7% of total energy intake. In human adults consuming 65 g of protein, the maintenance requirement was 15% lower than for those consuming 45 g of protein at isocaloric intake. Miller and Payne (1962) found pigs fed diets having 2 and 15% of calories from protein differed in the energy required to maintain weight; those on the low protein (deficient) diet consumed five times as many calories. Protein deficiency leads to a less efficient utilization of food energy in general (Campbell and Dimkin, 1983; Close et al., 1983). Thus, in addition to "charging" the cost of urea synthesis against the energy from protein, some consideration has been given to shifts in gluconeogenesis and protein turnover as a function of diet composition and level of energy intake (Elia and Livesey, 1983; Livesey and Lund, 1980). At high protein intakes, there may be a higher component of liver gluconeogenesis as opposed to transport of nitrogen from tissues to liver by an alanine cycle that predominates at lower protein intakes. The composition and amount of dietary protein are inter-related with the efficiency of utilization of energy (Bier et al., 1981; Curr et al., 1980; Rao et al., 1975). A low, but adequate, protein diet is more efficiently used than is a high protein diet.

A basic question relates to the inherent efficiency with which protein can be used as an energy source. A variety of proteins and diets could be studied in experimental animals. An animal having urinary composition similar to that of human should receive particular consideration. The digestibility coefficients also need to be measured in the target species; but, the energy value of protein can be measured in any of several experimental models, having similar urinary and fecal nitrogen-containing compounds, such as mice, rats, or pigs. The metabolic end products and the composition of the excreted endogenous products do not interfere with the question of comparable sparing of body energy for maintenance by carbohydrate and protein. The urinary elimination of 3-methyl histidine is different if it comes from exogenous or endogenous sources. For instance, the excretion of this compound is much higher on a meat diet than on a meat-free diet (Huszar et al., 1983). The rat excretes a different form and it excretes a greater quantity on the latter diet. The amount of creatinine excreted is also affected by a meat-free diet. Thus, the study of protein metabolism using an adult experimental animal during maintenance offers several advantages: the use of extremely high protein intakes; longer study periods; and, better control of experimental variables than is possible in the study of human subjects.

The ad hoc group discussed alternate means of measuring and expressing the energy contributed by the protein component of foods. Currently, energy is expressed in terms of nitrogen rather than carbon as might be done if energy calculations were based on
amino acids (Heidelbaugh et al., 1975; Schulz, 1975). The
accuracy with which amino acid analysis can be performed severely
restricts the utility of this method for many foods. The best that
is currently expected would be repeatability of between 5 and 10%
of an amino acid analytic value (Sarwar et al., 1983). A further
complication involves assumptions concerning the availability of
amino acids for absorption (Bodwell et al., 1980; Calloway and
Yates-Zezulka, 1980). The utility of this approach may be limited
to less processed foods to avoid problems introduced by practices
such as the addition of essential amino acids or reformulations
employing new sources of food proteins. In fact, the source of
protein for a particular food item is not always known and may be
changed (e.g., source or proportion) without consumers' knowledge.

D. 

EMPIRICAL RELATIONSHIPS OF GROSS AND METABOLIZABLE ENERGY

Recognizing the potential uses for a simplified method
for estimation of metabolizable energy, Bernstein et al. (1955)
suggested that deducting 8.42% of the bomb calorimeter values for
their diets gave a good estimate of metabolizable energy. When a
correction was made for nitrogen balance, the total caloric loss
in urine and feces was 9.15% of the ingested calories. This agrees
with the statement that urine plus feces contain between 8 and 9%
of the calories of the diet as determined by bomb calorimetry
(Atwater and Bryant, 1900).

Levy et al. (1958) proposed a system for estimating the
metabolizable energy value of diets from two measurements on a
dietary composite, (1) gross energy (GE) as measured by bomb
calorimetry and (2) total nitrogen of the diet. On the basis
of metabolic balance studies of human subjects consuming a variety
of diets having different protein and energy contents, an equation
was developed:

\[ \text{ME} = 0.976 \text{ GE} - 7.959 \text{ N(g)} - 59.3. \]

The mean metabolizable energy values derived by applying this
equation to 23 diets of widely different composition agreed within
1.8% of values determined using the bomb calorimeter balance tech-
nique. The metabolizable energy per gram of absorbed protein was
a function of protein source, but independent of the levels of
dietary protein intake over a wide range. The urinary calorie
content in the study of Levy et al. (1958) was predicted by the
equation, \( \text{UE} = 6.23 \text{ N_t} + 37 \), where \( \text{N_t} \) is the daily total urinary
nitrogen excretion. This relationship gives an increment of
6.28 kcal/g nitrogen or 1 kcal/g protein. A plot of Atwater's
original data gave similar results, \( \text{UE} = 6.22 \text{ kcal/gN} + 29.7 \text{ kcal} \).

Thus, the factor of 1.25 kcal/g protein as used by Atwater was
valid for a protein intake of about 100 g/d which is similar
to present day diets. Levy et al. (1958) pointed out that the
correction for urinary nitrogen is small in any case.
Miller and Payne (1959) proposed the following relationship for metabolizable and gross energy of human diets:

\[ \text{ME} = 0.95 \text{GE} - 7.5 \text{N}. \]

Southgate and Durnin (1970) and Macy (1942) have provided data for derivation of another empirical system for determining metabolizable energy of a mixed diet (Southgate, 1975):

\[ \text{ME} = 0.977 \text{GE} - 6.6 \text{N} - 4 \text{UC}, \]
where UC = unavailable carbohydrate.

The lack of assumptions in an empirically derived system has been attractive to a number of investigators who have proposed the above relationships. Inclusion of a term for unavailable carbohydrate, as proposed by Southgate (1975), offers the potential of accounting for the effects of dietary fiber in a variety of diets; however, many more studies are required to develop an appropriate empirical relationship between gross and metabolizable energy for widely different diets. It may be necessary to include additional variables. Compilation of gross energy values of individual foods, e.g., infant formulas (Barley and Brooke, 1976; Lemons et al., 1982), would be a useful component of any studies directed toward the empirical relationships of gross and metabolizable energy of diets.
V. ASSESSMENT OF THE ATWATER SYSTEM

Members of the ad hoc group suggested that assessment of the Atwater system be separated into two collections of issues. In the first section, issues are presented relating to estimation of energy intake including accuracy of the Atwater system per se and the use of food composition tables to estimate fat, carbohydrate, and protein intake and hence energy. These issues are most pertinent to the objectives of this report. In the second section, examples in addition to those discussed under protein metabolism (see pages 28-31) are presented of studies that relate to potential variance in energy metabolism and energy requirements among individuals. An understanding of such differences relates to the ultimate utility of the Atwater system for selecting foods to meet energy requirements. This latter group of issues is of current research interest and may take on added relevance should diet composition and diet history be shown to substantially influence energy metabolism (Garrow and Blaza, 1982).

1. Calculated and measured metabolizable energy value of foods

In the studies of Marshall and Judd (1982) and Olubajo et al. (1982), free living subjects were fed mixed diets composed of foods which were carefully selected to represent foods whose compositions were tabulated. Analysis of the gross energy content of diets by bomb calorimetry unexpectedly gave heat of combustion values that were the same as the metabolizable energy calculated from tabulated values of individual foods in Agriculture Handbook No. 8. This result raised a question of the representiveness of food tables for the foods currently available; however, tabulated values are not expected to match particular food items since average values are reported. Tabular values might not accurately predict the chemical composition for foods selected for particular studies. The source of the variance was not identified. Fat and protein for the diet composites were higher as calculated from the table values than as determined by analyses of the actual composites. The error was greater for low fat diets than high fat diets and was greater at high calorie levels for both low and high fat diets. Two high fat diets (43% of calories) and two low fat diets (25% of calories) having a P/S ratio of 0.3 or 1.0 at each fat level were fed in the study. Fiber, calculated as crude fiber, was 6 to 8 g/d for the high fat diets and 8 to 11 g/d for the low fat diets. Digestibility of fat (intake minus fat in feces) was 95.8 and 95.6% on high fat, and 94.4 and 93.8% on low fat diets; digestibility of protein (N x 6.25) was 91.3 and 90.2%, and 89.0 and 87.4%, respectively; digestibility of energy was 95.0 and 94.7%, and 94.5 and 93.6%, respectively, for the same diets (Olubajo et al., 1982).
In Webb's studies (unpublished), a diet composite contained 2300 kcal by bomb calorimetry (gross energy) and had a physiological energy value of 2113 kcal according to Agriculture Handbook No. 8. The predicted physiological energy value of this and other composites studied was about 92% of gross energy (i.e., ratio of table values to bomb calorimetry values). But by actual determination of energy losses in urine and feces, ME was only 90% of gross energy. The digestibility of today's diets may differ from those used by Atwater. Webb's values indicated a greater loss of energy in feces possibly due to induced changes in transit time, which may have reduced the digestibility.

Bernstein et al. (1955) compared the Atwater and bomb calorimeter balance methods for determining the metabolizable energy of a mixed diet in an extensive attempt to validate Atwater's original work. Eleven male subjects (one moderately obese) consumed three diets (rotated daily) for two consecutive 8-day balance periods. The chemical composition and bomb-calorimetry value of individual food items were determined. In all cases, carbohydrate was determined by difference. In the bomb balance method the gross energy value of the food eaten, feces, and urine were determined by bomb calorimetry. The metabolizable energy was calculated by subtracting the energy of the excreta from that of the food and making a correction for nitrogen balance of the subjects. The caloric content of the feces was measured by bomb calorimetry and also calculated from proximate analysis using Atwater's heat of combustion factors of 4.15, 9.40, and 5.65 kcal/g for carbohydrate, fat, and protein, respectively. Urinary nitrogen was assumed to have a calorie value as assigned by Rubner, 7.45 kcal/g urinary nitrogen. To minimize the effect of nitrogen balance, eventual excretion of retained nitrogen as urea, 5.62 kcal/g, was assumed.

The gross energy of ingested food expressed as the mean consumption of all subjects for 3 days as measured by the bomb calorimeter was compared by Bernstein et al. (1955) with comparable values calculated from proximate analysis and Atwater's heats of combustion for carbohydrate, fat, and protein of different food groups. The mean daily metabolizable energy by the bomb balance method was 3340 kcal, 3464 kcal by Atwater's general factors, 3417 kcal using specific Atwater factors, and 3681 kcal from metabolizable energy values for individual foods given in available food composition tables. There appeared to be an excellent correlation between the metabolizable energy as determined by the bomb calorimeter balance method and the metabolizable energy as determined by the Atwater general or specific factors. For the total diet there was little advantage in using the Atwater specific factors over the Atwater general factors. The sum of the metabolizable energy assigned to individual foods in food composition tables was 164 kcal higher than the estimate of metabolizable energy from the Atwater specific factors and approximately 340 kcal higher than the estimate of metabolizable energy from the bomb balance method.
Bernstein et al. (1955) discussed a series of factors that might have contributed to these discrepancies. For example, with the exception of two items of meat and poultry, gross energy values calculated from proximate composition using Atwater's heat of combustion values were generally significantly greater than bomb calorimetry values of the individual foods fed in this study. That Atwater's gross energy value for carbohydrate (by difference) was high and in error was argued by examining individual items in which very little fat or protein was present. In vegetables, even when the total caloric content as measured by bomb calorimetry was attributed only to the carbohydrate, the calories per gram of carbohydrate were less than Atwater's factor. The heat of combustion value for fat (8.388 ± 0.226 kcal/g) was more in line with values obtained by Atwater on extracted fats rather than pure fats. Analytical differences may have confounded the comparisons, e.g., mean fecal loss calculated by the Atwater system was 184 kcal as compared with 148 kcal measured by bomb calorimetry. Bernstein et al. (1955) concluded from comparisons of gross food energy, fecal and urinary energy loss, and metabolizable energy by the Atwater and bomb balance methods that the discrepancy between the two systems was in the gross energy values assigned to food by the Atwater system.

Southgate and Durnin (1970) designed a study specifically to test the applicability of Atwater's procedures for calculating metabolizable energy in diets composed of foods consumed in Britain at the time of the study. The plan involved four groups of subjects (54 young and elderly men and women) eating two diets in sequential study periods. Diet 1 was lower in dietary fiber (unavailable carbohydrate) than diet 2. One group of young women (10) consumed a third diet containing still larger amounts of fruits and vegetables. Total nitrogen, fat, various forms of carbohydrate, and the heats of combustion of the diet, urine, and feces were measured. Dietary carbohydrate content by direct analysis was similar to carbohydrate by difference. The dietary fiber provided by the foods was composed of cellulose and a mixture of heteropoly-saccharides consisting mainly of pentoses, xylose, and arabinose. Negligible amounts of pectic substances were present. Cellulose excretion was proportional to intake, which was 0.2-0.4%, 1%, and 1.5% of gross energy intake for the three diets, respectively. Pentosans represented 1% and 2-3% of the gross energy of diets 1 and 2, respectively; however, fecal excretion of pentosans was 8-10 times higher on diet 2. The greater apparent digestibility of pentosans in diet 1 was attributed by the investigators to qualitative differences between the pentosans contained in the diets. The apparent digestibility of the energy of the diets was lower for higher levels of dietary fiber. Increased fecal excretion of nitrogen and fat in addition to dietary fiber contributed to greater fecal energy losses.
A series of calorie conversion factors were developed by Southgate and Durnin (1970) using Atwater's procedures for the three diets studied. These conversion factors were close to Atwater's general factors of 4, 9, and 4 kcal/g for protein, fat, and carbohydrate (by direct analysis). The investigators concluded that for diets high in dietary fiber, the Atwater factors for fat and protein may overestimate the metabolizable energy derived from these components. For practical purposes, the Atwater factors for fat and protein were applicable to British diets; however, for several of the individual diets studied, the calculated gross energy intakes were between 4 and 5% lower than measured by bomb calorimetry. The study demonstrated that the accuracy with which the gross energy was predicted by the conversion factors determined the accuracy of the predicted metabolizable energy content of the diet. Southgate and Durnin (1970) concluded that efforts to improve accuracy should emphasize gross energy determinations rather than "digestibility" of food components.

2. **Energy requirements and efficiency of energy utilization**

The ability to assess the validity of a food energy system ultimately depends on the precision and accuracy with which energy metabolism can be studied by available methodology. The accuracy needed in any system for estimating the metabolizable energy value of foods can be assessed in terms of the intended applications and the variability of energy requirement within the populations of animals or humans of interest. These considerations are a valuable criteria for determining the accuracy that should be obtained by a food energy system and in assessing needed changes.

**Experimental animals.** Investigations with domestic and laboratory animals are useful in determining the precision that can be obtained in measurements of energy utilization (Moe, 1981). The most extensively studied models are livestock in which feed energy intake is measured and performance such as weight gain, milk production, or maintenance is predicted. In carefully controlled studies, the precision with which these predictions can be made for groups of animals is about ± 2% and for individual animals ± 5-6%. These results are obtained with animal breeds that represent genetically homogeneous populations, and better precision should not be expected from systems used to measure human energy metabolism.

One of the factors affecting efficiency of energy utilization is the basal metabolic rate (BMR). In general, higher BMR is associated with less efficient performance because within the thermal neutral zone the heat increment associated with a higher BMR is not needed to maintain body temperature (National Research Council, 1981). (A thermal neutral zone is that environmental
temperature range in which additional energy is not expended either to produce or dissipate heat. This zone is influenced by several factors, e.g., insulation and the inherent basal rate of heat production.) In animals, previous nutritional history has an influence on maintenance requirement for energy or BMR. However, in inbred experimental animals such as a strain of rats, the variance is much less than observed in production animals. Lactation, corrected for the energy cost of milk synthesis, increases BMR. Also, BMR changes with age, thyroid status, and other physiological factors. The use of animals to investigate species-independent questions of energy metabolism can reduce uncertainties associated with short observation periods and changes in body composition associated with observations on humans.

In growing animals, the caloric value of protein in feed is about 5.5 kcal/g of protein when the amino acids are retained in the body as added protein (i.e., growth) compared with 4 kcal/g of protein when the amino acids are used as an energy source. Retention of protein energy may be as high as 25% in very young human infants, decreasing to 5% at 1 year of age. In contrast, protein energy retained by a growing rat may amount to 150% of maintenance. Thus, while this is a source of error in the physiological fuel value systems when applied to growing infants, the magnitude of the error is not persuasive for changing the Atwater system. The difference between animals and humans needs to be considered, however, if energy values of foods determined from animal studies are being considered for measuring physiological energy values for applications to human foods (Karimzadeh et al., 1979).

**Humans.** Studies of energy metabolism in humans utilize a variety of techniques such as balance studies and experiments involving direct and indirect calorimetry measurements, the latter requiring analysis of the composition of inhaled and exhaled air. In general, the objective of such studies is to partition the gross energy of foods as measured by bomb calorimetry to various of the metabolic products or processes outlined in Figure 1 (see page 6). Assumptions are necessary concerning the representativeness of the sampling periods which are shorter than can be obtained using experimental animals. Urine and feces must be collected and this energy loss measured by bomb calorimetry. External work must be estimated and a correction made for energy storage in fat, protein, and glycogen. For example, estimates of changes in body fat may involve measurements of energy balance, nitrogen balance, body density, total body water, or total body potassium. Garrow (1982a, b) calculated that the standard deviation due to measurement error of body fat was about ± 3.5 kg for body potassium, ± 2.3 kg for water, and ± 2.2 kg for density in a study of obese subjects (97.55 ± 19.81 kg) having about 45 kg body fat. In addition to experimental and intrinsic errors of indirect methodologies for determining whole body composition, uncertainties in the "biological constants" (e.g., muscle potassium concentration) on which these methods are based mean that the accuracy of in vivo estimates of body composition is unknown (Lukaski et al., 1981).
Measurement of intraindividual variability in digestibility, energy retention, and basal metabolic rate (BMR) or resting metabolic rate (RMR) has been studied by feeding a standard diet for periods ranging from several days to several weeks. Through regimenting physical activity, some information has been obtained. For example, Calloway and Zanni (1980) reported the coefficient of variation in BMR of six individual subjects (aged 63 to 77 years) during a 7-day trial ranged from 3 to 9% while it was 12% for the group of six.

Resting metabolic rate or oxygen consumption as an indication of RMR varies greatly among persons of the same weight (Doré et al., 1982; Warwick et al., 1978). In one set of observations of obese women (80-85 kg) in standardized exercise protocols, the RMR ranged from 1500 to 2300 kcal/d (Durnin, 1983). In another study, young men and women were selected from a normal, sedentary population to have the same body weight (males, 70 ± 2 kg; females, 58 ± 2 kg) and body composition (males, 15 ± 2% body fat; females, 25 ± 2% body fat). Day to day RMR of the same individual showed little variation in these subjects. Variation in protein intake between subjects was about 12 to 16% of energy intake and total energy intake varied about 300 to 400 kcal. Basal metabolic rates or metabolic rate during walking at 3 mph on a treadmill showed a standard deviation of 15% of the mean. This suggests a range in RMR of 400 to 500 kcal/d among individuals with similar dietary habits and body compositions.

Webb et al. (1980) have studied the ability of direct and indirect calorimetry to measure 24-hour energy balance in a group of 13 experiments. Measurements differed by about 3% when subjects were sedentary, but this precision decreased to about 8-12% when subjects did not sleep at night or when long periods of work were performed. The amount of food consumed in comparison with energy expenditure "dramatically" affected measurements of energy balance. Undereating increased and overeating decreased energy expenditure. The authors question the ability of conventional theory and methodology to adequately account for energy balance in human subjects (Webb, 1981; Webb et al., 1980).

Webb and Annis (1983) overfed groups of four subjects on three different diets providing 1000 kcal/d in excess of maintenance for 30 days following a 30-day control period. A gain of 5 kg body weight was expected, but an average gain of 2.5 kg occurred. The first diet was selected as average for the U.S. population and contained 14% protein, 41% fat, and 45% carbohydrate. The second diet, a high fat, high protein diet, provided 30% of calories as carbohydrate; the third diet, a high carbohydrate diet, provided 60% of calories as carbohydrate. Increased heat loss averaged 7% during the overeating period for the three diets compared to control. There were small increases in the caloric content of urine and feces, but most of the excess energy was stored as increases in fat and lean tissue.
In a similar study of undereating by 1000 kcal/d below maintenance (Webb and Abrams, 1983), there was decreased 24-hour energy expenditure, the change averaging 12%. The diet contained 20% of energy as protein, 40% as fat, and 40% as carbohydrate. Crude fiber was 6 g/d, P/S ratio 0.4, and the carbohydrate component was 50% sugar and 50% starch. There were small decreases in the energy of urine and feces. Most of the extra energy needed for maintenance (which was reduced by 12%) came from fat stores. The availability of food energy on this diet was predicted to be 93.8% using Atwater's specific factors, but was actually only 86.2% during control and 83.3% during the undereating period. In both studies subjects were in positive nitrogen balance and there was a nearly constant loss of nitrogen in the urine. The percentage of loss of energy in urinary nitrogen during the undereating phase is higher, causing a decrease in the apparent availability. In the overeating study (Webb and Annis, 1983), the apparent availability increased, that is, energy lost in urine and feces increased, but in percentage terms, there was less undigested food compared to the control period.

Variability in the efficiency of food energy utilization within the human population can be predicted to be large considering genetic heterogeneity, physiological status, age, and other factors. Quantitation of this variability requires measurements of energy intake and expenditure. In the experience of the ad hoc group members, an error of about 5% exists in each of these measurements. They noted that control and measurements of activity level were particular problems in early studies of energy balance. Currently, researchers are finding novel ways of better quantifying physical activity of free-living subjects (Acheson et al., 1980a,b; Bouchard et al., 1983; Schoeller and van Santen, 1982) and subjects in respiratory chambers (Schutz et al., 1982).
VI. CONCLUSIONS AND RESEARCH NEEDS

A. CONCLUSIONS

The Atwater system is empirically sound and there is no evidence that indicates a substantial problem in applying it to the determination of the metabolizable energy value of foods and diets. It is known that the proteins, fats, and carbohydrates in different foods have different heats of combustion; however, how the presence of other components in the diet alters the individual apparent digestibilities of various foods is not known. The use of human subjects rather than animal models should be emphasized when attempting to validate metabolizable energy of food items, either individually or in various diets. Any program to increase the accuracy of energy values published in food composition tables should consider the value of such refinements, given the uncertainties in our knowledge of the energy requirements of the human population.

Large variance exists in the energy requirements of people with similar characteristics (weight, sex, age, etc.). The causes of this variance, as large as 15% even among persons of apparently identical physiological status, remain largely unidentified. The largest source of error in tailoring a diet to an individual's needs is the inability to predict energy requirements accurately. The Atwater system as currently used provides an estimate of food energy of mixed diets and many individual foods well within the variability from subject to subject, and although it may be improved in certain details, it does not need to be substantially modified. As a practical scheme, the Atwater system gives values that are within the limits of accuracy for (a) measuring food intake and (b) the predictive limits of food composition tables.

Summations of handbook values for metabolizable energy values of foods based on the Atwater system have in some studies failed to predict the same energy content for a mixed diet as that determined by bomb calorimetry balance studies. Contemporary data are inadequate to draw valid statistical inferences concerning possible systematic errors in the measurement of food energy values by the Atwater system.

Opportunities for improvements in the application of the Atwater system lie principally in improvement of food composition data. It is recognized that there is no practical alternative to listing average values for the composition of various food products. Composition may, however, vary greatly by variety, location, and season.
Although the use of nitrogen to protein conversion factors in calculating protein is a preferred method from the viewpoint of simplicity of application, it appears that these factors are not yet accurately known for many foods. Under the current system of determining carbohydrate by difference, any over- or underestimate of protein content will make little difference in the calculated energy value of the food since it will be compensated for in the carbohydrate fraction. However, counting nonprotein nitrogen as protein will generally lead to overestimates of energy values for protein. If a system of direct determination of the carbohydrate fraction is instituted, then reevaluation of factors in calculating protein should also be undertaken. The calorie to urinary nitrogen ratio is related to the amount of digestible protein in the diet; however, the Atwater factor as currently applied does not account for this variation and may lead to a significant error in this regard for low protein diets.

- Fat content of foods determined by ether extraction may be underestimated to the extent that ether fails to extract fat in phospholipid form and fat bound to protein. A solvent with more polarity than ether is needed for complete extraction and chloroform-methanol is increasingly used for this purpose. However, when more complete extraction is accomplished, Atwater's specific factors may require adjustment both for the lipid fraction and the residual lipid-free protein.

- The use of Atwater's general factors (4, 9, 4 kcal/g) in calculating food energy values of individual foods and formulated food products as is frequently done for labeling purposes can lead to substantial errors.

- Much research is currently focused on available carbohydrate in foods particularly as related to dietary fiber content and to the energy value of the fiber. Some members of the ad hoc study group believed that this issue was the most important one to address in improving calculation of the energy value of foods. Dietary fiber is included in carbohydrate by difference as presently determined in the Atwater system. The relatively low energy value of fiber as it occurs in certain foods is compensated, at least in part, by the digestibility factors assigned to these foods. Currently there is emphasis on increasing the dietary fiber content of diets and of various formulated food products. The dietary fiber content of natural and formulated foods, its digestibility and energy value, and its effect on the digestibility of other components of the diet should
be determined. It has been suggested that dietary fiber content of foods should be subtracted along with protein, fat, ash, and moisture from the total composition of the food in order to determine the level of available carbohydrates. Although this procedure may give reliable results for certain types of dietary fiber, e.g., crystalline cellulose, its general applicability may be questioned. In addition, some dietary fiber is apparently digested and could therefore be considered "available carbohydrate" in the broad sense. The ease and accuracy of measuring sugars and starches directly should be considered.

B. CONSIDERATIONS FOR FURTHER RESEARCH

The gross energy values of modern foods needs to be determined by bomb calorimetry and compared systematically to Atwater's values. Reformulations and changes in commercial processing practices may change the energy content of specific food products. Care should be taken to use proper sampling techniques of well described foods. Compositional data and energy values should be obtained on the same samples. A comparison of compositional values obtained previously to values obtained with newer methods of analysis will provide a useful "bridge" between older and newer methodology, e.g., methods of lipid extraction, should be carefully documented.

Some of the study participants suggested that development of an empirical scheme based on gross heat of combustion for predicting metabolizable energy should be investigated. A range of mixed diets of different composition studied in an appropriate number of subjects would provide data to derive a predictive method that does not have certain weaknesses associated with apparent digestibility of fats, proteins, and carbohydrates in the Atwater system.

It is not possible, with any degree of confidence, to say whether the Atwater system, as currently applied, has significant systematic errors. To distinguish among potential error sources such as under- or overestimating the energy value of foods in certain categories (e.g., nuts, fruits, and vegetables) versus overpredicting the energy value for some kinds of fat or carbohydrate, additional data are required on well-defined, representative foods of sufficiently varied composition to permit rigorous statistical analysis.

The varied applications of the food energy values and other information as currently provided in Agriculture Handbook No. 8 should be documented and evaluated. Continued examination of the applications for which these
figures are used would be desirable in order to develop the most effective method of presenting composition data to consumers and health professionals.

- The caloric values assigned to foods including those designed for special dietary purposes assume normal digestion processes. The need for, and the potential effects of, providing supplemental information to dietitians and physicians to assist in the appropriate application of assigned energy values should be assessed.

- The USDA's Nutrient Data Bank is a computerized system utilized for compiling information on the nutrient composition of foods. This information is made available on computer tapes and in Agriculture Handbook No. 8 and other publications. The need for and feasibility of an on-line, interactive, computerized data base on food composition containing appropriately updated, reviewed, and authenticated information including gross energy values, amino acid composition, and variability of all values should be assessed. Different data bases may be needed for food consumption surveys, food labeling, and menu planning; the data sets and the precision needed for these purposes differ.

- Methodologies for defining the amount of energy available from protein and the amount of true protein in foods with provisions to account for nonprotein nitrogen should be developed. Amide nitrogen methodology should be refined. Specific nitrogen to protein conversion factors are needed for more proteins, particularly those in fruits and vegetables. Systems that determine the protein content of foods on the basis of nitrogen require corrections for nonprotein nitrogen.

- In carefully conducted investigations of food energy and energy metabolism, the gross energy value of foods and wastes is determined by bomb calorimetry (heat of combustion). Bomb calorimeters are not commonly used in nutrition and clinical investigations. Food energy tables cannot be expected to provide data of sufficient accuracy to meet many research needs. Methodology that permits routine direct determination of total energy or gross energy of foods would be useful.

- There is a need for data that indicate the reliability of the energy values in handbook tabulations. Inclusion of a measurement or estimation of statistical variance for handbook entries would be desirable.

- A limited number of foods have been analyzed for energy content by both the U.K. system (direct analysis for starch, dextrins, and utilisable sugars) and the Atwater
system (carbohydrate by difference). There needs to be careful metabolic studies to compare the relative merits. However, for energetic purposes the differences would be measurable only at high dietary fiber intakes. A careful study comparing the U.K. and the Atwater systems would demonstrate whether either system offers significant advantages in terms of potential applications.

An analysis of the relative benefits of determining carbohydrate by difference versus analyzing for specific carbohydrates can be targeted by careful selection of the particular foods selected for comparison. Fruits, vegetables, and nuts have been less studied than other food categories.

The Atwater system may incorrectly evaluate the caloric value of certain foods high in dietary fiber, such as cereal products. There is a need to measure digestibilities for some cereal products, e.g., corn bran, oat bran, barley, and rye. Experimental data are lacking on the effects of dietary fiber on the utilization of energy from other diet components.

Energy values currently listed in handbooks should be re-examined after development and validation of methodology for measuring total dietary fiber including soluble dietary fiber. Dietary fiber contents should be included among nutrient composition data.

The influence of mixed diets on efficiency of food energy utilization should be studied with modern diets containing a range of complex carbohydrates. For example, the applicability of handbook data for high fiber diets that are similar to diets of less developed countries should be assessed. Digestibility of dietary fiber and the availability of energy may be important for low energy, high fiber diets; this problem needs to be addressed more critically through direct human metabolic study. Further analyses of excretory and secretory products with respect to different food intake patterns and energy sources would be useful.

There is a need for research directed at identification and characterization of factors which affect fasting heat production and energy requirements. Current equipment for direct and indirect calorimetry is excellent. Both animal and human work are appropriate. Included should be studies of the efficiency with which biochemical energy, e.g., ATP is utilized for such processes as urea synthesis, protein synthesis, mechanical work, etc.
VII. LITERATURE CITED


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VIII. STUDY PARTICIPANTS

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