Energy values of unavailable carbohydrate and diets: an inquiry and analysis¹,²

Geoffrey Livesey

ABSTRACT To determine digestible-energy values (DEVs) for unavailable carbohydrate (UC), an analysis was made of published data on 29 human diets with UC from several sources and intakes ranging from 4 to 93 g/d. A distinction was made between apparent DEVs, derived from UC intake and fecal loss, and partial DEVs, derived from energy intake and fecal loss. By use of a proposed calculation, partial DEVs ranged from −20 to +10 kJ/g (−4.8 to +2.4 kcal/g) in different diets; all values were below the corresponding apparent DEVs. Factors explaining this range, including analytical problems, are considered. Rather than finding discrepancies, both the partial DEVs and the energy available from the whole diet were found to be related to the apparent digestibility of UC (r = 0.88), the proportion of the diet estimated as UC (r = 0.73), and both combined (r = 0.98). Several food-energy evaluation systems are also assessed for accuracy and the implications of these observations for food-energy evaluation are discussed. Am J Clin Nutr 1990;51:617–37.

KEY WORDS Metabolizable energy, digestible energy, food-energy values, dietary fiber, unavailable carbohydrate, fecal energy, nonstarch polysaccharides, resistant starch, complex carbohydrates

Introduction

With the rise in the consumption of carbohydrates that resist digestion in the small intestine (unavailable carbohydrate, dietary fiber including any starch that resists enzymatic degradation during fiber analysis) and products free of these carbohydrates, such as enteral and parenteral feeds used in hospitals, there is renewed attention to procedures for calculating the quantities of available energy in the human diet and, with this, the contribution from unavailable carbohydrates (1–6). The current trend for individuals and groups of individuals to eat diets containing more unavailable carbohydrate appears to have arisen from their suggested benefits to health (7–11). Their putative efficacy as an aid to slimming (12) and as a possible adjunct to the clinical management of obesity (9, 13–17), whether effective or not, has also focused attention on this component of the diet. Particular needs for information in this area are from nutritionists attempting to assess the probable validity of low-calorie claims about certain foods and ingredients containing combustible “low-calorie” materials, especially unavailable carbohydrates; from manufacturers attempting to design foods of low-calorie value; from governing bodies who ascribe energy values (calorie conversion factors) for the purpose of food labeling; from those relating food-energy values to energy requirements (18), particularly where the intake of unavailable carbohydrate is much higher than it is in Western populations; from those who seek to design and interpret nitrogen-balance studies in relation to protein requirements, particularly in field studies of natives consuming traditional diets (19); and from those who attempt to compare equicaloric diets with different amounts or types of unavailable carbohydrate.

There are divergent claims about the calorie conversion factor appropriate for the unavailable carbohydrates. For example, the now classic paper of Southgate and Durnin (20) seemed to indicate that unavailable carbohydrates contribute no energy value to the human diet whereas a value > 10 kJ/g (2.4 kcal/g) was suggested by Göransson et al (4) and by Göransson and Forsum (5). An appraisal of both this difference and of experimental data from other studies (3, 21, 22) is made difficult because authors use different calculation procedures to assess their experimental data. It is not immediately clear, therefore, whether the differences are related to dietary attributes or whether they are artefacts arising from either the difficulty of performing accurate energy-balance experiments in humans (2, 23) or the inappropriate choice of the procedure used to analyze the data (24).

A source of difficulty when addressing the topic of calorie values for unavailable carbohydrates arises from the popular misconception that a caloric value of zero for dietary fiber or unavailable carbohydrate, for example, in the British system of food-energy assessment (20, 25), is a consequence of the ingested unavailable carbohydrate being wholly or mostly lost to the feces. The source of this misconception is difficult to trace in the literature. It could arise as the simplest interpretation of a zero energy value by those who have no knowledge about how the zero energy value for unavailable carbohydrate was arrived at. In more formal terms this misconception states “the apparent digestibility of unavailable carbohydrate is close to zero.” Apparent digestibility is the balance between the intake of unavailable carbohydrate and its loss to feces when the balance is expressed as a fraction of unavailable carbohydrate in-
take. However, unavailable carbohydrate in mixed diets fed to humans usually has an apparent digestibility > 0.5 (20) and therefore must have an apparent digestible-energy value greater than half of the heat of combustion of unavailable carbohydrate (17.2 kJ/g, or 4.1 kcal/g), that is, > 9 kJ/g (> 2 kcal/g).

A scientific rationale for accepting a zero caloric value for unavailable carbohydrate was provided by Southgate and Durnin (20). These authors recognized that the apparent digestibility of unavailable carbohydrate in human diets was > 0.5. However, they also showed that the energy obtained from unavailable carbohydrate by humans (including colonic microorganisms) was approximately equally balanced by additional losses of energy to feces in the form of fat and protein (6.25 × nitrogen), which arose from an increased intake of the unavailable carbohydrate. According to this scientific rationale, the zero caloric value for unavailable carbohydrate is not an apparent-digestible-energy value but fits the concept of partial digestibility, as described for dietary supplements by Kleiber (26). Most simply, the difference in apparently digested energy provided by two diets equal in gross energy from sources other than unavailable carbohydrate, all divided by the difference in unavailable carbohydrate intake, in units of energy, is called (rather ineluctably) "partial digestibility of energy for unavailable carbohydrate." Also, the difference in apparently digested energy provided by these two diets divided by the differences in weight of unavailable carbohydrate intake is called the "partial digestible-energy value" of the unavailable carbohydrate.

Differences between apparent digestibilities and partial digestibilities arise from what is sometimes called the "associative effect" (27). Increased unavailable carbohydrate intake is often associated with effects on the losses of protein and fat to feces. As Southgate and Durnin (20) found, this effect, in units of energy, can be as large as the energy available from the unavailable carbohydrate alone, that is, its apparent-digestible-energy value. Because the associative effect can be large it is important to distinguish between partial and apparent digestibilities and energy values. Often the term apparent is used when partial would be correct; this is usually when the associative effects are thought to be small so that the difference between partial and apparent values is small, as is often the case with nutrients that are almost completely absorbed. However, with unavailable carbohydrate, its fermentation is likely to lead to additional losses of bacteria in feces so that the energy in these bacteria, when eliminated, becomes part of the associative effect.

Apart from the problems of identifying the caloric or values of unavailable carbohydrate, there is concern (2, 28) that the current methods (29) for calculating the energy value of whole diets based on analysis of foods for protein, fat, and carbohydrate do not adequately account for the presence of unavailable carbohydrate, especially when intakes of the last are high. Several different "improved methods" have been proposed (3, 30, 31) but they have not been tested on a wide range of diets. Further concern exists about the accuracy of various methods used to analyze food and diets for unavailable carbohydrate. Without a proper analysis of energy-balance data, the consequence of using different analytical methods for unavailable carbohydrate on the assessment of energy values of both the unavailable carbohydrate and the whole diet cannot be determined.

This paper has several objectives. It suggests a calculation procedure for obtaining partial-digestible-energy values for unavailable carbohydrate that can be used with data on gross energy intake and fecal energy loss. The procedure is then used to reevaluate published information both where energy values for unavailable carbohydrate were reported (4, 5, 20) and where no such values were reported (21, 22, 28, 32–34). Hence, partial-digestible-energy values for unavailable carbohydrate for all these studies are provided herein by use of a common calculation procedure. These partial-digestible-energy values are then compared with calculated apparent-digestible-energy values for unavailable carbohydrates. Further, to help clarify confusion arising from the proposal of several different methods for the assessment of energy available from foods (3, 20, 30, 31, 35, 36) and to help validate some observations presented here, the accuracy of these methods for diets containing low to high amounts of unavailable carbohydrate is considered. Both the accuracy of the dietary-energy-balance method and the consequence of using certain methods (to be defined) for determining unavailable carbohydrates in foods are considered in relation to energy value. Finally, some implications of the present observations for users of food-energy assessment systems are discussed.

This paper is accompanied by an appendix that describes and discusses in detail the calculation of partial-digestible-energy and metabolizable-energy values.

Data on dietary intakes and apparent digestibilities

To undertake this inquiry and analysis, information was needed both on the intake by adult subjects of unavailable carbohydrate, gross energy, nitrogen, fat, and available carbohydrate and on the apparent digestibilities of each of these dietary components. This information was obtained from the literature (4, 5, 20–22, 28, 32–34) and is given in Table 1.

The literature sources did not always report the necessary information in a form appropriate for inclusion in Table 1. For example, Southgate and Durnin (20) provided the information for diets 1–9 in Table 1 but they did not report for each diet a single value for unavailable carbohydrate nor for its apparent digestibility. These had to be calculated from Southgate and Durnin’s (20) reported values for the intake and fecal losses of cellulose and pentosans. All values in Table 1 that were calculated from other reported information carry a superscript letter that refers to the footnote in Table 1 where the method of calculation is given. Not all values in Table 1 carrying a superscript letter had to be calculated. Because precise values for unavailable carbohydrates determined in diets are method dependent, a second purpose for giving a superscript is to indicate the reported method of unavailable carbohydrate determination.

For example, Göranzon et al (4) provided information in Table 1 for diets 10 and 11. These authors reported values for unavailable carbohydrate intake in a form appropriate for inclusion in Table 1. The superscript then refers to the footnote that both acknowledges this fact and indicates the method of determination of the unavailable carbohydrate—in this instance, the rapid method of Asp (38). A third reason for values having a superscript applies only to the available carbohydrates, where the footnote gives the reported method of expressing the weight of available carbohydrate ingested, ie, expressed as the equivalent weight of monosaccharide (where 1 g starch is equivalent...
TABLE 1  Published and calculated dietary intakes and apparent digestibilities*

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<th>Diet</th>
<th>Intake</th>
<th>Digestibility</th>
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<th>Fat</th>
<th>Available carbohydrate† intake</th>
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* Intakes and digestibilities determined or estimated by the following methods: ¹ Calculated from the sum of the published values (20) for intakes of cellulose (including lignin) and pentosans; each was analyzed by the method of Southgate (37). ² Published values (4) analyzed by the rapid method of Asp et al (38). ³ Published values (22) analyzed by a modification (39) of Van Soest's neutral-detergent fiber method (40). ⁴ Published values (28, 33) analyzed by a neutral-detergent fiber method (41). ⁵ Published values (21) analyzed by the method of Meuser et al (42). ⁶ Published values (32) were based on The Composition of Foods (25), which employed the Southgate analytical method (37). ⁷ Published values (5) analyzed by the method of Theander and Westerlund (43). ⁸ Published values (34) analyzed by the enzymatic gravimetric method of Prosby et al (44).

¹ Values were calculated as 1 – (A/B) in which A is the sum of published values (20) for pentosans and cellulose (plus lignin) in feces and B is the sum of published values for these constituents in the foods. ² Values were calculated, assuming no loss of available carbohydrate to the feces, as 1 – (A/B) in which A and B are the published values (4) for carbohydrate in feces and unavailable carbohydrate in food, respectively. ³ Values were calculated from published values (22) for fecal energy and apparent digestibility of dietary gross energy. ⁴ Values were calculated from reported metabolizable energy values (28) by use of the formula employed by the reporting authors (28) to calculate metabolizable energy from their experimental data: metabolizable energy (kcal) = gross energy – fecal energy – 6.28 × (diet N – fecal N) and by use of reported values for fecal energy, dietary nitrogen, and fecal nitrogen. ⁵ Values were calculated from reported metabolizable energy values (32) by use of the formula employed by the reporting authors (32) to calculate metabolizable energy from their experimental data: metabolizable energy intake (kcal) = gross energy intake × apparent digestibility of dietary gross energy – 7.8N and by use of the reported values for apparent digestibility of dietary gross energy and nitrogen intake. ⁶ Values were calculated from the published values (28) for digestive energy intake and the calculated (see footnote 1) values for gross energy intake. ⁷ Values for apparent digestibility of dietary gross energy not given. Values for metabolizability calculated from reported values (5) for gross energy intake and metabolizable energy intake were of use and were 0.864 and 0.901 for diets 24 and 25, respectively. ⁸ Calculated from published digestible energy intake and fecal energy loss (34). ⁹ Values were calculated as 1 – (A/B) in which A and B are published values (28) for fecal and dietary N, respectively. ¹⁰ Values were calculated as the product of the published values (28) for the designed fat content of the diet (g/kg body wt) and the mean body weights of the subjects. ¹¹ Values were calculated as 1 – (A/B) in which A and B are published values (28) for fecal fats and the calculated (see footnote r) values for fat intakes, respectively. ¹² Values are for the sum of published values (20) for sugars and starch expressed as the equivalent weight of monosaccharide. ¹³ Published values (4, 22) expressed as carbohydrate by difference excluding unavailable carbohydrate. ¹⁴ Values were calculated as the difference between gross energy intake and the sum of the energy in protein [6.25 × published N intake × 23.6 kcal (5.65 kcal/g protein)], fat [published intake × 39.5 kcal (9.4 kcal/g fat)], and unavailable carbohydrate (UC) [published intake of UC × 17.2 kcal (4.1 kcal/g UC)] and expressed as mixed carbohydrate assuming an energy value of 16.7 kcal (4 kcal/g). All published intakes in this footnote are from reference 28. ¹⁵ Apparent digestibility of available carbohydrate (starch and sugars) is taken to be 100%.
to 1.1 g glucose) or expressed as carbohydrate by difference excluding unavailable carbohydrate.

Calculations on partial-digestible-energy values and partial indigestibilities will be described immediately before their use. They required that groups of subjects ingest two diets: one of low or lower unavailable carbohydrate intake and one of high or higher unavailable carbohydrate intake. For a few of the diets in Table 1 (diets 20, 21, 24, and 25) of high or higher-than-usual intake of unavailable carbohydrate, there was no corresponding information for a diet of low intake of unavailable carbohydrate. Useful data could be calculated from this limited information only by making certain assumptions about the apparent digestibility of gross energy in diets without unavailable carbohydrate; these assumptions will be described and justified as the need arises.

Diets with high and low amounts of unavailable carbohydrate

The kinds of diets low in unavailable carbohydrate were as follows: low in fruit and vegetables except potato, diets 1, 3, 6, and 8; low in fruit and vegetables except potato and low in cereal except polished rice, diet 10; low in fruit and vegetables, diet 12; low in fruit, vegetables, and cereals, diet 14, an egg-formula diet; low in high-fiber cereal foods, diet 18; low in fruit and vegetables and no cereal or nuts, diet 22; a mixed diet with fruit, vegetables, and cereals but no bran or other supplement of unavailable carbohydrate, diet 26.

The kind of diets with high or higher content of unavailable carbohydrate were obtained by including foods high in unavailable carbohydrate from mixed sources (diets 2, 4, 7, 9, 11, and 13), mostly from fruit and vegetables (diets 5, 23, and 25), and mostly from cereals (diets 19–21 and 24). Diet 20 is a cereal-based diet with unavailable carbohydrate predominantly from barley kibbling (broken dehusked grain) and barley flour. Diets 15 and 16 are egg-formula diets with added oat bran or toasted oat bran. Diets 27–29 are mixed diets (like diet 26) with added wheat bran or psyllium gum or both, respectively. Further details of all these diets are given in the references cited in Table 1. However, quantitative information on the intakes of each food item are seldom given; exceptions are for diets 12–17, 21, 39, and 41.

Publications not included in Table 1 and subsequent analysis were either unknown to the author at the time the analysis began, provided too little information, or had fewer than five subjects per diet fed.

Observations on the apparent digestibility of dietary gross energy and the meaning of partial indigestibility

Figure 1 shows the effects of increasing the proportion of dietary gross energy intake from unavailable carbohydrate on the apparent digestibility of dietary gross energy. As this proportion increases the apparent digestibility of dietary gross energy decreases. The magnitude of this decrease differs among experiments. By contrast, extrapolation to zero intake of unavailable carbohydrate shows that all experiments predict similar values for diets free of unavailable carbohydrate [0.978 ± 0.007 (x ± SD); range 0.972–0.993; n = 13].

A formal description of Figure 1 is needed to facilitate an objective analysis of the observations it illustrates and to describe the meaning of partial indigestibility of energy for unavailable carbohydrate. Each curve in Figure 1, if assumed to be linear, is described by equation 1:

\[ \frac{DE}{E} = 0.978 - 17.2I^{UC}\frac{S}{E} \]  

(1)

where \( E \) is gross energy intake from the whole diet (kJ), \( DE \) is the apparently digested-energy intake from the whole diet (kJ), \( DE/E \) is the apparent digestibility of dietary gross energy (kJ/kJ; y-axis in Fig 1), 0.978 is the average apparent digestibility of dietary gross energy when there is no unavailable carbohydrate in the diet (kJ/kJ; intercept on y-axis in Fig 1), 17.2 is the heat of combustion of unavailable carbohydrate in kJ/g (equivalent to 4.1 kcal/g), \( I^{UC} \) is the intake of unavailable carbohydrate (g), and \( S \) is the absolute, or downward, slope of a line in Figure 1.

Equation 1 is made more convenient as a predictor of apparent digestible energy available from the whole diet after multiplication of each term by \( E \) to give equation 2:

\[ DE (kJ) = 0.978E - 17.2I^{UC}\frac{S}{E} \]  

(2)

Equation 2 is a simple formal description of the observations.
in Figure 1; however, the meaning of the term $S$ is difficult to conceive and is explained below together with other terms: $0.978E$ is the apparent digestible energy when no unavailable carbohydrate is present in the diet. When unavailable carbohydrate is present, the term $E$ is increased by an amount equal to the gross energy in the unavailable carbohydrate. With more unavailable carbohydrate being ingested, there are also additional losses of energy to feces, which need to be deducted (hence, the minus terms in Eqs 1 and 2). The additional losses of energy to feces (below abbreviated to $\Delta FE$) is given by the whole term $17.2I^E \alpha$ in equations 1 and 2 according to equation 3.

$$\Delta FE = 17.2I^E \alpha$$  \hspace{1cm} (3)

Equation 3 rearranges to give equation 4, which describes the term $S$:

$$S = \Delta FE / 17.2I^E$$  \hspace{1cm} (4)

Equation 4 shows that the absolute value of the slope ($S$) in Figure 1 is equal to the additional loss of energy to feces that results from an increase in the intake of unavailable carbohydrate when the latter is expressed in kilojoules; equation 4 also defines partial indigestibility of energy for unavailable carbohydrate.

$S$, in equation 4, may be regarded simply as an operational term. Alternatively, it is readily envisaged that changes in fecal energy when more unavailable carbohydrate is ingested, may arise from additional losses of protein and fat besides unfermented unavailable carbohydrate. Indeed, the value of $S$ can be estimated from the sum of the losses of these components (see Appendix, Eqs 13–16 and associated text for details). Precise values for the slopes, $S$, in Figure 1 are given in Table 2 and range between 0.3 and 2.2. The meaning of the value of $S$ can be remembered as easily as remembering 1, 2, 3. When $S$ equals 1, additional energy lost to feces is equal to one times the gross energy in the additional unavailable carbohydrate ingested; when $S$ equals 2, additional energy lost to feces is two times the gross energy in the additional unavailable carbohydrate ingested; when $S$ equals 3, it is three times; and so on. When $S$ equals 0, there is no additional loss of energy to feces when additional unavailable carbohydrate is ingested.

Now equation 2 provides a formal description of the apparent digestible energy in the whole diet, which is of use in a subsequent section. Note that, in addition to the definition of partial indigestibility of energy for unavailable carbohydrate as defined by equation 4, equations 1 and 2 show how the apparent digestibility of dietary gross energy and digestible energy values of the whole diet, respectively, are related to the value $S$, the partial indigestibility of energy for unavailable carbohydrate. The causes of the variation in the apparent digestible energy of the whole diet can be determined by asking what factors modify the slopes of the curves in Fig 1, $S$ in equations 1–4. There is no doubt that some of the different slopes arise from inaccurate measurements of unavailable carbohydrate in the various diets but other possible factors also need to be assessed.

**Relationships among the apparent digestibility of unavailable carbohydrate, its intake, and its partial indigestibility for energy**

The relationship between the downward slope of the plots in Figure 1, or partial indigestibility of energy for unavailable carbohydrate ($S$ calculated precisely by Eq 3 in the Appendix), the apparent digestibility of the unavailable carbohydrate (taken from Table 1 and called $\alpha$), and the proportion of gross energy intake attributable to unavailable carbohydrate (calculated from Table 1 and called $\beta$) were examined by linear-regression analysis.

Best fits between these variables ($S$, $\alpha$, and $\beta$ collected together in Table 2) were obtained after first transforming $S$ to its reciprocal, $1/S$, which was found to be related ($r = 0.88; p < 0.001; n = 10$) to the apparent digestibility of unavailable carbohydrate ($\alpha$) according to equation 5, as shown in Figure 2.

$$1/S = 4.46\alpha - 1.77$$  \hspace{1cm} (5)

In equation 5 the value of $S$ was calculated from the balance of energy intake and fecal-energy loss (see Appendix, Eq 3) but can also be estimated from the increased loss of protein, fat,
and unfermented unavailable carbohydrate in feces, which results from more unavailable carbohydrate in the diet (Appendix, Eqs 13–16). This estimate is called $S'$; the prime distinguishes it from the $S$ calculated from the dietary-energy-balance data. Interestingly, $1/S'$ also shows a relationship ($r = 0.845; p < 0.01; n = 17$) with the apparent digestibility of unavailable carbohydrate ($\alpha$), as shown in Figure 2. The equation describing the relationship

$$
1/S' = 4.22\alpha - 1.35
$$

(6)
is similar to that obtained with the data on the balance of energy intake and fecal loss (Eq 5). This similarity lends confidence to the assertion that, in general, the measurements on energy intake and fecal loss are free from analytical errors that significantly affect the relationships obtained in equation 5. Note, however, that equations 5 and 6 make similar assumptions about the estimates of unavailable carbohydrate intake, so that errors from this source are not excluded by the similarity of these equations (ie, of Eqs 5 and 6).

A relationship ($r = 0.73; p < 0.001; n = 16$) was also observed between the reciprocal of partial indigestibility ($1/S$) and the calculated proportion of the dietary gross energy due to unavailable carbohydrate ($\beta$), according to equation 7:

$$
1/S = 11\beta + 0.38
$$

(7)

Multiple regression indicates that partial indigestibility ($S$) is more highly correlated ($r = 0.98; p < 0.001; n = 10$) with $\alpha$ and $\beta$ as the independent variables in a single equation (Eq 8):

$$
1/S = 2.6\alpha + 6.2\beta - 0.96
$$

(8)

An important question is whether errors in the determination of unavailable carbohydrate alone explain the different slopes in Figure 1 and the coefficients for $\beta$ in equations 7 and 8. It is obvious that variance in $1/S$ (Eqs 7 and 8) may be related to variance in $\beta$ for two reasons: 1) if $S$ is truly dependent on the amount of unavailable carbohydrate in the diet and 2) if $S$ varies because of errors in the determination of unavailable carbohydrate. For example, if $\beta$ is overestimated because of some error in the unavailable carbohydrate analysis, say by a factor of 2, then the calculated value of the slope, $S$, in Figure 1 will be a half of the true value. That is, there is a natural reciprocal relationship, with $1/S$ being directly proportional to $\beta$. The coefficient of proportionality is unity, ie, when $\beta$ doubles because of an error, the calculated $1/S$ doubles also. But the actual coefficient of proportionality is very nearly given by the regression coefficient in equation 7 and is an order of magnitude higher, 11 not 1. This indicates that errors in the determination of unavailable carbohydrate do not alone explain the different values of $S$ in Figure 1 and Table 2, nor the dependence of $S$ on $\beta$. The observations (Eqs 1–8), therefore, appear to give underlying trends, which closely relate the variability in the digestion of gross energy in the whole diet to the measured occurrence ($\beta$, Fig 1) and utilization ($\alpha$, Fig 2) of unavailable carbohydrate in diets 1–17 (Table 1) and indicate a major and precise role for unavailable carbohydrates in modifying apparent digestibility of gross energy of the whole diet.

The next problem is to assess whether this conclusion applies to digestive energy in the whole diet as well as to the apparent digestibility of dietary gross energy. A decrease in the apparent digestibility of dietary gross energy, $DE/E$, is expected to occur because of additional gross energy intake from unavailable carbohydrate, which adds to $E$, even if this additional gross energy is unused so that $DE$ remains unchanged; this decrease is a simple dilution effect on $DE$. It is important to recognize that such a circumstance would cause a downward slope in Figure 1 equal to 1 (ie, $S$ would equal 1 only). Further, it needs to be recognized that the high correlation coefficients for equations 5, 6, and 7 and the especially high correlation for equation 8 arise independent of this dilution effect. Indeed, variation in the slope of plots such as those in Figure 1, where $DE/E$ is plotted against $\beta$ (which is $E^{uc}/E$) is not decreased by removing the influence of $E^{uc}$, the gross energy from unavailable carbohydrate, from the denominator $E$. Thus, plots of $DE/(E - E^{uc})$ against $E^{uc}/(E - E^{uc})$ (not shown) give a slope of 1, which has a variance equal to the variance for $S$. Proof of this is given in the Appendix. Moreover, the range of values for $DE/E$ for diets 1–17 (Table 1) is $0.82–0.97$ (difference 0.15), whereas the range for $DE/(E - E^{uc})$ is $0.89–1.05$ (difference 0.16). That is, the range is not lessened by removing the influence of $E^{uc}$ from $E$. Therefore, it is concluded that unavailable carbohydrate is the major dietary factor influencing digestible energy in the whole diet, as well as being the major factor influencing the digestibility of dietary gross energy. To this author’s knowledge, there has not been any previous formal treatment of experimental observations that have drawn this conclusion.
FOOD ENERGY AND UNAVAILABLE CARBOHYDRATE

Apparent- and partial-digestible-energy values for unavailable carbohydrate: calculations and general observations

The energy value of unavailable carbohydrate can be expressed in two ways. First, it can be expressed as an apparent digestible-energy value, $DE_{\text{app}}$, obtained from the product of its heat of combustion (17.2 kJ, or 4.1 kcal/g) and its apparent digestibility ($\alpha$) (Eq 9). Second, it can be expressed as a partial-digestible-energy value, $DE_{\text{par}}$, obtained as the product of its heat of combustion and its partial digestibility for energy ($1 - S$) (Eq 10):

$$DE_{\text{app}}^{UC} (\text{kJ/g}) = 17.2\alpha$$

$$DE_{\text{par}}^{UC} (\text{kJ/g}) = 17.2(1 - S)$$

In equation 10, $1 - S$ gives the partial digestibility of energy for unavailable carbohydrate. This is because the sum of partial digestibility and partial indigestibility ($S$) is always equal to 1 (just as the sum of apparent digestibility and apparent indigestibility is always equal to 1). In equation 9 $\alpha$ is not the same as $1 - S$ in equation 10 because $S$ includes losses to feces of protein and fat that occur as a consequence of ingestion of unavailable carbohydrate. Such losses will arise from the conversion of unavailable carbohydrate that reaches the colon into bacterial matter, which is mostly protein and fat but could also arise from other sources. The algebraic relationship between $\alpha$ and $1 - S$ is given in detail in the Appendix (Eqs 13–16 and associated text).

For the diets in Table 1 of high or higher unavailable carbohydrate intake, apparent-digestible-energy values of unavailable carbohydrate were calculated with equation 9, and partial-digestible-energy values for unavailable carbohydrate were calculated with equation 10, in which the term $S$, the slope in Figure 1, was calculated precisely by equation (Eq 3 in the Appendix).

That apparent-digestible-energy values differ from partial-digestible-energy values for unavailable carbohydrate is well illustrated in Figures 3 and 4. These show how the two energy values appear to change in relation to the apparent digestibility of the unavailable carbohydrate ($\alpha$, Fig 3) and changes in the intake of unavailable carbohydrate ($\beta$, Fig 4). Some partial-digestible-energy values are negative. It might be thought that these negative values could arise because energy is lost to feces even when there is no unavailable carbohydrate in the diet, but this is not a cause of the negative values in Figures 3 and 4 because such losses are accounted for in the calculation procedure. Had this not been accounted for, some partial-digestible-energy values would have been calculated incorrectly to be as low as $-35$ kJ/g (−8.4 kcal/g) of unavailable carbohydrate.

All the partial-digestible-energy values for unavailable carbohydrate are less than the apparent-digestible-energy values (Figs 3 and 4). This is explained by the additional loss of fat and protein to feces, which results from the intake of unavailable carbohydrate.

In Figure 3 both the apparent- and partial-digestible-energy values for unavailable carbohydrate decrease as the apparent digestibility of the unavailable carbohydrate decreases. However, the partial-digestible-energy value decreases more rapidly to become negative (Fig 3). This is when the losses of energy to feces, as unfermented unavailable carbohydrate, and the additional losses of fat and protein are greater in absolute energy terms than the gross energy content of the unavailable carbohy-

FIG 3. Relationship between the apparent- and partial-digestible-energy values for unavailable carbohydrate (UC) and the apparent digestibility of UC. The apparent- and partial-digestible-energy values of unavailable carbohydrate are shown with curves described by equation 9 (○) and by equations 8 and 10 together (○). Data are calculated from the experiments reported by Southgate and Durnin (20), Góranzon et al (4), Farrell et al (22), and Calloway and Kretsch (28).

FIG 4. Dependence of the apparent- and partial-digestible-energy values for unavailable carbohydrates (UC) on the proportion of gross energy intake due to UC. The line is described by equation 9. The curve is described by equation 10, in which $S$ is described by equation 8. Data are calculated from experiments reported by Southgate and Durnin (20), Góranzon et al (4), Farrell et al (22), Calloway and Kretsch (28), Wisker et al (21), Judd (32), and Kelsay et al (33).
drate eaten. Negative values are found more commonly when the proportion of gross energy intake due to unavailable carbohydrate ($\beta$) is low (Fig 4). The data are consistent with a view that when unavailable carbohydrate intake is low, it is very effective at causing losses of protein and fat to feces, but that each increment in unavailable carbohydrate intake tends to be progressively less effective.

There are several possibilities that could explain the trends underlying the observations in Figures 3 and 4, and that must also in part explain equation 8, which relate $\beta$ and $\alpha$ to $S$, the partial indigestibility of energy for unavailable carbohydrate. First, at high values of $\alpha$ and $\beta$, the differences between $DE_{\text{part}}$ and $DE_{\text{app}}$ are usually sufficiently small to be explained mostly as losses of bacterial protein and fat arising because of bacterial growth on the unavailable carbohydrate known to be ingested. At low values of $\alpha$ and $\beta$, other explanations are needed because there are more losses of protein and fat than can arise from bacterial growth on the measured amount of unavailable carbohydrate ingested.

One possible explanation of the trends is that more unavailable carbohydrate reaches the colon than is measured by current in vitro methods for determining unavailable carbohydrate, as suggested by Wisker et al (21) and which they suggest is particularly likely with whole-grain products, but this cannot be the whole explanation. Additionally, effects on the time for matter to traverse the colon are possible.

The last argument requires consideration of the quantities of substrate that seem to be fermented in the colon, particularly when they are extrapolated to zero intake of unavailable carbohydrate as measured in vitro. Wisker et al (21) already argued that the quantities of bacteria in human feces after ingestion of a British type of diet is consistent with the fermentation of 50–65 g carbohydrate/d, based on 15–20 g dry fecal bacteria eliminated/d, which requires 0.1 mol ATP/g. A further, related argument can be made. At zero intake of unavailable carbohydrate, energy lost to feces is $\sim 1 - 0.978$ times the dietary gross energy intake (Fig 1). For a daily gross energy intake of, say, 10 500 kJ (2500 kcal) this corresponds to 231 kJ (55 kcal) of energy in feces. A large fraction of this will be products of fermentation, i.e., bacteria (45). At least three times this amount of energy must be fermented to generate this amount of bacteria, so that 693 kJ (165 kcal) would be needed, equivalent to 40 g carbohydrate/d. This does not necessarily imply, however, that carbohydrate would be the only energy source.

When there is little intake of poorly fermentable unavailable carbohydrate, the time for matter to traverse the colon is relatively long (46), which gives time for autolysis of bacteria, releasing substrate for fermentation distally in the colon. Small additions of poorly fermentable unavailable carbohydrate added to a diet of low, measured unavailable carbohydrate content would quicken the time for matter to traverse the colon (45), giving less time for autolysis and reutilization of bacterial substrate in fermentation.

Losses of energy to feces by addition of small amounts of poorly fermentable unavailable carbohydrate to a diet otherwise low in measured unavailable carbohydrate is therefore likely to result in additional losses of energy to feces for three reasons: 1) transit time is decreased, which encourages loss of bacterial matter, which would otherwise have been autolyzed and fermented (together with a shorter time for fermentation of all the colonic substrates). 2) bacterial matter is generated from the additional intake of unavailable carbohydrate, and 3) there is a loss of a fraction of the additional unavailable carbohydrate ingested, that which is unfermented. Only the first of these would be sufficient to explain the large differences between apparent- and partial-digestible-energy values for unavailable carbohydrates at the low intakes ($\beta$, Fig 4) and low values for apparent digestibility of unavailable carbohydrate ($\alpha$, Fig 3). With individual subjects ingesting identical diets, Cummings (46) reports that the logarithm of fecal mass (hence, approximate energy) is linearly related to the mean transit time (mostly for travel through the colon) and that addition of unavailable carbohydrate has the largest effect on transit and fecal bulking in subjects with the slowest transit time.

It might be presumed that the influence of poorly fermented unavailable carbohydrate on the extent of bacterial autolysis would behave like a saturable process with greatest effect at low intakes and least effects above a point of “saturation,” where additional unfermented unavailable carbohydrate has no effect. A further possible saturable phenomenon would be the influence of dietary unavailable carbohydrates on endogenous secretions into the intestinal lumen, which could make a small contribution to the substrate load in the colon. The observations in Figures 3 and 4 are entirely consistent with such possible “saturable” phenomena.

Partial-digestible-energy values of unavailable carbohydrate: influence of analytical method, type of unavailable carbohydrate, and kind of diet

Table 3 gives the apparent- and partial-digestible-energy values of unavailable carbohydrate for each experiment and dietary source of unavailable carbohydrate separately. There is a considerable range of partial values between $-20$ and $+10$ kJ/g ($-4.8$ and $+2.4$ kcal/g), with values at the upper and lower ends of this range being significantly different from zero ($p < 0.01$). Hence, the claims that dietary fiber (unavailable carbohydrate) has a partial-energy value close to $13$ kJ/g (3.1 kcal/g) (4, 5) or zero (20) are not typical of information on the balance of energy intake and loss to feces presently available in the literature. Rather, a whole range of values (Table 3) can be obtained, which are related at least in part to intake of unavailable carbohydrate and in part to apparent digestibility of the unavailable carbohydrate (Figs 1, 2, and 3).

It is important to consider the large range of partial-digestible-energy values in Table 3 in relation to the various methodologies used to determine unavailable carbohydrate, because errors arising from this source affect the accuracy of the estimated partial-digestible-energy value (ie, its mean value) without affecting the precision of estimation (ie, its standard error). It is well recognized that different methods of quantifying unavailable carbohydrates give different values when applied to similar representative food samples. One (of several) explanations for this is that different amounts of starch that resists enzymatic hydrolysis in vitro are included as unavailable carbohydrate during the analytic procedure (47). That is, different methods give values for unavailable carbohydrate representing different combinations of nonstarch polysaccharide and resistant starch. Starch resisting digestion in vitro may be readily fermented in vitro (48) and in vivo (49). Consequently, the apparent digestibility of this unavailable carbohydrate, and there-
FOOD ENERGY AND UNAVAILABLE CARBOHYDRATE

TABLE 3

Apparent- and partial-digestible-energy values for unavailable carbohydrate

<table>
<thead>
<tr>
<th>Source of unavailable carbohydrate</th>
<th>Digestible-energy values†</th>
<th>Method for analyzing unavailable carbohydrate</th>
<th>Source of original data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Digestible-energy value‡</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>kJ/g (kcal/g)</td>
<td>kJ/g (kcal/g)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apparent [17.2a]</td>
<td>Partial [17.2(1 − S)]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Range for (β)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed*</td>
<td>1.2</td>
<td>8.9 ± 1.5 (2.1 ± 0.1)</td>
<td>−14 ± 3 (−3.3 ± 0.7)</td>
</tr>
<tr>
<td>Mixed*</td>
<td>12, 13</td>
<td>9.4 ± 0.2 (2.2 ± 0.1)</td>
<td>−1 ± 3 (−0.2 ± 0.7)</td>
</tr>
<tr>
<td>Mixed*</td>
<td>3.4</td>
<td>10.3 ± 0.2 (2.5 ± 0.1)</td>
<td>0 ± 3 (0.0 ± 0.7)</td>
</tr>
<tr>
<td>Mixed*</td>
<td>8.9</td>
<td>11.7 ± 0.3 (2.8 ± 0.1)</td>
<td>+1 ± 3 (0.2 ± 0.7)</td>
</tr>
<tr>
<td>Mixed*</td>
<td>6.7</td>
<td>13.2 ± 0.2 (3.2 ± 0.1)</td>
<td>+4 ± 3 (1.0 ± 0.7)</td>
</tr>
<tr>
<td>Mixed†</td>
<td>14, 17</td>
<td>13.2 ± 1.5 (3.2 ± 0.4)</td>
<td>+8 ± 1 (1.9 ± 0.2)</td>
</tr>
<tr>
<td>Mixed†</td>
<td>10, 11</td>
<td>12.8 ± 0.5 (3.1 ± 0.1)</td>
<td>+9 ± 2 (2.2 ± 0.5)</td>
</tr>
<tr>
<td>Fruit and vegetable</td>
<td>22, 23</td>
<td>0.005-0.027</td>
<td>−19 ± 4 (−4.50 ± 0.9)</td>
</tr>
<tr>
<td>Fruit and vegetable</td>
<td>3.5</td>
<td>0.011-0.047</td>
<td>−2 ± 1 (−0.5 ± 0.2)</td>
</tr>
<tr>
<td>Fruit and vegetable‡</td>
<td>−25§</td>
<td>0.000-0.105</td>
<td>+11§ (2.65)</td>
</tr>
<tr>
<td>Cereal, mainly barley</td>
<td>−**</td>
<td>0.03-0.49</td>
<td>−20 ± 2 (−4.8 ± 0.5)</td>
</tr>
<tr>
<td>Cereal, mainly barley</td>
<td>−††, 20</td>
<td>0.000-0.080</td>
<td>−17 (−4.15)</td>
</tr>
<tr>
<td>Cereal, mainly wheat</td>
<td>−††, 21</td>
<td>0.000-0.047</td>
<td>−13 (−3.19)</td>
</tr>
<tr>
<td>Cereal-based diet</td>
<td>18, 19</td>
<td>0.037-0.086</td>
<td>−5 (−1.27)</td>
</tr>
<tr>
<td>Cereal and vegetable†</td>
<td>−§, 24</td>
<td>0.000-0.080</td>
<td>+3§ (0.35)</td>
</tr>
<tr>
<td>Oat bran</td>
<td>14, 15</td>
<td>0.005-0.016</td>
<td>−17 ± 14 (−4.1 ± 3.3)</td>
</tr>
<tr>
<td>Oat bran</td>
<td>14, 16</td>
<td>0.005-0.016</td>
<td>−15 ± 20 (−3.6 ± 4.8)</td>
</tr>
<tr>
<td>Psyllium plus wheat bran</td>
<td>26, 29</td>
<td>0.040-0.0700</td>
<td>+2 ± 1 (0.7 ± 0.2)</td>
</tr>
<tr>
<td>Psyllium</td>
<td>26, 27</td>
<td>0.040-0.0748</td>
<td>+2 ± 1 (0.9 ± 1.0)</td>
</tr>
<tr>
<td>Wheat bran</td>
<td>26, 28</td>
<td>0.040-0.0719</td>
<td>+2 ± 1 (0.9 ± 0.2)</td>
</tr>
</tbody>
</table>

* Further breakdown of sources was as follows: † fruit, vegetables, and whole-meal bread; ‡ all-bran, wheat bran, peas, pumpkins, and pears; †§ Black beans, corn, rice, refined wheat rolls, squash, pumpkins, bananas; †§ whole-wheat bread, peanut butter, oranges, breakfast cereal with whole grain, carrots, cabbage, unpolished rice, peas, corn, pepper, whole-rye flour crisp bread, yellow peas, apples, and biscuits; †§ white bread, corn flakes, oranges, white beans, peas, corn, peppers, and potatoes; and † whole-wheat bread, breakfast cereal, rye-flour crisp bread, carrots, and cabbage.

† Diet combination from Table 1.
‡ Values (± SEM) apply to the upper level of intake for unavailable carbohydrate in the experiment.
§ The values (11 and 1 kJ/g) are approximate because it is assumed that metabolizable- and partial digestible-energy values are approximately equal. The calculation assumed also that the metabolizability of unavailable carbohydrate-free gross energy is 94% (see Appendix).
¶ The information was either not available or not calculable.
†† The source of the original data used to calculate energy values supplied insufficient information for calculating SEM.
‡‡ Unavailable carbohydrate was present at several levels in experiments partially reported by Judd (32), with detailed information supplied by PA Judd (personal communication, 1987).

Therefore, its partial-digestible-energy value, can be expected to be relatively high (compared with Fig 3). Indeed, studies in rats show retrograde α-amylase-resistant starches to have partial-digestible-energy values > 12 kJ/g (2.9 kcal/g) (50). A case might, therefore, be made to suggest that the range of apparent digestibilities for unavailable carbohydrate (Table 1, Fig 3) and the range of partial-digestible-energy values (Table 3, Fig 3) arise partly from different combinations of resistant starch and nonstarch polysaccharide in the analytic value for unavailable carbohydrate. This suggestion remains to be investigated. It matters for feeding studies whether diets are cooked because cooking can make some starch resistant to enzymatic hydrolysis (retrogradation) (51, 52). Recent observations indicate that it matters also what the source of the starch is. Retrograde corn starch is almost completely utilized in vivo whereas a retrograde pea starch under the same conditions shows some resistance to utilization (49).

In addition to the inclusion of resistant starch, the neutral-detergent-fiber (NDF) method excludes some soluble nonstarch polysaccharides. Hence the consistently low (though very imprecise) partial-digestible-energy value for oat bran (Table 3) must be partly underestimated for the total nonstarch polysaccharide in this product. Had the Southgate method (37) been applied, which includes soluble oat β-glucans (53), a measure of the unavailable carbohydrate in the oat bran would probably have been ~30% higher. Consequently, a higher partial-digestible-energy value (~ −10 kJ/g (~2.4 kcal/g) instead of ~ −16 kJ/g (~3.8 kcal/g) reported in Table 3) could have been expected for this material. Moreover, the low value (Table 3) probably arises also because the oat bran was incorporated at low levels into a diet with a very low unavailable-carbohydrate content. Had the oat bran been added to a basal diet with a higher unavailable carbohydrate content, and in greater amounts, it is anticipated from the observations in Figure 4 and equation 8 that the associative effects would be relatively less, so that an even higher partial-digestible-energy value would have been obtained. Similarly, the partial-digestible-energy value for the fruit-and-vegetable diet of Kelsay et al (33) could be too low for the nonstarch polysaccharide present, because the NDF method of unavailable carbohydrate analysis omits
the soluble fibers present in these sources. Again, the low-unavailable-carbohydrate diet of Kelsay et al (33) was very low and this seems to contribute to obtaining low partial-digestible-energy values.

Apart from the inclusion of starch or the exclusion of soluble nonstarch polysaccharide within the analytic value for unavailable carbohydrate, it does not seem possible that the range of the partial-digestible-energy values for unavailable carbohydrate shown in Table 3 could arise only from the use of the different analytical methods for unavailable carbohydrate. This is because, taking those values arising from studies where only the Southgate method (37) was applied, the range of values for partial digestible energy is still large: +4 to –20 kJ/g (+1 to –4.8 kcal/g) (Table 3). Similarly, considering only the NDF method, the range is +8 to –19 kJ/g (+1.9 to –4.5 kcal/g) (Table 3). The Southgate method and the NDF method give similar estimates of unavailable carbohydrate in feces and food sources with little soluble nonstarch polysaccharide (53). Also, the NDF method seems to adequately measure plant material in feces (45). The range of partial-digestible-energy values for unavailable carbohydrate is –5 to 11 kJ/g (–1.2 to 2.4 kcal/g) (Table 3) when other analytic methods for unavailable carbohydrate are used. It seems, therefore, that the large range of partial-digestible-energy values is not simply due to the application of different methods for the analysis of unavailable carbohydrate but arises from the unavailable carbohydrate being included at different levels in the diet (β) and having different apparent digestibilities (α), as discussed before.

From the range of observations in Table 3 it is difficult to firmly establish whether unavailable carbohydrate from cereals has partial-digestible-energy values similar to or even different from that for fruit and vegetables. Göranzon and Forsum (5) recently suggested that both have caloric values greater than zero and similar to each other [10.5 and 13.0 kJ/g (2.5 and 3.1 kcal/g), respectively]. These values (10.5 and 13.0 kJ/g) can now be compared with the whole range of partial-digestible-energy values shown in Table 3. Nonetheless, it does seem probable that the unavailable carbohydrate in cereal diets do give a calculated partial-digestible-energy value lower than the calculated value for fruit-and-vegetable diets. Even at the higher intakes of unavailable carbohydrate from cereals, as shown in Table 3, low partial-digestible-energy values, per gram unavailable carbohydrate, are obtained for the barley diet (–20 kJ, or –4.8 kcal), for the wheat diet (–13 kJ, or –3.1 kcal), and for the cereal diet of Wisker et al (21) (–5 kJ, or –1.2 kcal). Moreover, the cereal-and-vegetable-based diet of Göranzon and Forsum (5) is calculated here to give a partial-digestible-energy value of 1 kJ (0.3 kcal) per gram unavailable carbohydrate (by contrast with their reported value of 10 kJ (2.4 kcal) per gram unavailable carbohydrate and compared with a value of 11 kJ (2.6 kcal) per gram unavailable carbohydrate calculated here for the fruit-and-vegetable diet from the same authors (5). The low value for these cereal-based diets could arise because the determined values for unavailable carbohydrate are up to three times less than what is truly unavailable in vivo. Alternatively, or in addition, unavailable carbohydrate from cereal or some other cereal component may elicit malabsorption. Observations consistent with the occurrence of malabsorption with the barley-based diet are considered later in this review during commentary on the bias of the different food-energy assessment systems.

Comparison of food-energy assessment systems for predicting the energy value of diets with increasing unavailable carbohydrate content

Establishing an energy value for unavailable carbohydrate has not always been the primary objective of some authors investigating the effects of unavailable carbohydrate on dietary-energy balance. Rather, the primary objective has sometimes been to examine the accuracy of one or more methods for calculating the energy values of foods and diets and, in some instances, to propose new procedures for this to account for the presence and effects of unavailable carbohydrate. Presently, various procedures are examined for the accuracy and precision with which they predict the availability of energy from diets 1–17 of Table 1. This examination provides observations on a larger data set than have previous attempts, in which authors have usually used only their own experimental data. Further, it is of interest to examine the extent to which equations 2 and 8, when used together, adequately model the availability of energy from these diets. Assessment of this model is not to propose a new procedure; it is to check that there are no substantial flaws in these equations. This is useful also because the calculation procedures employed to obtain these equations, and the data shown in Figs 2, 3, and 4 and in Table 3, make a number of assumptions that, although largely justified, could leave room for some error (see Appendix).

Five systems of food-energy assessment for predicting metabolizable energy (ME) are examined: “Atwater” (35) (Eq 11), “British” (20, 54) (Eq 12), “Levy” (30) (Eq 13), “Southgate” (31) (Eq 14), and “Miller & Judd” (3) (Eq 15). For historical reasons, each equation derived values in kilocalories rather than kilojoules.

Each of these equations (Eqs 11–15) are used with intakes of protein, P (g); fat, F (g); carbohydrate determined by difference, C (g); available carbohydrate expressed as monosaccharide, Cm (g); unavailable carbohydrate, UC (g); unavailable carbohydrate relative to diet weight, UC% (g/100 g dry diet); dietary gross energy, E (kcal); and nitrogen, N (g).

In assessing the accuracy and precision of the various systems of food-energy assessment, the prediction of apparent digestible energy was examined because energy lost to urine was not always measured or reported. Nevertheless, assessment of apparent digestible energy has the advantage that accuracy and precision are not confounded by errors associated with the prediction of urinary energy losses. The components of equations 11–15 that predict digestible energy (DE) are given in equations 16–20, respectively.

\[ DE_{\text{atw}} = 5.25P + 9F + 4C \]  
\[ DE_{\text{brit}} = 5.25P + 9F + 3.75Cm \]  
\[ DE_{\text{levy}} = 0.976E - 59.8 - 7.959N \]  
\[ DE_{\text{south}} = 0.977E - 4UC - 6.6N \]  
\[ DE_{\text{mjd}} = 0.95 - UC\%E - 7.5N \]
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\[ DE_{\text{pred}} = (0.95 - UC\%)E \]  

Equations 16 and 17 differ from equations 11 and 12, respectively, in that the energy content of protein is taken to be 5.25 instead of 4 kcal/g; the 1.25P added is the portion of protein energy digested that is usually lost to urine in a subject in nitrogen balance (36). Equations 18, 19, and 20 differ from equations 13, 14, and 15, respectively, in that the terms for N have been omitted because these are considered to predict energy lost to urine.

The inaccuracy due to bias of each system of food-energy assessment was estimated by using equation 21, for which overprediction gives a positive bias and underprediction gives a negative bias:

\[ \text{Bias} = \left( \frac{DE_{\text{predicted}}}{DE_{\text{determined}}} - 1 \right) \]  

Values for \( DE_{\text{predicted}} \) were calculated with equations 16–20 and data in Table 1 and values for \( DE_{\text{determined}} \) were the results of the experiments summarized in Table 1. It should be noted that these diets are mostly with unavailable carbohydrate from mixed sources or from fruit and vegetables; there are no diets high in unavailable carbohydrate predominantly from cereals.

Figure 5 shows the mean bias for diets 1–17. It is evident that at low levels of intake of unavailable carbohydrate all assessment systems adequately predict availability of dietary energy. However, with increasing unavailable-carbohydrate content all the published systems of assessment of food energy show bias: the Atwater (Eqs 11 and 16) and Levy (Eqs 13 and 18) systems each appear to overpredict whereas the British (Eqs 12 and 17), Southgate (Eqs 14 and 19), and Miller & Judd (Eqs 15 and 20) systems each underpredict. For reference, Figure 5 also contains a single point representing the specific-factor method described by Merrill and Watt (sometimes called the Atwater specific system) (36). This method, represented by equation 22, uses specific calorie-conversion factors \( w, x, \) and \( y \) for protein \((P)\), fat \((F)\), and carbohydrate \((C)\), respectively, that apply to specified items of food or ingredients \((1, 2, \ldots, n)\). The available energy is calculated for each item and the sum for all items \((1 \text{ to } n)\) gives the available energy for the food products or whole diet—whichever the calculation is being applied to.

\[ ME_{\text{prod}} = (w_1P + x_1F + y_1C)_{\text{food } 1} + (w_2P + x_2F + y_2C)_{\text{food } 2} + \cdots + (w_nP + x_nF + y_nC)_{\text{food } n} \]  

The method is simple in principle but cumbersome to practice for popular users of food-energy systems, so it finds disfavor especially with manufacturers of food. The point that represents the “Merrill & Watt” specific-factor system shown in Figure 5 is based on measurements made on four diets containing 93, 86, 56, and 65 g \((\bar{x} \pm 75 \text{ g})\) unavailable carbohydrate/d. The corresponding reported errors are 6% (28) overprediction and 3.6%, 0.4% (5), and 2.1% (5) underprediction (mean bias 0.0; SD \(\pm 4.2\%\), respectively. Generally, therefore, the Merrill & Watt specific-factor system (36) appears to predict availability of energy from diets containing large amounts of unavailable carbohydrate with a bias probably less than that for the other published systems presently examined.

The present analysis began before the publication by Miles et al (55) of a study where unavailable carbohydrate was fed to humans at two levels in the diet: fruit and vegetable juice in a diet of low unavailable carbohydrate intake and fruits and vegetables in a diet with a higher level of unavailable carbohydrate intake. Intakes of unavailable carbohydrate were 16.4 and 37.4 g/d, measured according to Prosky et al (44). Miles et al (55) also noted that the Miller & Judd equation underestimated, that the Atwater system overestimated, and that the Southgate equation adequately predicted their own (55) determined metabolizable-energy intake. These observations (55) are in keeping with the observations in Figure 5 at the lower intakes of unavailable carbohydrate.

Figure 5 also shows the precision of each food-energy system...
represented by the standard deviation of the mean bias. At intakes of unavailable carbohydrate commonly encountered in diets of people from industrial populations (represented in Fig 5 by the 8.63–25.7 g intake/d) each factorial system of food-energy assessment (Atwater and British) appeared less precise than each empirical system (Southgate, Levy, and Miller & Judd). This distinction is not as evident at the high levels of intake of unavailable carbohydrate. The greater precision, where observed, probably arises because the empirical systems use measures of gross energy directly whereas this energy is predicted in the factorial approaches, so the latter approaches include both errors of determination of protein, fat, and carbohydrates and errors arising from differences between the true heats of combustion of these components in foods and that assumed within the caloric conversion factors of the factorial systems.

Equations 8 and 2, when used in combination to predict \( DE \) for diets 1–17 (Table 1), showed (Fig 5) no bias and had a relatively high precision of estimation. Hence, these equations describe the availability of digestible energy from these diets fairly well, indicating that they are substantially free of errors arising from the assumptions the equations make (see Appendix). Of course, equations 8 and 2 are currently impractical for estimating food-energy values because apparent digestibility of unavailable carbohydrate cannot be predicted yet and there are currently no tables giving gross energy values for foods, although they are being planned. However, the accuracy and precision of these equations (Eqs 8 and 2), as judged from Figure 5, support the present view that variance in the availability of dietary energy is more closely related to the occurrence, utilization, and effects of unavailable carbohydrate than had been previously thought.

Figure 5 is based on diets with unavailable carbohydrate from mixed sources or from fruit and vegetables. The curves in Figure 5 do not, therefore, necessarily represent what may happen with diets containing large amounts of unavailable carbohydrate from cereal sources. After deriving these equations and during consideration of this review for publication, Wisker et al (21) published in full their data on dietary energy balance in human subjects. They provided a diet containing large amounts of cereal. A value for the apparent digestibility of the unavailable carbohydrate in that diet was given (0.466), together with values for daily gross energy intake, \( E \) [9795 kJ (2341 kcal)], and the daily intake of unavailable carbohydrate, \( I^{UC} \) (48.3 g). This enabled equations 8 and 2 to be tested on a type of diet not included in the data set for their derivation.

The proportion of gross energy intake attributable to unavailable carbohydrate (17.2 \( I^{UC}/E \)) in the cereal diet (21) is calculated to be 0.084, and the partial indigestibility of energy for unavailable carbohydrate, \( S \), is calculated (Eq 8) to be 1.29. Then digestible energy intake, \( DE \), is calculated (Eq 2) to be 8510 kJ (2034 kcal). This compares accurately with the value of 8511 kJ (2034 kcal) obtained experimentally (21) and further appears to support the validity of the equations and the assumptions that underlie their derivation.

**Commentary on the bias of each food-energy assessment system**

Some commentary is needed to explain why each published system of food-energy assessment either overpredicts or under-

predicts availability of energy and perhaps why the Merrill & Watt specific-factor method shows no overall bias.

At the 26-g daily intake of unavailable carbohydrate, the Atwater general factors (Eqs 11 and 16) only slightly overestimate available energy (Fig 5). The reason for a small bias only is probably that his factors were derived for diets that contained similar (low-to-moderate) quantities of unavailable carbohydrate. Atwater and Bryant (35) obtained apparent digestibilities for protein and fat that are less than is expected at zero intake of unavailable carbohydrate (56). The influence of unavailable carbohydrate on apparent digestible energy for the whole diet was, on average, partly accounted for within Atwater and Bryant's general caloric conversion factors. An implication is that at typical levels of unavailable carbohydrate intake in the United States, Britain, and other Western countries, it is incorrect to deduct a determined value for unavailable carbohydrate from the value for carbohydrate calculated by difference, then imply a zero partial-energy value for unavailable carbohydrate, as is now often practiced. This gives a situation analogous to that in Britain, where the British factor system underestimates available energy for these diets (Fig 5).

The caloric conversion factors derived in the British system were determined with diets that contained \( \sim 10–30 \) g unavailable carbohydrate/d (20). Again, the influence of unavailable carbohydrate on losses of protein and fat to feces up to this level of intake were approximately accounted for in the British caloric conversion factors, which are less than expected for diets containing no unavailable carbohydrate (56). The extent to which the British system of food-energy assessment underestimates available energy at the lower (16–30 g) daily intakes of unavailable carbohydrate is due mostly to a failure to account for the apparent digestible energy in the unavailable carbohydrate, which is \( \sim 10–13 \) kJ/g (Table 3). The implication here is that use of a zero partial-digestible-energy value for unavailable carbohydrate with the British caloric conversion factors results in a double accounting for those losses to feces of protein and fat that arise because of ingestion of the unavailable carbohydrate—first, because these losses are accounted for in the caloric conversion factors for protein and fat, and second, because these losses are then accounted for in the zero partial-digestible-energy value implied by discounting unavailable carbohydrate in the calculation procedure (Eqs 12 and 17).

At levels of unavailable carbohydrate intake greater than those in the diets of Atwater and Bryant (35) and of Southgate and Durnin (British) (20), the available energy is overpredicted and underpredicted, respectively, by the Atwater and British systems. This results from the use of a caloric conversion factor for unavailable carbohydrate that is too high in the Atwater system (16 kJ/g, or 4 kcal/g) and too low for those diets in the British system (0 kJ/g, or kcal/g). It seems that a value midway between 16 kJ/g (4 kcal/g) and 0 kJ/g (0 kcal/g) would be appropriate for most practical purposes; this is considered in more detail later.

The Miller & Judd equation (Eq 15) underestimates the availability of dietary energy because it was derived with diets containing barley, which seem not to be representative of diets 1–17. Large intakes of barley perhaps cause malabsorption; in one subject receiving the barley, an equivalent of 33% of dietary gross energy and \( \geq 26\% \) of the combined energy contained in the protein, fat, and available carbohydrate was lost to feces. It is difficult to conceive that this large loss of energy could arise...
from any source other than directly from the diet. Should the large loss arise directly from the diet, an implication is that certain cereal carbohydrates, carbohydrate fractions, or other cereal fractions may elicit malabsorption at high intakes.

The Southgate equation (Eq 14) was derived empirically by using diets with between 6 and 30 g unavailable carbohydrate/d (20, 31). It is not surprising therefore that it should accurately predict diets with this quantity of unavailable carbohydrate in diets 1–17 of Table 1. The Southgate equation applies an apparent digestibility coefficient of 0.977 for dietary gross energy, which appears appropriate for a diet without unavailable carbohydrate (Fig 1; Eqs 1 and 2). Southgate and Durnin (20) and Southgate (31) observed that ingestion of more unavailable carbohydrate did not, on average, appear to alter the apparently digested dietary gross energy. Therefore, 4 kcal/g unavailable carbohydrate was then subtracted to balance the gross energy intake from the unavailable carbohydrate, which is included in the term 0.977E of the Southgate equation. However, at the high intakes of unavailable carbohydrate, the effect on losses of protein and fat to feces diminishes (Fig 4), so that the Southgate equation then overestimates additional losses of energy to feces, thus underpredicting the dietary-energy value. This, too, is what appears to happen with the British system of assessment at high intakes. The reason that the Southgate equation more accurately estimates available energy than the British system of assessment is both because it does not account twice for losses of protein and fat to feces and because it does not involve a prediction of dietary gross energy from analytic values for protein, fat, and available carbohydrate.

The Levy equation (Eqs 13 and 18), like the Atwater general-factor system (Eqs 11 and 16) was derived on diets containing low-to-moderate quantities of unavailable carbohydrate; therefore, like the Atwater system, it predicts dietary energy adequately except when unavailable carbohydrate are very high. In this circumstance the 0.976 apparent digestibility coefficient in the Levy equation (Eqs 13 and 18) multiplied by the heat of combustion of the unavailable carbohydrate [17.2 kJ/g (4.1 kcal/g)] gives an available-energy value of 16.7 kJ/g (4 kcal/g), which, as in the Atwater system, is too high.

The Merrill & Watt specific-factor system (Eq 22) shows no overall bias at high intakes of unavailable carbohydrate. Presumably this is because the specific factors were derived by addition of large amounts of the plant foods to basal diets so that these diets as a whole contained relatively large amounts of unavailable carbohydrate (36). For fruits, legumes, vegetables, and cereals with appreciable contents of unavailable carbohydrate, the specific-factor system calculates available energy to be between 2% and 30% lower than the Atwater general factors predict (36). It is not surprising, therefore, that the Merrill & Watt specific factors should predict the available energy at high intakes of unavailable carbohydrate more accurately than do the Atwater general factors.

Equations 2 and 8 adequately predict available energy for several reasons. At low intakes of unavailable carbohydrate, low and negative partial-digestible-energy values are implied but at very high intakes these equations imply a high (≈9 kJ/g. or ≈2 kcal/g) partial-digestible-energy value for unavailable carbohydrate, a value that is midway between that implied by the Atwater factor (per gram unavailable carbohydrate, 16.7 kJ, or 4 kcal) and the British factor (zero kJ/g, or kcal/g). Further, the influence of the apparent digestibility of the unavailable carbohydrate (α) is taken into account (Eq 8). Above all, however, the present equations adequately predict digestible energy from the whole diets because they seem to adequately describe underlying trends between availability of dietary energy and unavailable carbohydrate intake, utilization, and effects on losses of protein and fat to feces for diets 1–17 and for the diet of Wisker et al (21), which was high in unavailable carbohydrate from cereals.

Is a simple practical approach to assessment of dietary energy possible?

It is not yet certain that a simple approach can be devised that will accurately predict available energy from all types of diets. However, it would seem from Fig 5 that for diets with unavailable carbohydrate from mixed sources or from fruit and vegetables (diets 1–17, Table 1) a caloric value for unavailable carbohydrate about midway between that implied in the Atwater (16.7 kJ/g, or 4 kcal/g) and the British systems (0 kJ/g or kcal/g) could be of practical use. Such a value, 8.4 kJ (2 kcal) per gram unavailable carbohydrate, if adopted with a factorial approach, could give either a modified Atwater system or a modified British system. For example, a modified British system would be equation 23 that adopts 16.7 kJ/g protein (4 kcal/g); 37.7 kJ/g fat (9 kcal/g); 15.7 kJ (3.75 kcal, per gram available carbohydrate determined directly and expressed in monosaccharide weight equivalents; 8.4 kJ/g (2 kcal/g) unavailable carbohydrate. Equation 24 is the corresponding equation for digestible energy.

\[
ME_{\text{modified by}} = 4P + 9F + 3.75Cm + 2UC
\]

\[
DE_{\text{modified by}} = 5.25P + 9F + 3.75Cm + 2UC
\]

The bias (Eq 21) of equation 24 is compared in Figure 6 with the bias of the Atwater (Eqs 11 and 16) and British (Eqs 12 and 17) systems. A comparison is also made with the error due to bias in the prediction of the gross energy (GE) content of these diets, calculated according to equations 25 and 26:

\[
GE = 5.65P + 9.4F + 3.75Cm + 4.1UC
\]

\[
\text{Bias} \ GE = 100 \left( \frac{GE_{\text{calculated}}}{GE_{\text{determined}}} - 1 \right)
\]

It was expected from Figure 5 that the modified British system (Eq 24) would give a mean bias midway between that of the Atwater and British systems, and this is evident in Figure 6. It is also evident (Fig 6) that the calculated mean bias of the modified British system is close to that for the prediction of gross energy (Eq 25). This can be explained as the modified British system, on average, accounting adequately for the apparent digestibilities of energy in protein, fat, and all carbohydrates in these diets but not accurately accounting for gross energy. Several explanations are possible for the discrepancy between the determined and predicted gross energies, the most likely being the incomplete determination of protein, fat, or carbohydrate. Because the effects of unavailable carbohydrate on losses of protein and fat to feces at low-to-moderate intakes of unavailable carbohydrate are mostly accounted for already in the British and Atwater systems of food-energy assessment, it is not appropriate to also use the zero partial-digestible-energy values.
caused by possible increased intestinal secretions or change in colonic transit time, and to compare this estimate with the suggested value of 8.4 kJ (2 kcal) per gram unavailable carbohydrate.

The fecal energy losses caused by the ingestion of unavailable carbohydrate will be equal to the sum of the losses of unfermented unavailable carbohydrate and the additional losses of bacteria to feces attributable to fermentation of the remainder of the unavailable carbohydrate. The fraction of unavailable carbohydrate reaching the feces is \(1 - \alpha\), i.e., the apparent digestibility. It is becoming evident that for every additional unit of carbohydrate energy fermented, between 0.2 and 0.4 units of additional energy arise in feces, probably as bacteria, when unavailable carbohydrate intakes are high in humans and laboratory rats (50, 57–59); taking a middle value we have a loss of \(-0.3\alpha\). The above sum is, therefore, \(1 - \alpha + 0.3\alpha\), or \(1 - 0.7\alpha\). Such losses to feces correspond to a utilization of \(0.7\alpha\) (i.e., \(1 - (1 - 0.7\alpha)\)). Hence, the digestible energy gained from unavailable carbohydrate can be estimated (\(DE_{\text{est}}\)) approximately by equation 27:

\[
DE_{\text{est}} (\text{kJ/g}) = 17.2 \times 0.7\alpha
\]  

Values for \(\alpha\), \(1 - 0.7\alpha\), \(0.7\alpha\), and \(DE_{\text{est}}\) are given in Table 4 for the same three groups of diets at low, moderate, and high intakes of unavailable carbohydrate shown in Figures 5 and 6. At all levels of unavailable carbohydrate intakes, the average values of \(\alpha\) (the apparent digestibility of unavailable carbohydrate) were \(-0.7\alpha\), which resulted in values for \(1 - 0.7\alpha\) and \(0.7\alpha\) of \(-0.5\) and which gave estimated digestible-energy values for the unavailable carbohydrate of \(-8.4\) kJ (2 kcal) per gram unavailable carbohydrate (Table 4). It seems, therefore, that the average values of \(-8.4\) kJ (2 kcal) per gram unavailable carbohydrate suggested by Figure 5 and evident in Figure 6 can be derived approximately on theoretical grounds.

The modified British equation (Eq 24) appears suitable for use in most circumstances, but calorie conversion factors for unavailable carbohydrate in diets of cereals need to be re-searched further. It remains conceivable that cereal-based diets elicit malabsorption at very high intakes, and measurement of unavailable carbohydrate in vitro may underestimate truly unavailable carbohydrate in vivo by a factor of two to three times for certain cereal diets, a possibility suggested earlier in this review and before by Wisker et al (21). Additionally, specific calorie conversion factors are likely to be more useful for supplements of unavailable carbohydrate obtained by manufacture

### TABLE 4

<table>
<thead>
<tr>
<th>Unavailable carbohydrate intake*</th>
<th>(\alpha)†</th>
<th>(1 - 0.7\alpha)</th>
<th>(0.7\alpha)</th>
<th>(17.2(0.7\alpha))</th>
<th>(4.1(0.7\alpha))</th>
</tr>
</thead>
<tbody>
<tr>
<td>g/day</td>
<td>(k\text{j/g})</td>
<td>(k\text{cal/g})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.6 ± 3.0</td>
<td>0.75 ± 0.16</td>
<td>0.48</td>
<td>0.52</td>
<td>8.9 ± 1.8</td>
<td>2.1 ± 0.4</td>
</tr>
<tr>
<td>25.7 ± 6.3</td>
<td>0.66 ± 0.09</td>
<td>0.53</td>
<td>0.47</td>
<td>8.1 ± 1.1</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>77.4 ± 21.0</td>
<td>0.69 ± 0.11</td>
<td>0.51</td>
<td>0.49</td>
<td>8.4 ± 1.3</td>
<td>2.0 ± 0.3</td>
</tr>
</tbody>
</table>

* \(\bar{x} \pm \text{SD.}\)

† \(\bar{x} \pm \text{SEM.}\)
when these have an apparent digestibility differing appreciably from 0.7, the average values for diets 1–17 (Tables 1 and 4).

Final discussion

For 22 of the 29 diets listed in Table 1 statistical information was available (4, 20–22, 28, 33) to determine the between-subject variation for the apparent digestibility of dietary gross energy. The mean coefficient of variation was 1.09% (SD ± 0.59) and is small by comparison with the range of mean values for groups of subjects (0.82–0.97, or 15%; see Table 1 and Fig 1). It is inconceivable, therefore, that intrinsic differences between groups of subjects in the various studies could ever explain the differences. Rather, the variation in the digestibilities of dietary energy must be related to dietary composition. The present observations formally relate this variability to the occurrence, utilization, and effects of unavailable carbohydrate.

With meticulous experimentation there is no suggestion that the standard error of estimation (precision) of the partial-digestible-energy values for unavailable carbohydrate (Table 3) is poor. The only exception to this generalization is for oat bran, where the precision for the apparent digestible energy value was also poor (Table 3). A view that the energy-balance procedure in man could be too imprecise to obtain energy values for the unavailable carbohydrates (23, 60) therefore appears to be difficult to substantiate in practice. The difficulties relate more to accuracy of analytical methods for determining unavailable carbohydrates.

The partial-digestible-energy values include the associative effects on losses of protein and fat to feces, which appear to be substantial at low intakes of unavailable carbohydrate, so that, it is suggested, evaluations of digestible-energy values of supplements need to be made by supplementing diets that already contain moderate quantities of unavailable carbohydrate, say 20 g/d. The study by Stevens et al (34) with wheat bran and psyllium gum (Table 3) meets this condition so that the partial-digestible-energy values of 4 kJ/g (0.9 kcal/g) for both of these supplements (Table 3) are probably of practical use in calculating the energy value of diets to which they are added but only when added to diets already of moderate unavailable carbohydrate content. The low [−16 kJ/g (−3.8 kcal/g)] partial-digestible-energy value for oat bran in Table 3 is an inappropriate energy value for this type of product if added to a diet already containing moderate amounts of unavailable carbohydrate, for reasons cited previously. Crystalline cellulose was calculated (58) to have a partial-digestible-energy value in man of −0.7 ± 0.7 kJ/g (−0.2 ± 0.2 kcal/g), based on the study reported by Slavin and Marlett (61). Although the study procedure involved feeding 16 g cellulose to humans in a diet with 10 g neutral detergent fiber, the influence on losses of protein and fat to feces, although discernible, were such that a value for crystalline cellulose of −0 kcal/g (0 kcal/g) (61) would seem realistic.

Psyllium gum (62), wheat bran (63), and crystalline cellulose (61) each have very low apparent digestibilities. Their effect on energy loss to feces is not predicted by equation 8, which was shown to predict fecal energy loss due to unavailable carbohydrates in the diet; rather, losses of energy to feces after ingestion of the supplements are more in keeping with their apparent digestibilities as predicted by equation 27. Potentially, therefore, nonstarch polysaccharide in whole foods may exert an effect because of encasement of other energy sources in foods. With nonstarch polysaccharide isolated from foods, then added back to a diet, any such effect is expected to be diminished. Potentially, therefore, isolates may have higher partial-digestible-energy values than the corresponding nonstarch polysaccharides in whole foods, especially, perhaps, whole-grain products (21).

For other supplements for which a partial-digestible-energy value has not been determined experimentally, it is probable that an approximate energy value can be estimated by use of equation 27 when the apparent digestibility of the unavailable carbohydrate is known and when the supplement is included within a diet already of moderate unavailable carbohydrate content. Hence, the soluble gums, e.g., gum arabic and guar gum, are completely fermented in humans (63, 64) and likely to have a digestible energy value of ∼12 kJ/g (2.8 kcal/g), in accordance with equation 27. (The partial-metabolizable-energy values of these gums are similar to the digestible-energy values.) This value [12 kJ/g (2.8 kcal/g)] compares with partial-digestible-energy values determined in the rat of 10 kJ (2.4 kcal) per gram guar gum (59) and 14 kJ (3.3 kcal) per gram gum arabic (58), which are not significantly different from that predicted for man by equation 27.

Finally, all the digestible-energy values considered above neglect the production of hydrogen and methane. In man, compared with ruminants, these losses are relatively small (<5% of gross energy in unavailable carbohydrate ingested) both for unavailable carbohydrates of natural origin (65) and for many artificial unavailable carbohydrates made for use as replacements for sucrose in the diet (57).

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APPENDIX

A procedure for calculating partial-digestible- and metabolizable-energy values by use of dietary-energy-balance data

Graphical description of energy-balance data

Dilution of digestible energy in a diet with any combustible, low-calorie substance results in a decrease in the apparent digestibility, or an increase in the apparent indigestibility, of dietary gross energy. This can be represented by the solid curve between b and c in Figure 1. When there is no dilution the apparent digestibility of dietary energy is at a maximum for that diet, at b in Figure 1; in this example it is shown at 0.98. When the extent of dilution is maximal, i.e., virtually all the diet is the combustible, low-calorie substance, the apparent digestibility of dietary energy is equal to the digestibility of the combustible, low-calorie substance, zero in this example (at c in Fig 1). For practical reasons, e.g., intolerance to the intake of large amounts of low-calorie material, the extent of dilution may be limited. The practical range for unavailable carbohydrate appears to be between 0 and 0.15 on the x-axis. (see Fig 1 of main paper).

As the apparent digestibility of dietary energy decreases from 0.98 to 0.0 (b to c in Fig 1), the apparent indigestibility of energy increases from 0.02 to 1.00 according to a general expression described by Kleiber (1):

\[
\text{Digestibility} = 1 - \text{indigestibility}
\]  

(1)

The slope of the curve b-c (Fig 1) gives the partial indigestibility of the combustible low-calorie diluent; proof of this is given below. The statement is strictly correct only when the apparent digestibility of dietary gross energy in the absence of the diluent is close to unity (it is 0.98 in this example), as will be discussed further below. The slope of the curve b-c is negative when apparent digestibility of dietary energy is plotted and positive when apparent indigestibility is plotted, so that with either plot, the absolute value of the slope gives the partial indigestibility of the combustible, low-calorie diluent for energy. In the example given in Figure 1 the absolute value for the slope is close to +1 but in experiments with unavailable carbohydrate, absolute values for the slopes ranging between +0.3 and +2.2 are found (see Table 2 of main paper).

Southgate and Durnin (2) made a plot of the type shown in Figure 1, obtaining a slope, or partial indigestibility, of 0.945 for unavailable carbohydrate. According to equation 1, this gives a partial digestibility of energy for unavailable carbohydrate near zero (0.055). This is the basis of the generally assumed zero-energy value for dietary fiber.

In experiments the extreme values of digestibility at b and c (Fig 1) are not obtained. Two intermediate values between these extremes are nearly always determined. These are represented in Figure 1 by \(D_h\) and \(D_l\), which are the apparent digestibilities of dietary gross energy, corresponding to when the proportion of gross energy intake due to the combustible low-calorie substance is \(\beta_h\) and \(\beta_l\), respectively. (The subscripts \(l\) and \(h\) refer to the diets of low and high caloric dilution, respectively.)

The absolute value for the slope of the curve b-c is given by equation 2:

\[
S = \frac{D_l - D_h}{\beta_h - \beta_l}
\]  

(2)

Equation 2 can be expanded to give equation 3 because \(\beta_h\) and \(\beta_l\) are equal to \(E_l/E_I\) and \(E_h/E_I\), respectively \([E_I, E_h, \beta_h, \beta_l]\) and \(E_I\) are the gross energy intakes of the low-calorie substance (superscript \(s\)) and whole diet (no superscript) for the diets of low dilution (subscript \(l\)) and high dilution (subscript \(h\), respectively.) The superscript \(s\) is used in this appendix to indicate that application can be for any combustible substances, not just for unavailable carbohydrate.

\[
S = \frac{D_l - D_h}{E_h/E_I - E_l/E_I}
\]  

(3)

Note that equation 3 provided estimates for the partial indigestibilities of unavailable carbohydrate (S) used in the main paper (see Table 2).
Proof that $S$ is the partial indigestibility and the calculation of partial-digestible-energy values

Equation 3 derived above expands to give equation 4, in which apparent digestibilities ($D$) are defined, according to Kleiber (1), as the difference between energy intake ($E$) and energy losses to feces ($FE$) expressed as a fraction of $E$, i.e., $(E - FE)/E$:

$$S = \frac{(E_i - FE_i) - (E_a - FE_a)}{(E_i - E_a)}$$

When gross energy intake is made the same for the two diets, then $E_i$ equals $E_a$ and equation 4 simplifies to equation 5, then equation 6:

$$S = \frac{FE_i - FE_a}{E_i - E_a}$$

Equation 6 shows that $S$, the absolute value of the slope of the curve b-c in Figure 1, is equal to the change in fecal energy ($\Delta FE$) brought about by a change in gross energy intake caused by the low-calorie substance ($\Delta E^*$); this is partial indigestibility as defined by Kleiber (1). Equation 7 was also given by Kleiber (1) as the method for calculating partial digestibility; hence, equation 8, which gives partial digestibility $(1 - S)$, applies also:

$$D_{part} = 1 - \left(\frac{\Delta FE}{\Delta E^*}\right)$$

Partial-digestible-energy values ($DE_{part}^*$) are products of the partial digestibility and the heat of combustion ($\Delta H_i$) of the combustible low-calorie substance, according to equation 9.

$$DE_{part}^* = \Delta H_i (1 - S)$$

Equation 9 is used in the main paper (as Eq 10).

Calculation of partial digestibility and partial-digestible-energy values when $D_o < 1$

The above procedures are applicable only when the apparent digestibility of dietary gross energy at zero dilution with the combustible, low-calorie substance ($D_o$ in Fig 1) is close to unity. When this is not the case a correction term needs to be applied to obtain a slope that would have been obtained had $D_o = 1$. An appropriate correction term is given by the slope of the curve b-d in Figure 1, which is equal to $1 - D_o$. This needs to be added to the absolute value of the slope for the curve b-c in Figure 1 to give the correct partial indigestibility for the low-calorie substance, $Z$ in equation 10:

$$Z = S + (1 - D_o)$$

The need for the correction term is readily envisaged by considering a hypothetical case in which a substance is added to a diet with an apparent digestibility of energy of, say, 0.8. If the partial digestibility of energy for the substance was also 0.8, the slope of the line would be zero, implying a partial digestibility of energy for the substance of 1.0 when the correction term is not applied. In this hypothetical case, $S$ is zero and $D_o$ is 0.8; hence, according to equation 10, the absolute value of $Z$ is 0.2. According to equation 1, when $Z$ is partial indigestibility, then the partial digestibility is $1 - 0.2$, or 0.8, the value hypothesized.

When the apparent digestibility of the undiluted diet tends towards unity, ($D_o = 1$), then $S$ tends to be equal to $Z$ because the term $1 - D_o$ tends towards zero. When $D$ is not close to zero, it follows that the partial indigestibility is given more accurately by equation 11 than by equation 3:

$$Z = \frac{D_i - D_o}{(E_i/E_a) - (E_i/E_i)} + (1 - D_o)$$

Also, the partial-digestible-energy value is more accurately calculated by equation 12 than by equation 9:

$$DE_{part}^* = \Delta H_i (1 - Z)$$

Generally, the term $1 - D_o$ is small, ~0.02, because $D_o$ is generally ~0.98 (see Fig 1 in main paper). Omitting this term, therefore, generally results in an overestimation of partial digestibility and the digestible-energy value by ~2% of the gross energy of dietary unavailable carbohydrates, $\Delta H_i$, in equation 12. If equations such as these are applied to partial indigestibility of substances at the end of the ileum (eg, with ileostomy subjects or animals with surgically placed fistulas), then the correction term can be quite large. This is because apparent digestibility of energy to the ileum is much lower than for the alimentary tract as a whole and may be as low as 0.8, for example, so that the correction term $1 - D_o$ becomes 1 - 0.8, or 0.2. This is equivalent to 20% of the gross energy value of the substance and should not be ignored.

Calculation of the partial digestible energy of a supplement of unavailable carbohydrate

When a supplement is added to a basal diet that already contains a moderate amount of unavailable carbohydrate, the basal diet can be considered to contain no supplement, and $\beta_i$ in Figure 1 (which is $E_i/E_i$ in Eqs 3 and 11) becomes zero. The value of $D_o$ in these circumstances is then equal to the apparent digestibility of dietary gross energy in the basal diet. The advantage of doing this is that it removes the assumption that the unavailable carbohydrate in the basal diet behaves like that in the supplement. (The same applies to determining partial-metabolizable-energy values, where $E_i/E_i$ becomes zero and $Q_o$ is the metabolizability of the gross energy in the basal diet; see Eq 19 below.)

Alternative procedure for estimating partial indigestibility ($S'$) of unavailable carbohydrate

This procedure uses nutrient-balance data from two diets expressed in units of energy. By definition, no available carbohydrate is lost to feces. All additional energy lost to feces on increasing the intake of unavailable carbohydrate should, therefore, be accounted for by the additional loss of protein, fat, and unfermented unavailable carbohydrate. With this premise an alternative procedure can be used to calculate the partial indigestibility of the unavailable carbohydrate for energy ($S'$). The
prime is used ($S'$) to distinguish this estimate from $S$ obtained by using equation 3. $S'$ is the sum of the apparent indigestibility of the unavailable carbohydrate ($A$), the "partial indigestibility of fat for unavailable carbohydrate" ($B$), and the "partial indigestibility of protein for unavailable carbohydrate" ($C$), according to equation 13. The values for $A$, $B$, and $C$ are obtained from equations 14, 15, and 16, respectively.

$$S' = A + B + C$$  \hspace{1cm} (13)

$$A = 1 - \alpha$$  \hspace{1cm} (14)

$$B = \frac{D_f - D_h}{E_f^c - E_h^c}$$  \hspace{1cm} (15)

$$C = \frac{D_h - D_s}{E_h^c - E_s^c}$$  \hspace{1cm} (16)

Equations 15 and 16 are analogous to equation 3 for the determinations of partial indigestibility of energy for unavailable carbohydrate. The variables in these equations are defined as follows: $\alpha$ in equation 14 is the apparent digestibility of the unavailable carbohydrate, so the term $1 - \alpha$ is the apparent indigestibility. $D_h$ and $D_f$ (Eq 15) are the apparent digestibilities of fat in the diets of higher and lower unavailable carbohydrate intake; $D_h$ and $D_f$ (Eq 16) are the corresponding values for protein. $E_f^c$ and $E_h^c$ (Eqs 15 and 16), $E_h^c$ and $E_s^c$ (Eq 15), and $E_h^c$ and $E_s^c$ (Eq 16) are intakes in energy terms (kJ), with subscripts $UC'$ for unavailable carbohydrate, $f$ for fat, and $p$ for protein. Again, the subscripts $h$ and $l$ refer to diets of higher or lower intakes of diluent (unavailable carbohydrate in this instance), respectively. These energy terms are products of values for weighed intakes of proximate substances (Table I in main paper) and the corresponding heats of combustion. The latter are generally 17.2, 39.5, and 23.6 kJ/g for unavailable carbohydrate, fat, and protein, respectively.

**Calculation of partial metabolizability and metabolizable-energy value**

The above theory for partial-digestible-energy values applies also to the calculation of partial-metabolizable-energy values when digestibility of dietary gross energy ($D_i$ and $D_h$) is replaced with metabolizability ($Q_i$ and $Q_h$) where

$$Q_i = \frac{(E_i - FE_i - UE_i)}{E_i}$$  \hspace{1cm} (17)

$$Q_h = \frac{(E_h - FE_h - UE_h)}{E_h}$$  \hspace{1cm} (18)

Again, in these equations (Eqs 17 and 18) the subscripts $h$ and $l$ refer to diets of low and high dilution with the combustible low-calorie substance, and $E$, $FE$, and $UE$ refer to gross energy intake and losses to feces and urine, respectively. Partial-metabolizable-energy values for a substance ($ME_{part}$) is then obtained from equations 19 and 20 when $Q_o$ is the metabolizability at zero dilution (compare with $D_o$):

$$Z^* = \frac{Q_l - Q_o}{E_l - E_o} + (1 - Q_o)$$  \hspace{1cm} (19)

$$ME_{part} = \Delta H_f (1 - Z^*)$$  \hspace{1cm} (20)

Equations 19 and 20 for the calculation of partial-metabolizable-energy values are analogous to equations 11 and 12 for the calculation of partial-digestible-energy values. The need for the term $1 - Q_o$ in equation 19 is greater than the need for the term $1 - D_o$ in equation 11. This is because $(1 - Q_o)$ is greater than $(1 - D_o)$ because of additional losses of energy to urine. Plots (not shown) of metabolizability ($Q$) against the proportion of gross energy intake caused by unavailable carbohydrate ($\beta$) were made to estimate $Q_o$ by use of published data on 16 diets (from references 2, 3, and 4). This gave a mean value for $Q_o$ of 0.94 (SD ± 0.02), so that ignoring the term $1 - Q_o$ in equation 19 would result, on average, in an overestimation of partial metabolizability and metabolizable-energy values by ~6% of the gross energy in dietary unavailable carbohydrates ($\Delta H_f$ in Eq 20).

**Assumptions made when calculating partial-digestible- and metabolizable-energy values**

The calculation procedures described above assume linearity for the curve of the type $b-c$ (Fig 1) for plots of experimental data. The observation in the main paper that almost all such plots extrapolate back to give a value, $D_o$, close to 0.98 is consistent with this view. Further, the study by Judd (5) with a whole range of levels of intake of unavailable carbohydrate (with $\beta$ ranging between 0.02 and 0.09) gave data consistent with a linear relationship. Additionally, the accurate and precise prediction of digestible energy for diets 1-17 by use of equations 8 and 2 in the main paper (see Fig 5 of main paper) would not be expected had the slopes not been approximately linear. Linearity implies that the partial-digestible- and metabolizable-energy values for particular unavailable carbohydrates are constant, independent of the quantity in the diet. This is an assumption common to all procedures for estimating energy values of unavailable carbohydrate based on feeding studies with two levels of unavailable carbohydrate. The present observations showing that the partial-digestible-energy value of unavailable carbohydrate rises with increasing intake (Fig 4, main paper) is evidence against linearity. Should the curves be nonlinear, the partial-digestible-energy values apply only as average values over the range tested—hence the suggested need (main paper) to assess energy values of unavailable carbohydrate supplements by addition to a basal diet already of moderate unavailable carbohydrate content.

When the dietary source of protein and fat (though not available carbohydrate) differs for the two experimental diets of different unavailable carbohydrate content, the procedure for calculating partial digestibility or metabolizability of energy assumes that true availability of energy from protein and fat in these different sources is the same between diets. There is a large literature on apparent digestibility, which could be used to argue against this assumption and the assumption that digestibilities are dependent on dietary source [eg, see the extensive tables in Merrill and Watt (6)]. However, the cause of this variability has not yet been adequately explained. Part of the variability is related to the presence in foods of unavailable carbohydrate (2-5) (see also main paper). The observations in the main paper are consistent with the view that for the diets examined the variability is practically all related to the occurrence, intake, and effects of unavailable carbohydrate.

When the food source of unavailable carbohydrate differs for the two experimental diets of different unavailable carbohy-
drate content, one assumption made when calculating partial-digestible-energy values is that the unavailable carbohydrate in the two diets is similar with regard to its effects on the digestibility of dietary gross energy. Alternatively, the intake of unavailable carbohydrate at the lower level of caloric dilution needs to be relatively small compared with that at the higher caloric dilution. The range of partial-digestible-energy values in Table 3 of the main paper suggests the first of these alternative assumptions could easily be invalidated. It is important, therefore, to minimize the error introduced because of that assumption. One can test whether the value of $D_0$, (Fig 1) predicted from the two (or more) experimental diets is close to 0.98, which is commonly the case (Fig 1, main paper). This does not of itself validate the assumption, though it can be considered to indicate that errors arising from this source are not likely to be great in practical terms. When $D_0$ is not close to 0.98, the assumption is not necessarily invalid, though some errors might be suspected.

There is an exception to the above general rule that the diets with low and high unavailable carbohydrate content should contain unavailable carbohydrate that is similar in its effects on digestibility of dietary gross energy. This exception occurs when the unavailable carbohydrate is added as a supplement to a diet already containing unavailable carbohydrate. The calculation procedures still give the partial-digestible- (or metabolizable-) energy values of these substances but the value of $D_0$ may not be close to 0.98. It is important in these circumstances to make $D_0$ equal to the apparent digestibility of the dietary gross energy when intake of the supplement is zero (see earlier section on calculation of the partial digestible energy of a supplement).

The consequence of excluding $E^\text{uc}$ from $E$ on the variability of the slope and the meaning of the slope

In the main paper the consequence of excluding $E^\text{uc}$ from $E$ on the variability of the slope was discussed. The following proof was referred to. The plot (Fig 1 here and Fig 1 of main paper) of $DE/E$ against $E^\text{uc}/E$ gives a downward slope equal to the partial indigestibility ($S$) of the substance (unsalvable carbohydrate) investigated. The slope is partly dependent on $E^\text{uc}$, which is added to $E$ to give a higher value of $E$ and a lower value of $DE/E$. The influence of $E^\text{uc}$ on the slope can be eliminated by plotting $DE/E - E^\text{uc}$ against $E^\text{uc}/E - E^\text{uc}$; this plot gives a line described by equation 21, which is of the form

$$\frac{DE}{E - E^\text{uc}} = c + m \left( \frac{E^\text{uc}}{E - E^\text{uc}} \right)$$  

(21)

Equation 21 becomes equation 22 after multiplication of each term by $E - E^\text{uc}$, then equation 23 after collection of terms in $E^\text{uc}$:

$$DE = cE - cE^\text{uc} + mE^\text{uc}$$  

(22)

$$DE = cE - E^\text{uc}(c - m)$$  

(23)

When no unavailable carbohydrate is present in the diet the intercept of the plot (Eq 21), $c$, is 0.978 (compare with Fig 1, main paper). Also $E^\text{uc}$ is equal to the product of the heat of combustion of the unavailable carbohydrate [17.2 kJ/g (4.1 kcal/g)] and its intake ($I^\text{uc}$, g), which, when introduced into equation 23, gives equation 24. Now equation 24 compares with equation 2 in the main paper, reproduced here as equation 25:

$$DE (kJ) = 0.978E - 17.2I^\text{uc}(0.978 - m)$$  

(24)

$$DE (kJ) = 0.978E - 17.2I^\text{uc}S$$  

(25)

It follows from equations 24 and 25 that

$$S = 0.978 - m$$  

(26)

Now 0.978 is almost equal to 1 (and would have exactly equaled 1 had the correction term 1 - $D_0$ been involved in the proof) so that

$$S = 1 - m$$  

(27)

In accordance with equation 1, $m$ is then the partial digestibility of the unavailable carbohydrate for energy. It will be remembered that $m$ is the slope of a plot of $DE/E - E^\text{uc}/E$ against $E^\text{uc}/E - E^\text{uc}$ (Eq 21). It is immediately apparent from equation 27 that the variation in the slope of such a plot between experiments must be identical to that for $S$ derived from plots of $DE/E$ against $E^\text{uc}/E$. The consequence of excluding $E^\text{uc}$ from $E$, therefore, is that it has no effect on the variability of the slope. The slope becomes partial digestibility of energy for unavailable carbohydrate rather than partial indigestibility of energy for unavailable carbohydrate.

**Magnification of measurement errors**

Errors in the measured variables (weights and heats of combustion of food, feces, and urine) are magnified to produce larger errors in the calculated partial-digestible- and metabolizable-energy value (7–10). The effects of errors in the measurement variables need to be minimized by selection of an appropriate calculation procedure for determining partial digestible and metabolizable energy (7). The following inappropriate method is sometimes used in the literature (11–13):

$$DE^\text{var} = \Delta DE_{\text{diet}}/\Delta I^\prime$$  

(28)

$$ME^\text{var} = \Delta ME_{\text{diet}}/\Delta I^\prime$$  

(29)

In these equations $\Delta DE_{\text{diet}}$ and $\Delta ME_{\text{diet}}$ are the differences in apparent digestible and metabolizable energy intake, respectively, and $\Delta I^\prime$ is the increase (from one diet to the other of higher intake) in weight that is ingested of the substance under investigation. (These values may or may not have been normalized for the masses of food eaten, and other variables may also have been considered.) With equations represented by equations 28 and 29, considerable errors can be introduced. Representative values of $\Delta I^\prime$ expressed in units of energy intake can be obtained from the differences in $\beta_\gamma$ and $\beta_\delta$ shown in Table 3 of the main paper. In Table 3, for the 20 values shown to represent the data available in the literature, the mean and median values of $\beta_\gamma - \beta_\delta$ are 5% and 3%, respectively. Even a 1% error in the measured heat of combustion of a diet is magnified to become a 20% error in the derived energy value for the unavailable carbohydrate when the change in intake of the low-calorie substance ($\Delta I^\prime$) is equivalent to the above-mean value of 5% of gross energy intake from the whole diet. Correspondingly, the 1% error magnifies into a 33% error when $\Delta I^\prime$ is the above-median value of 3% of gross energy intake from the whole diet. In marked contrast, the corresponding error magni-
The large magnification of measurement errors associated with equations represented by equations 28 and 29 makes it inadvisable to calculate partial-digestible- or metabolizable-energy values of unavailable carbohydrate in a manner tentatively suggested recently (11). The manner was to derive the ΔMEₐ₈₉ in equation 29 as the difference between the metabolizable-energy intake determined by dietary-energy balance and the metabolizable intake predicted from the intakes of protein, fat, and available carbohydrate by using the British system of food-energy assessment (14). The prediction of gross energy from compositional data may incur an error as large as 4% (2), which is magnified severalfold (×20 in the above sample) to produce errors that should be considered unacceptable. For example, it can be calculated (with Eqs 19 and 20) that for the cereal-based diet in reference 5 the metabolizable energy value is 1 kJ (0.3 kcal) per gram unavailable carbohydrate when Q₀ (Eq 19) is assumed to be 0.94 (as indicated above); this compares with the previously published value of 10.5 kJ/g (2.5 kcal/g) (3).

Application to noncombustible materials

The procedure described (Fig 1) applies to combustible materials. A modification is needed for noncombustible materials because they cannot increase the quantity β (the proportion of dietary gross energy attributable to the low-calorie substance). However, such substances can still have partial-digestible-energy values. They may either increase the losses of carbohydrate, fat, or protein to feces or decrease these losses. In such instances plots of apparent digestibility of dietary gross energy vs the ratio of mass of the noncaloric substance to gross dietary energy intake can be used. The slope of such a plot gives the partial-indigestible-energy value of the noncombustible substance directly, with negative slopes indicating negative energy values.

References