Review article

A perspective on food energy standards for nutrition labelling

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Food energy values used for nutrition labelling and other purposes are traditionally based on the metabolisable energy (ME) standard, which has recent support from Warwick & Baines (2000). By reference to current practices and published data, the present review critically examines the ME standard and support for it. Theoretical and experimental evidence on the validity of ME and alternatives are considered. ME and alternatives are applied to 1189 foods to assess outcomes. The potential impact of implementing a better standard in food labelling, documentation of energy requirements and food tables, and its impact on users including consumers, trade and professionals, are also examined. Since 1987 twenty-two expert reviews, reports and regulatory documents have fully or partly dropped the ME standard. The principal reason given is that ME only approximates energy supply by nutrients, particularly fermentable carbohydrates. ME has been replaced by net metabolisable energy (NME), which accounts for the efficiency of fuel utilisation in metabolism. Data collated from modern indirect calorimetry studies in human subjects show NME to be valid and applicable to each source of food energy, not just carbohydrates. NME is robust; two independent approaches give almost identical results (human calorimetry and calculation of free energy or net ATP yield) and these approaches are well supported by studies in animals. By contrast, the theoretical basis of ME is totally flawed. ME incompletely represents the energy balance equation, with substantial energy losses in a missing term. In using NME factors an account is made of frequent over-approximations by the ME system, up to 25 % of the NME for individual foods among 1189 foods in British tables, particularly low-energy-density traditional foods. A new simple general factor system is possible based on NME, yet the minimal experimental methodology is no more than that required for ME. By accounting for unavailable carbohydrate the new factor system appears as specific to foods as the USA's food-specific Atwater system, while it is more representative of energy supply from food components. The NME content of foods is readily calculable as the sum from fat (37 kJ/g), protein (13 kJ/g), available carbohydrate (16 kJ/g), fully-fermentable carbohydrate (8 kJ/g), alcohol (26 kJ/g) and other components. Obstacles to the implementation of NME appear to be subjective and minor. In conclusion, the ME standard is at best an approximate surrogate for NME, and inadequately approximates food energy values for the purpose of informing the consumer about the impact on energy balance of the energy supply for equal intake of individual foods. NME is superior to ME for nutrition labelling and other purposes.

Food energy: Food labelling: Net metabolisable energy

Warwick & Baines (2000) propose that energy factors used for food labelling and other purposes should be based on a definition of metabolisable energy (ME). To some experts this proposal would seem sound, but to others it may be surprising. A superior alternative to ME is the quantity termed net metabolisable energy (NME), which accounts for the efficiency of energy utilisation in metabolism including physical activity (Fig. 1). NME is determinable in two ways: by 24-h indirect calorimetry and by calculation of 'high-energy' bond yields, with the same result. NME
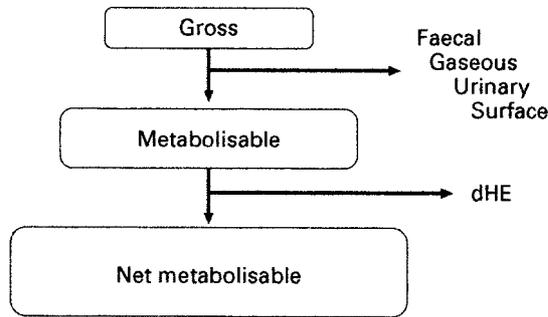

Fig. 1. Energy supply and loss in the net metabolisable energy standard. Energy supplies are shown together with energy losses. Heat energy loss (dHE) is the difference in heat energy expenditure of subjects when they replace available carbohydrate in their diet with another substrate. By convention dHE for available carbohydrate is zero. Net metabolisable energy values of available carbohydrate, unavailable carbohydrate, protein, fat, alcohol, etc. are isodynamic equivalents for energy expenditure and balance.

was reviewed perhaps for the first time in 1980 by an expert panel of the Agricultural Research Council (1980). After an influential report from the Dutch Nutrition Council (1987) led by Professor van Es, who adopted the NME approach, twenty-one other expert reports, reviews and regulatory documents have supported its use for carbohydrates (Bässler, 1989; Bär, 1990; Bernier & Pascal, 1990; British Nutrition Foundation 1990; European Communities, 1990; Japanese Ministry of Health and Welfare, 1991; Livesey, 1991a, 1992; van Es, 1991; Food and Drug Administration, 1993, 1995; Roberfroid et al. 1993; Life Science Research Office, 1994, 1999; Brooks, 1995; Ellwood, 1995; Agriculture and Agri-Food Canada, 1996; Cummings et al. 1997; Wolever, 1997; Food and Agriculture Organization, 1998; International Life Sciences Institute, see Livesey et al. 2000). Collectively these many reports strongly favour the view that metabolisable energy is only an approximation of the energy supplied by nutrient energy sources.

The rationale behind NME is that nutrients do not replace one another in proportion to their ME values or heat equivalents (Rubner, 1902), but in proportion to NME values or ATP equivalents, as noted by the Agricultural Research Council (1980), Blaxter (1989) and others (see previous citations). The validity of NME derives from the close agreement of the two independent state-of-the-art approaches to its determination (noted earlier). By reference to the full energy balance equation ME is totally flawed; by similar reference, NME is valid. A minimum of practical methodology is needed to implement NME; usefully this methodology is no more than that needed for ME, as will be described. The consumer may now be considered to be misled by ME values on labels, because ME does not inform about the ability of individual food items or ingredients to contribute to energy requirements (however, these values are determined). The poor approximation of energy supply by ME for equal energy balance and intake is most evident for low-energy-density foods, traditional and novel. Thus, the ME standard has depreciated and is inadequate for food labelling and other purposes.

The present paper re-examines issues addressed by Warwick & Baines (2000), and asks how food energy

standards (regulations) can be improved. Implications arising from changes that may be made to food energy factors are considered. Contrary to the views of Warwick & Baines (2000), strong support is found for an NME standard and its implementation. More important than ever before is the adoption of NME for dietary fibre and resistant starches, just as it has been for oligosaccharides and sugar alcohols. Indeed, there is now adequate evidence and sufficient information on all macronutrients to apply NME throughout food standards. This approach would make all foods and exchangeable food components have energy values that are comparable with respect to impact on energy balance of energy supply for equal intake. This purpose of food energy evaluation and labelling is achieved by NME but not by ME. The comments of Warwick & Baines (2000) are therefore of great concern, because their view to the contrary forms the basis of advice to the Australia New Zealand Food Authority (ANZFA).

International significance

The Australia New Zealand Food Authority (1991) is currently examining over 100 food regulations to set joint standards for the two countries. Their problems are similar to those in the EU, where joint or international standards are developed. Similarly, in North America there is no joint authority, but concordant outcomes are attempted (Food and Drug Administration, 1993, 1995; Agriculture and Agri-Food Canada, 1996). ANZFA are considering which energy factors to use; certain factors differ in the two countries, and values have yet to be assigned to dietary fibre and some novel food ingredients. No food ingredient with a previously agreed energy value has escaped scrutiny.

ANZFA could choose energy factors concordant with those in the USA, Canada and Europe (Livesey et al. 2000). However, a proposal submitted to Codex by the Australian National Codex Delegation (1998) suggests that this might not happen. Codex sets international standards and those standards are incomplete for energy factors. It would be imprudent to set those standards without adequate review and due regard to the efforts of so many working parties during the past 15 years. The conclusions from these working parties on carbohydrates are equally applicable to protein and other energy sources.

Australia and New Zealand Food Authority, other regions and Codex: the present and the future

Under the ME standard the Atwater system of general factors for food components are usually protein 17 kJ (4 kcal)/g, fat 37 kJ (9 kcal)/g, and carbohydrate 15·7 kJ (3·75 kcal)/g as available monosaccharide or 17 kJ (4 kcal)/g as total available carbohydrate. Although in use across various world regions, this system is little better now than when it was elaborated in 1900 (see British Nutrition Foundation, 1990; Livesey, 1995a). The general factors are far inferior to the food-specific Atwater factors (Merrill & Watt 1973) used where possible in the USA. However, both general and specific food energy factors are under strain: the specific factor system because of its complexity (with different factors being used for different foods) and the

general factor system because of inaccuracies relative to the specific factors. Both specific and general factor systems are under strain because of the increasing recognition that ME provides only approximate food energy equivalents.

The adoption of energy factors varies with time and local regulatory preferences. Unless strongly guided by science there is scope for considerable inaccuracies and conflict. There are three scientifically valid ways to improve food energy factors, but first consider the following.

Energy availability: a general factor system can be practically food specific

A notion has arisen that general energy factors cannot predict energy values of individual traditional foods, because of interactions between components. Thus, specific energy factors are preferred in the USA (Merrill & Watt, 1973). Unavailable carbohydrate has been the main cause of suggested interactions. In practical terms the notion is now untrue, because an account of unavailable carbohydrate is possible (British Nutrition Foundation, 1990; Livesey, 1990a, Livesey 1991a,b). To perpetuate this notion, as do Warwick & Baines (2000), is anachronistic.
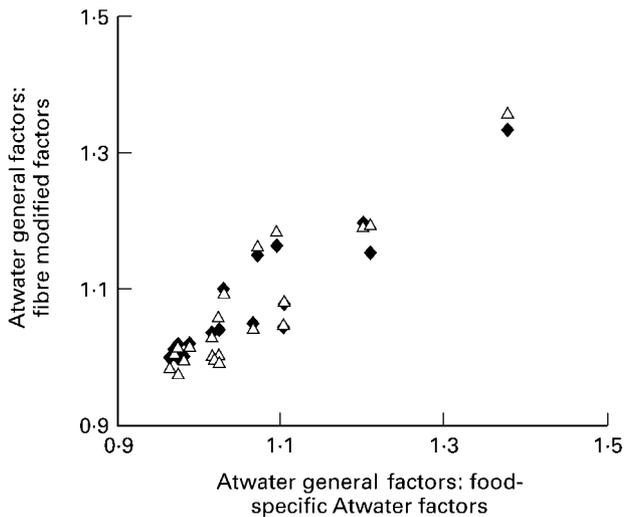

Fig. 2. Factors for unavailable carbohydrate make energy values effectively food specific. X axis: Merrill & Watt (1973) showed for the several foods (beef, salmon, eggs, milk, butter, vegetable fats and oils, oatmeal, brown rice, white rice, wheat flour, whole-wheat flour, beans, peas, snap beans, cabbage, carrots, potatoes, turnip, apple, lemon and peach) that food energy declared using general factors (16·7, 37 and 16·7 kJ (4, 9 and 4 kcal respectively) metabolisable energy (ME)/g protein, fat and total carbohydrate respectively) ranged from 1·0 to 1·38 when expressed relative to the energy value obtained using specific factors for individual foods. Thus, general factors can result in errors of up to 38 % for individual food items and these are corrected by using food-specific factors. Y axis: this error can be similarly eliminated for the same foods from the British food tables (McCance & Widdowson, 1991) by replacing total carbohydrate 16·7 kJ (4 kcal) (ME/g) with both available 15·7 kJ (3·75 kcal) ME/g monosaccharide and unavailable carbohydrate (UC; and 8 kJ (2 kcal) ME/g respectively (◆). Alternatively, error can be eliminated by using an empirical equation: $0.95IE - 7N - 2UC$ kcal/g or $0.95IE - 30N - 9UC$ kJ/g (Livesey, 1991a) where IE is ingested (gross) energy and N is protein nitrogen intake (△). For the present illustration UC was Southgate (1969) dietary fibre.

To add emphases see Fig. 2, which shows two things: first, general energy factors with no account of unavailable carbohydrate may cause up to 38 % error in the estimate of energy from food items (x axis, see Fig. 2 legend; Merrill & Watt, 1973); second, general energy factors modified to include unavailable carbohydrate closely predict energy availability from specific foods (y axis compared with x axis). Methods comparison analysis, i.e. a regression of methods difference v. methods means (Altman, 1991), shows no significant difference between the modified general and specific factor methods (comparison regression coefficient $P > 0.6$; differences from methods mean 0·01 (SD 0·02) kJ/g). Consequently, we can regard the modified general factor approach as being reasonably applicable to foods in addition to diets.

That unavailable carbohydrate has a marked impact on the assessment of energy value of common food items (Fig. 2) is not always appreciated, owing to a tendency amongst nutritionists to think about impact on diets. For the purpose of food labelling, the focus should be on foods and not on diets.

Three ways to improve food energy factors

Gross energy

Instead of implicitly estimating this element within food energy factors, it might be measured directly as suggested previously (Merrill & Watt, 1973; Southgate, 1975; Allison & Senti, 1983; Miller & Judd, 1984; Livesey, 1991b). However, this is less important than other improvements mentioned below. Regrettably insufficient data exist at present for implementation.

Unavailable carbohydrate

Separate factors for fermentable (8 kJ (2 kcal)/g) and non-fermentable unavailable carbohydrate (0 kJ (0 kcal)/g) can be adopted (British Nutrition Foundation, 1990; Livesey, 1992). Dietary fibre comprises both forms, and so for mixed diets an intermediate value (6·2 kJ (1·5 kcal)/g) would apply (British Nutrition Foundation, 1990; Livesey, 1990a, 1991a,b, 1992; Table 1). The value for fermentable carbohydrate applies also to oligosaccharides, resistant starch, sugar alcohols and certain rare sugars and corresponds to 50 % of the gross energy in fermentable carbohydrate being available, a value that enjoys widespread support (for references, see pp. 271–272). All these values are NME.

Protein

Protein (17 kJ ME/g or 4 kcal ME/g) is particularly thermogenic, and so the NME standard may reasonably be extended to protein, at 13 kJ NME/g (3·2 kcal NME/g) (British Nutrition Foundation, 1990; Livesey, 1995a).

Combined improvements

Combined adoption of NME for fermentable unavailable carbohydrate and protein would avoid substantial errors

Table 1. Gross intake (IE), digestible (DE), metabolisable (ME) and net metabolisable energy (NME) factors for important food components and the prediction of specific food NME values (for factors for other components, see Independent Nutrition Logic, 2000)

	IE*	DE*	ME*	NME	Units
General factors					
Fat (F; g)	39·3	37·4	37·4	36·6	kJ/g ingested F
Protein (P; g)	23·6	21·5	16·7	13·3	kJ/g ingested P
Available CHO (AC; g)†	15·7	15·7	15·7	15·7	kJ/g ingested AC as monosaccharide
Dietary fibre (DF; g)	17	7·8	7·8	6·2	kJ/g ingested DF‡
Fermentable†	17	11	11	8	kJ/g ingested fermentable DF
Non-fermentable†	17	0	0	0	kJ/g ingested non-fermentable DF
Alcohol (Alc)	29·4	29·4	28·8	26·4	kJ/g ingested Alc

Food energy (ME; kJ) = 37 F + 17 P + 16 AC + 8 DF + 29 Alc (rounded from 37·4 F + 16·7 P + 15·7 AC + 7·8 DF + 29·4 Alc).
Food energy (NME; kJ) = 37 F + 13 P + 16 AC + 6 DF + 26 Alc (rounded from 36·6 F + 13·3 P + 15·7 AC + 6·2 DF + 26·4 Alc).
* From Merrill & Watt (1973), using their IE, digestibilities and urinary energy loss (5·2 kJ/g digestible N) and energy loss in breath (2 % energy losses from alcohol as volatile substances in breath and urine).
† NME and ME values also applicable to isolates of NSP, resistant starch oligosaccharides and sugar alcohols.
‡ For traditional foods this can be Southgate (1969) dietary fibre, Association of Official Analytical Chemists (Prosky *et al.* 1988) dietary fibre or the sum of NSP and associated resistant starch when it is <20 % of non starch polysaccharide.

(Fig. 3). ME as an approximation of the NME standard is in error by up to 25 % of the energy value for an individual food. The error is most marked for low-energy-density foods, in this case traditional foods. Such errors in weights and volumes on food labels would see a weights and measures inspector taking action. The measure is energy (kJ or kcal) on food labels and the consumer should beware and be adequately informed. These data illustrate that the ME standard provides only an illusion of comparability between foods. Extending the use of NME would continue the rapidly-developed trend to remove approximations.

Metabolisable energy is totally flawed, and at best is an approximate surrogate of available energy

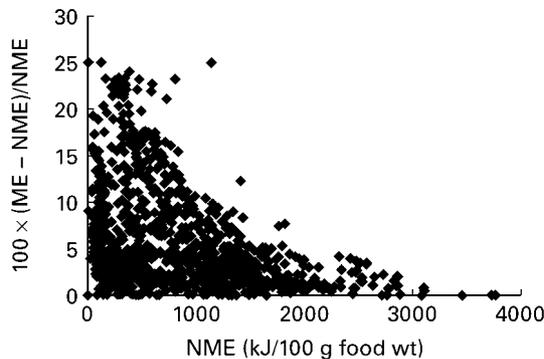The full energy balance equation (National Research Council, 1981) comprises ingested energy (IE), faecal energy (FE), gaseous energy (GaE), surface energy (SE), heat energy (HE) and retained energy (RE), such that:

$$IE = FE + GaE + UE + SE + HE + RE. \quad (1)$$

Rearrangement to obtain retained energy gives:

$$RE = IE - FE - GaE - UE - SE - HE. \quad (2)$$

Energy available (kJ/g) from an ingested substrate (IS; g) is the change (d) in retained energy (dRE; kJ) with change in the ingestion of a substrate (dIS; g), which gives the following simple differential:

$$\frac{d\text{RE}}{d\text{IS}} = \frac{d\text{IE}}{d\text{IS}} - \frac{d\text{FE}}{d\text{IS}} - \frac{d\text{GaE}}{d\text{IS}} - \frac{d\text{UE}}{d\text{IS}} - \frac{d\text{SE}}{d\text{IS}} - \frac{d\text{HE}}{d\text{IS}}. \quad (3)$$

When an ingested substrate has no influence on HE expenditure the term dHE$/d$IS in equation 3 is zero, and the quantity dRE$/d$IS is a ME (kJ/g) value (*v.* ME = IE − FE − GaE − UE − SE; Australia New Zealand Food Authority, 1999*a,b,c*). Otherwise dHE$/d$IS is not zero and the quantity dRE$/d$IS is a net energy (NE) value (kJ/g). It is clear that metabolisable energy is valid only when dHE$/d$IS can be proved negligible. Otherwise the ME concept is flawed, and dropping dHE$/d$IS is improper with respect to a substrate's impact on energy balance. A special condition would arise should the ratio of dHE$/d$IS to the metabolisable energy (dME$/d$IS) be the same for all energy substrates. ME would then be proportional to NE, and a useful surrogate for NE. As this special condition does not hold (as will be shown), then ME is totally flawed.

Entry of net energy terminology into human nutrition

The term 'net energy' (NE) was formally introduced to human nutrition for the US Department of Agriculture via Allison & Senti (1983) when adopting animal nutrition terminology (National Research Council, 1981). NE differs from ME by an amount of heat released during metabolism, which some have called dietary-induced thermogenesis. However, none of the many reviews and reports concerned with the determination of human food energy factors use such NE values; all derive quantities that are NME values, which are derived from the NE concept (equation 3).

Fig. 3. Over-estimation of the isodynamic equivalents for energy expenditure and energy balance (net metabolisable energy; NME) by the (metabolisable energy; ME) standard when applied to 1189 foods in the British food tables, due to protein and unavailable carbohydrate. ME of foods was calculated using available carbohydrate as monosaccharide (15·7 kJ (3·75 kcal) ME/g), fat (37 kJ (9 kcal) ME/g), protein (16·7 kJ (4 kcal) MEkJ/g), dietary fibre (8·4 kJ (2 kcal) ME/g), alcohol (29 kJ (7 kcal) ME/g) and appropriate factors for organic acids. NME was calculated by replacing the ME factors for protein and dietary fibre with NME factors from the British Nutrition Foundation (1990) report: 13 kJ (3·2 kcal) NME/g and 6·2 kJ (1·5 kcal) NME/g respectively. For the present illustration dietary fibre was Southgate (1969) dietary fibre.

Net metabolisable energy

Empirical net metabolisable energy

This derives from the NE concept, which interrelates NE, change in stored or retained energy (dRE; kJ) and change in ingested energy (dEI; kJ; National Research Council, 1981) or substrate (dIS; g; equation 3):

$$NE = dRE/dIS. \qquad (4)$$

Applying terminology used in human nutrition (dRE is energy balance; EB) and rearranging gives:

$$EB = dIS \times NE. \qquad (5)$$

For intakes of different composition (substrates 1 and 2) of potentially different efficiencies of utilisation for the same energy balance (prime on IS$'$) we have equation 6 and its rearrangement equation 7:

$$EB = dIS_1' \times NE_1 = dIS_2' \times NE_2, \qquad (6)$$

$$NE_2/NE_1 = dIS_1'/dIS_2'. \qquad (7)$$

Equations 6 and 7 indicate that the relative NE value of substrates 1 and 2 is equal to the relative mass intakes that ensure the same energy balance. Here, substrate can mean either ingredient or food component or food or meal or diet. NE_2:NE_1 is the determinant of NME (equation 8):

$$NME_2 = ME_1 \times (NE_2/NE_1). \qquad (8)$$

Practical experiments

In equation 8, NE_1 is for a known substrate, and NE_2 is for a test substrate. Typical of large animal studies, the relative amounts of substrate required to establish zero energy balance (dIS_1'/dIS_2' in equation 7) can be used in place of NE_2/NE_1 in equation 8. Typical of small-animal studies, the intakes of control and test substrates are the same ($dIS_1 = dIS_2$), and so the ratio of energy retention (dRE_2/dRE_1) is used in place of NE_2/NE_1 in equation 8. Typical of human studies, the intake of the two substrates are the same ($dIS_1 = dIS_2$) and NE_2/NE_1 in equation 8 is replaced not by (dRE_2/dRE_1) but by its equal ($dME_2 - dHE_2$)/($dME_1 - dHE_1$). When $NME_1 = ME_1$ as for available carbohydrate then $dHE_1 = 0$ and $dHE_2 = dHE_2 - dHE_1$. Hence, NE_2/NE_1 in equation 8 can be replaced with ($ME_2 - dHE_2$)/ME_1 to give equation 9:

$$NME_2 = ME_2 - dHE_2. \qquad (9)$$

In human subjects NME can be determined by indirect calorimetry; in animals it may be determined by either calorimetry or 'difference trial'. Since NME is derived from NE, it is open to influence by hormones that are responsive to dietary intake. The scheme showing disposition of energy suggested by Warwick & Baines (2000) is incorrect for NME determined in practice.

Human studies

The NME value of a test substrate is obtained using equation 9 in which ME_2 is the ME of a test substrate and dHE_2 is the difference in 24 h heat energy expenditure of subjects on test (HE_1) and control diets (HE_2), while undertaking similar expenditure on physical activity and after exchanging available carbohydrate for a test substrate:

$$dHE_2 = HE_2 - HE_1. \qquad (10)$$

The approaches to derivation of NME do not feature BMR. However, where BMR is considered to be the same for subjects on two different diets, NME may be calculated by replacing dHE in equation 9 with the differential heat increment (dH$_i$):

$$NME_2 = ME_2 - dH_i, \qquad (11)$$

where $dH_i = H_iE_2 - H_iE_1$ for test substrate (2) and available carbohydrate (1) and $H_iE = HE - BMR$.

Theoretical net metabolisable energy

This is simply (equation 12) the ME value of a substrate (2) multiplied by the 'high-energy' bond yield of the substrate oxidised *in vivo* (net ATP gain per kJ ME):that for available carbohydrate (1):

$$NME_2 = ME_2 \times \left(\frac{netATP_2}{ME_2} \middle/ \frac{netATP_1}{ME_1} \right), \qquad (12)$$

$$NME_2 = ME_1 \times (netATP_2/netATP_1). \qquad (13)$$

Equation 12 rearranges to equation 13, which has an identical form to equation 8 for empirical NME. Theoretical NME relates to energy supply and the derivation does not discount energy utilisation on such as glycogen synthesis or gluco-sympathetic thermogenesis. These contributions to thermogenesis vary, at least in short-term studies, with eating behaviour and the metabolic state of an individual and are not obligatory to the food component, but to the circumstances of the observation; for example, the amount administered (low intakes of glucose simply replace hepatic glucose production; Livesey *et al.* 1998), the route of administration (the oral, intragastric and parenteral routes affect thermogenesis from glucose) and the subjects chosen to study (insulin resistance affects 'facultative' thermogenesis). Such thermogenesis cannot be attributed to the substrate administered, because the ATP expended may have been generated from other endogenous or dietary components (Elia & Livesey, 1988).

Heat, a large contributor to energy loss from dietary components

Energy lost from ingested energy (IE) is the sum of faecal energy (FE), urinary energy (UE), gaseous energy (GaE), surface energy (SE) and differential heat energy (dHE), from which NME (see equation 3) is derived:

$$NME = IE - (FE + UE + GaE + SE + dHE). \qquad (14)$$

These energy losses are shown in Fig. 4, except for surface energy, which is negligible. Values of dHE shown were calculated two ways; in theory (dHE_{the}) based on net ATP gains (equation 13) and in practice based on observations (dHE_{obs}) from indirect calorimetry studies (equation 9; see legend to Fig. 4).
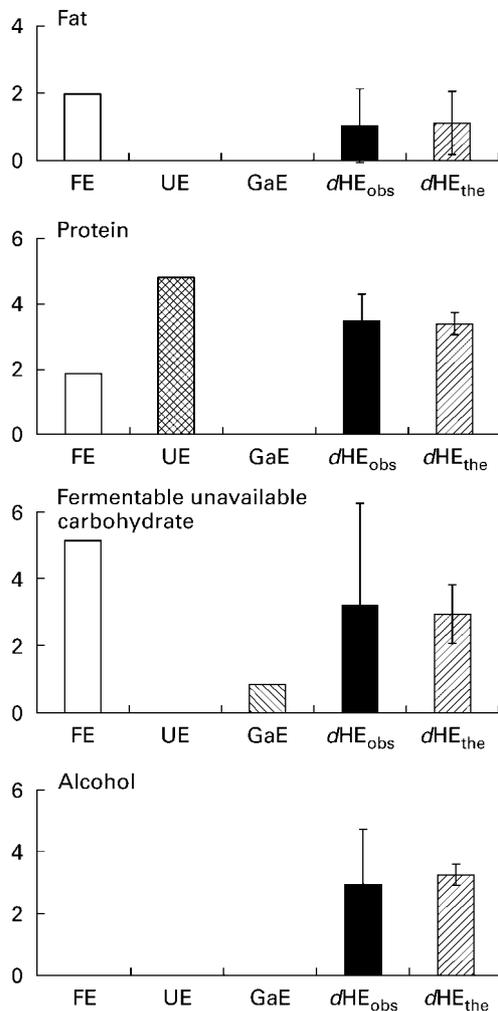
Fig. 4. The nature of energy loss (kJ/g) from food components on the net metabolisable energy (NME) standard in human subjects. FE, faecal energy; UE, urinary energy; GaE, gas energy (gaseous hydrogen and methane); dHE$_{obs}$, the difference in heat production in human subjects between the component shown and available carbohydrate in the mixed diet; dHE$_{the}$, component net ATP gain:net ATP gain for available carbohydrate (glucose) calculated as described by Livesey (1984, 1985). Surface energy losses are negligible (not shown). Available carbohydrate is not shown because FE, UE, GaE and dHE are zero. The values of FE and UE are from Merrill & Watt (1973). GaE is from the British Nutrition Foundation (1990). The values are means and the vertical bars for dHE$_{obs}$ represent the standard deviations for the number of observations stated, and for dHE$_{the}$, represent the range of uncertainty in the relative net ATP gains due to ±10 % uncertainty of the efficiency of mitochondrial respiration *in vivo* (Livesey, 1984, 1985). In the case of alcohol the most efficient metabolic pathway was assumed. dHE$_{obs}$ was calculated (see equation 9) applying appropriate corrections to zero nitrogen and energy balance using data from human studies: fat (Hurni *et al.* 1982; Hill *et al.* 1991; Rumpler *et al.* 1991; Thomas *et al.* 1992; Stubbs *et al.* 1995a; Raben *et al.* 1997); protein (Dauncey & Bingham, 1983; Nair *et al.* 1983; Steiniger, 1983; Karst *et al.* 1984); fermentable unavailable carbohydrate (where non-fermentable unavailable carbohydrate was assigned a zero energy value: van Es *et al.* 1986; Heijnen *et al.* 1995; Poppitt *et al.* 1998; Buemann *et al.* 1998; Castiglia-Delavaud *et al.* 1998; Rumpler *et al.* 1998); and alcohol (Suter *et al.* 1994; Klesges *et al.* 1994; Sonko *et al.* 1994). The number of observations (and significance of mean dHE$_{obs}$ using Student's t test) were: fat n 8, $P < 0.05$; protein n 8 $P < 0.001$; unavailable carbohydrate n 8, $P < 0.05$; alcohol n 3, $P < 0.05$, where each nth observation is a mean result for an experimental group.

Fig. 4 clearly shows four points: (a) For fat, protein, fermentable unavailable carbohydrate and alocohol, dHE$_{the}$ and dHE$_{obs}$ are practically identical. There is therefore no ground for concern (Warwick & Baines, 2000) over the use of the theoretical approach to determine NME. Indeed, for novel foods yielding known metabolites it may be more reliable than using 24-h chamber calorimetry. Nevertheless, the two approaches when concordant provide reasonable validation of an energy claim; (b) for each substrate, dHE is large relative to total energy losses, and so warrants being taken into account in food energy evaluation; (c) dHE is very dependent on the energy source and so should be accounted for in food energy evaluation, rather than by adjusting food energy requirements; (d) for alcohol and fat the dHE relative to available carbohydrate is higher than expected from studies measuring dietary-induced thermogenesis over 2–3 h duration.

For alcohol, point (d) was noted by Prentice (1995, 1996), who like Flatt (1985) and Blaxter (1989) reasoned that longer studies would be more representative. Short studies also show fat to yield a low thermic response (0–4 % intake, less than for glucose about 8 %; Flatt, 1978; Karst *et al.* 1984) compared with longer studies (Fig. 4). This finding is not unexpected; lipid is generally assimilated slowly, pools in the lymph and circulation and is oxidised secondarily to other substrates. Moreover, when glycogen is stored it is not just glucosyl units but also one ATP equivalent per glucose stored, so that short studies under-emphasize the efficiency of glucose utilisation. Another case in point with respect to short studies is the suggested absence of thermogenesis from resistant starch (Raben & Astrup, 1996). This study was too short for thermogenesis associated with fermentation to have been observed.

It is worth noting that dietary-induced thermogesnesis is frequently related to the amount of substrate ingested. Originally it was related to BMR, the change being made simply to lower the variance (Kleiber, 1975). Neither expression is appropriate for assessing the efficiency of substrate utilisation because rarely is the oxidative fuel mix identical to the mix of ingested energy sources during short intervals of time. Conditions necessary for the assessment of NME in human subjects are that N and energy balance be the same in the two arms of the study (substrate *v.* available carbohydrate). Departure from these conditions requires simple adjustments to be made.

Similarity of differential heat energy (hence net metabolisable energy) from theory and practice

It is usual in human studies to compare the observed change in heat production with that expected from the theory of net ATP gains. The difference is said to be facultative and mediated by hormonal and/or neural stimuli. Warwick & Baines (2000) indicate that food-related hormonal stimuli are determinants of NE (and so dHE). However, we have already encountered how dHE determined by indirect calorimetry is practically identical to dHE calculated from knowledge of net ATP gains in the metabolic pathways (Fig. 4). As we shall see, this similarity also applies in animals (Fig. 5). Thus, hormonal and neural stimuli are not
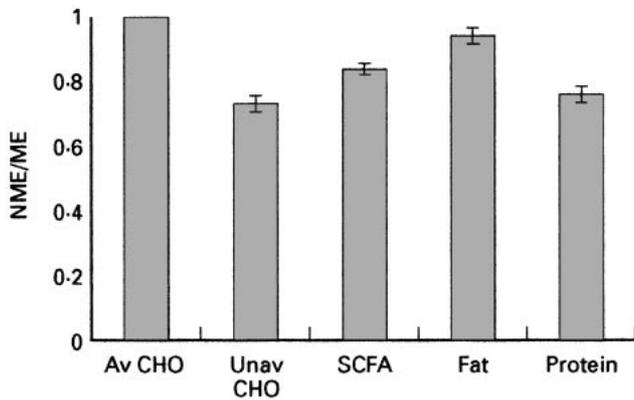
Fig. 5. Efficiency of utilisation of metabolisable energy (ME) for net metabolisable energy (NME) in single-stomached animals including stomach-fed sheep. Values relative efficiency of ME utilisation for energy expenditure and balance (k_{ee}, equation 15, see p. 277) are means and standard deviations for observations pooled from the rat, pig, dog and stomach-fed sheep, and are from Rubner (1902), Schiemann et al. (1971), Hoffmann et al. (1986), Livesey (1990b), Jørgensen et al. (1997), Smith et al. (1998) and Jørgensen & Lærke (1998). Available carbohydrate (Av CHO) has NME/ME = k_{ee} = 1 by convention. The number of observations are: unavailable carbohydrate (Unav CHO) n 3, short-chain fatty acids (SCFA) n 7, fat n 5, protein n 6, where each nth observation is a mean result for an experimental group. Each difference from 1·00 was significant (Student's t test, $P < 0.001$). Bars are SEM.

evidently determinants of NME; rather the key determinant is metabolic pathway efficiency.

Relative efficiency of metabolisable energy utilisation for energy expenditure and balance

The relative efficiency of ME utilisation for energy expenditure and balance, k_{ee}, is given by:

$$k_{ee} = \frac{\text{NME}}{\text{ME}} = \frac{\text{ME} - d\text{HE}}{\text{ME}}. \quad (15)$$

Relative efficiencies are 1·00 for available carbohydrate (by convention, Agricultural Research Council, 1980; Livesey, 1984,1985; Dutch Nutrition Council, 1987; Blaxter, 1989) and calculated (equation 15) from $d\text{HE}_{obs}$ (Fig. 4) they are 0·97 (SEM 0·1; $P < 0.02$, Student's t test, when compared with 1·00) for fat, 0·79 (SEM 0·02; $P < 0.001$) for protein, 0·71 (SEM 0·09; $P < 0.001$) for fermentable unavailable carbohydrate and 0·90 (SEM 0·04; $P < 0.05$) for alcohol. Values of k_{ee} calculated (equation 15) from $d\text{HE}_{the}$ (Fig. 4) are 0·98, 0·80, 0·76 and 0·9 respectively, and are in close agreement. Support for these values comes from animal studies.

Relative efficiencies of metabolisable energy use for energy expenditure and balance: animal studies

Data from the Agricultural Research Council (1980) and Blaxter (1989) from animal studies have been pooled with other data and reported in Fig. 5. In animals the efficiency of use of protein energy (0·8) is the same as in human subjects (see p. 276). As in human subjects, fat is used

in animals less efficiently than available carbohydrate (glucose or starch). Studies on alcohol in animals have not been reviewed here, except to say that those in rats indirectly referred to by Warwick & Baines (2000) are not physiological, owing to the absence from the diet of adequate amounts of available carbohydrate (Prentice, 1996). A similar derangement of metabolism due to absence of adequate glucose was observed after high doses of acetate in sheep in the thorough work and reasoned discussion of Armstrong (see Blaxter, 1967, 1989).

In human subjects, the $d\text{HE}_{obs}$ for fermentable unavailable carbohydrate (Fig. 4) corresponds closely to the k_{ee} from animal studies (Fig. 5). The animal studies (Fig. 5) also show information on the efficiency of short-chain fatty acid utilisation, which is lacking in human subjects except for a single estimate of 0·85 kJ/kJ for acetate (Livesey & Elia, 1995), which is in agreement with the animal data. The mean difference in the efficiency of use of short-chain fatty acids and fermentable carbohydrates in animals (Fig. 5) is 10 (SD 3) %. This difference is due to the heat of fermentation and compares with a directly determined value in vivo of 7 % (Webster, 1978) and a theoretical value of 6·5 % (Hungate, 1966).

The underlying basis of the relative efficiencies (k_{ee}, Fig. 5) and differential heat energy loss ($d\text{HE}_{obs}$, Fig. 4) is the relative net gain of ATP (Agricultural Research Council, 1980; Blaxter, 1989), and this is confirmed for human subjects (Fig. 4) and for fermentable unavailable carbohydrate in both human subjects and animals (Figs. 4 and 5). Indeed, it seems that individual substrate values of k_{ee} are identical or remarkably similar across human and experimental animal species; this finding is consistent with the major metabolic pathways having an early evolutionary development. Data from modern human and animal studies in vivo provide added validity to the widely held view that ME is only an approximation of equivalent energy values, and that energy values are better represented by NME.

Two different approaches are available to us to determine NME values, one being experimental, the other being theoretical. Deriving energy values both ways provides regulatory authorities with evidence of validity of energy claims for food components. By contrast, ME values are not comparable with respect to impact on energy balance for equal intake, and are almost as misleading as are gross energy values as approximations of ME values. The various authorities and reviewers choosing the NME standard are justified in doing so.

NME values of important energy sources

ME values of 17, 37, 17 and 11 kJ (4, 9, 4 and 2·6 kcal)/g are general standard values for available carbohydrate 'by difference', fat, protein and fermentable unavailable carbohydrate, respectively (Merrill & Watt, 1973; British Nutrition Foundation, 1990; McCance & Widdowson, 1991). Given these, multiplication by the relative efficiencies (k_{ee}) gives NME values (equation 16, a rearrangement of equation 15):

$$\text{NME} = \text{ME} \times k_{ee} = \text{ME} - d\text{HE}. \quad (16)$$

NME values corresponding to the above ME values are 17,

37, 13 and 8 kJ (4, 8·8, 3·2 and 2 kcal)/g. As noted earlier, dietary fibre is not completely fermentable, and so a lower general NME factor applies, 6·2 kJ (1·5 kcal)/g corresponding to a fermentability of approximately 70 % for diets of traditional foods (Livesey, 1990a). This factor appears reasonably applicable to individual foods for the purpose of calculating energy values (Fig. 2), but is not applicable to all isolates of dietary fibre, since fermentability may vary between isolates (British Nutrition Foundation, 1990; Livesey et al. 1995).

Individual energy factors are summarised in Table 1, in which available carbohydrate 'by difference' is replaced with available carbohydrate 'as monosaccharide'. Subclasses of protein, fat, available and unavailable carbohydrates are considered further later (see p. 278).

Net metabolisable energy values of minor energy and replacement components

Components that we regard as minor may have a substantial impact on the assessment of the energy value of foods (see Fig. 2), and so require appropriate energy values. In Europe, novel foods require their energy values to be assessed as part of their safety evaluation (European Communities, 1997).

Carbohydrate substitutes

These components include dietary fibre isolates, resistant starch, oligosaccharides, and sugar alcohols. All components comprise available and unavailable carbohydrate and can be treated similarly (e.g. 17 kJ/g available carbohydrate and 8 kJ/g fermentable unavailable carbohydrate, see earlier). Sugar alcohols have been widely reviewed (Livesey et al. 2000) and those suggested by the Life Science Research Office (1994) have provided a basis for food regulations.

In traditional foods the amount of resistant starch is small and can be considered to nest with dietary fibre in the Association of Official Analytical Chemists (Prosky et al. 1998) and Southgate (1969) dietary fibre methods. Where resistant starch replaces available starch in foods, knowledge about its utilisation in human subjects is advisable for estimation of its energy value (Livesey, 1994). For the present, most resistant starch may be considered to be fermentable. The starch and resistant starch content of foods may vary with processing, which can be accounted for in food analysis. However, it is impossible to account for post-sale processing of foods, which may vary resistant starch content to a small extent. Nutrition labelling of energy value can only apply to the food as sold or food as commonly prepared.

Fat-based fat substitutes

NME values can be derived as described by Livesey et al. (2000). Certain values are given later (p. 279).

Protein-based fat substitutes

These can be treated like all other dietary proteins, with

NME of 13 kJ (3·2 kcal)/g (Fig. 4; British Nutrition Foundation, 1990).

Organic acids

These acids occur in foods as acidulants and preservatives and in fruits (<3 % total energy). As such in foods they are very minor components and so their availability as energy is of little concern, with gross energy being adequately represented (Merrill & Watt, 1973; McCance & Widdowson, 1991). However, some organic acids are of metabolic interest and add to evidence supporting the appropriateness of the NME standard. Data from human studies suggest that lactic and short-chain fatty acids have thermogenic responses consistent with their net ATP yields. For acetate this response was 0·85 NME/ME (Livesey & Elia, 1995, based on data from Akanji et al. 1989). For lactate this response is as follows: gluconeogenesis from lactate costs 6 ATP/mol glucose formed (Newsholm & Leech, 1983), while glucose oxidation yields net 36·7 ATP/mol (Livesey, 1984). Thus, the thermogenic response expected of lactate is 6 ATP used/36·7 ATP equivalents gained or, in terms of heat, 0·16 kJ/kJ ME (i.e. 6/36·7). Ferrannini et al. (1993) showed thermogenesis to be higher by 0·48 kJ/min during the last 2 h of a steady-state lactate infusion at a constant rate of 2·23 kJ/min, which corresponds to a total thermogenic response of 0·21 kJ/kJ ME (i.e. 0·48/2·23). The value was 0·04 kJ/kJ ME for intravenous glucose, which has to be deducted to obtain the dH$_i$ (equation 11) for lactate of 0·17 kJ/kJ ME, essentially identical to the 0·16 expected. Thus again, net ATP yield appears to be the basis of the heat energy loss, and this without the facultative thermogenesis once supposed (Ferrannini et al. 1993).

Net metabolisable energy factors more specific than general ones: is there a need?

In many cases specific energy factors appear to be necessary. To allocate a specific NME value in Europe, and as a test of whether a macronutrient may be considered novel, the International Life Sciences Institute (see Livesey et al. 2000) declared it important to know when an energy value differs from the general energy value assigned in legislation (for example, see European Communities, 1990).

In the case of protein, the net ATP gain per kJ ME varies little (Livesey, 1985). Protein in different food groups (cereal, milk, eggs, meat, fish, vegetables, fruits, nuts, etc.) differs negligibly from the mean for 101 food proteins; by <0·03 parts of the mean with a CV of <0·02 in any one food group. The variation shown in Fig. 4 is small too, and includes information gained with casein, gelatine, egg-white and beef-and-cheese.

In the case of fats the net ATP gain per kJ ME has a CV amongst 116 food fats that is negligible, at 0·002 (Livesey, 1984). The variation shown in Figs. 4 and 5 is also remarkably small. Lichtenbelt et al. (1997) report a 4 h thermogenic response that is 1 % higher for polyunsaturated fat than for saturated fat. Longer studies are necessary because unsaturated fats are oxidised less quickly than

polyunsaturated fats; Rumpler *et al.* (1998) found no differences in 24 h chamber studies in human subjects. Chain length affects the efficiency of ME use for NME, k_{ee}; long chains being 0·98 (see p. 277), medium chains being 0·93 (Livesey, 1985) and short chains being 0·85 (see p. 277). In short-term studies of thermogenesis due to medium-chain fatty acids, higher energy expenditure is expected due to the lower k_{ee} value for relative efficiency, and rapid oxidation relative to long-chain triacylglycerols. Short- and medium-chain fats merit specific energy values because of differences in their heats of combustion (Livesey, 1992). However, much larger differences are found for low-energy alternative fats, which have NME values in the range from 0 to 23 kJ/g (Livesey *et al.* 2000).

Among the available carbohydrates, glucose, maltose, starch, galactose and lactose ingested singly elicit similar thermogenic responses in human studies of less than 24 h duration (MacDonald, 1984; Blaak & Saris, 1996; Raben *et al.* 1997). However, sucrose and fructose are more thermogenic than glucose and starch (Schwartz *et al.* 1989, 1992; Blaak & Saris, 1996; Raben *et al.* 1997). Fructose alone may cause lactic acidaemia and obligatory thermogenesis due to high lactate and gluconeogensis (see p. 278). The difference in thermogenesis (dH_i) between glucose (or starch) and fructose is 0·4 (SD 0·3) kJ/g (n 5; calculated from Simonson *et al.* 1988; Schwartz *et al.* 1989; Fukagawa *et al.* 1995; Blaak & Saris, 1996). Thus, k_{ee} for fructose is 0·97 (kJ NME/kJ ME). This difference can be explained by obligatory costs (Schwartz *et al.* 1992) or in part by facultative thermogenesis. It might also be considered that bolus ingestion of 75 g fructose in water, as in these studies, may also cause intestinal hurry and a thermogenic response simply due to early fermentation. The differential heat increment dH_i, for fructose is within the rounding error ($\pm 0·5$ kJ/g) and so might be neglected in food energy standards.

With sucrose or an equimolar glucose–fructose mixture, dH_i (equation 11) is 0·8 (SD 0·1) kJ/g (n 4) (*v.* glucose or starch) when based on data from MacDonald (1984), Blaak & Saris (1996) and Raben *et al.* (1997); and corresponds to a k_{ee} of 0·94 (SD 0·01; n 4, $P < 0·001$) and NME of 15 kJ/g as monosaccharides (*v.* 15·7 kJ ME/g).

Under the guidance given by the International Life Sciences Institute (see Livesey *et al.* 2000), no case mentioned earlier amongst traditional foods and ingredients necessitates assigning a specific NME factor. The possible thermogenic effect of sucrose is important quantitatively, at least for research purposes, and deserves further study. It is also of potential practical significance to the evaluation of low-energy sugar substitutes. When NME values are determined experimentally by sucrose replacement (van Es *et al.* 1986; Livesey, 1990*b*) the determined NME value of the sugar substitute will tend to be overestimated relative to available carbohydrates in general. However, the difference is sufficiently small to be of no real concern. Sugar substitutes have NME values that range from 0 to approximately 15 kJ (0 to approximately 3 kcal)/g and require specific NME factors (Livesey *et al.* 2000).

Simplicity of net metabolisable energy factors

Table 1 shows the general energy factors as gross energy, digestible energy, ME and NME values and how these come together as factors for the calculation of food energy. The equation shown in Table 1 for the calculation of food energy as NME is just as simple as the one for calculating ME, but avoids the bias and scatter shown in Fig. 3. Foods that include additional components (organic acids, fat and sugar substitutes, etc.) have additional energy (or less energy if it replaces a traditional component): for example, NME values (kJ/g) of isomalt 8, lactitol 8, polydextrose 4, caprenin 5, salatrim family 5, olestra 0, etc.

Minimal methodology for net metabolisable energy

In general, food energy values are generated not from energy balance studies but from determinations of the disposition of nutrients and quasi-constants validated *a priori* for each class of nutrient. This determination is summarised by equation 17 for NME, which is similar to that currently used for ME as modified to account for available (Av CHO) and unavailable (UnAv CHO) carbohydrate separately (equation 18):

$$\text{NME } (\text{kJ/g}) = (p \times H)_{\text{AvCHO}} + (p \times H \times 0·98D)_{\text{fat}}$$
$$+ (p \times (H - 5·2) \times 0·8D)_{\text{protein}}$$
$$+ (p \times H \times 0·50D)_{\text{UnAvCHO}}, \qquad (17)$$

$$\text{ME } (\text{kJ/g}) = (p \times H)_{\text{AvCHO}} + (p \times H \times 1·00D)_{\text{fat}}$$
$$+ (p \times (H - 5·2) \times 1·00D)_{\text{protein}}$$
$$+ (p \times H \times 0·65D)_{\text{UnAvCHO}}, \qquad (18)$$

where p is a proportion of food weight due to the specified component (g/g), H is heat of combustion (kJ/g), D is apparent digestibility (g/g; determined as I- (L/I), where I is intake and L is loss to faeces). The quasi-constants are: relative efficiency, k_{ee}, for fat 0·98, protein energy lost in urine 5·2 (kJ/g digestible protein; Merrill & Watt, 1973), k_{ee} for protein 0·80, the proportion of fermentable carbohydrate used as NME (i.e. not lost due to conversion to faecal biomass, flatal gases, heat of fermentation and assimilation) 0·50. The efficiency of energy utilisation assumed for ME equation 18 are 1·00, the proportion of fermentable carbohydrate used as ME (not lost due to conversion to faecal biomass and flatal gases) 0·65. When this 0·65 is multiplied by the relative efficiency, k_{ee}, of 0·76 for fermentable carbohydrate the result corresponds to the value of 0·50 in the NME equation. For mixed meals the apparent digestibility of unavailable carbohydrate (D_{UnAvCHO} in equations 17 and 18) is 0·7, whether estimating NME or ME, and is the same as fermentability (see Livesey *et al.* 1995); values for traditional foods may be considered to be similar, as in Fig. 2.

Equations 17 and 18 can be treated similarly, in that terms for available and unavailable carbohydrate, fat and protein can be repeated if there is more than one form for which either D or H differs from the general. For example,

the terms for available and unavailable carbohydrate may be repeated to include these fractions from sugar alcohols, polydextrose and similar carbohydrates, where 'available' means absorbed but not lost to urine.

The minimal methodology for NME is identical to that for ME; only the quasi-constants change. A determination of NME, like ME, therefore requires food analysis (p) and knowledge of D from previous balance studies *in vivo*. Food analysis needs also to determine available and unavailable carbohydrate separately. With sugar alcohols and novel carbohydrates, where single chemical entities may be distributed to available and unavailable fractions *in vivo*, this fraction is determined by previous studies *in vivo* (compared with previous prior studies to establish dietary fibre as unavailable carbohydrate). General values of H (gross energy intake in Table 1) are available from a variety of sources (for example, see Merrill & Watt, 1973; Livesey, 1992).

The need for net metabolisable energy in food standards

Energy values should provide adequate information relating to food to enable consumers to make informed choices and to prevent fraud and deception (Australia New Zealand Food Authority, 1991). Regulatory authorities also have objective responsibility, amongst other factors, for protection of health, promotion of commerce and fair trade, and promotion of consistency of domestic and international standards. Merrill & Watt (1973) had already considered in their well-appreciated document that general energy factors, as used in Europe and by ANZFA, were inadequate. It is now very clear that the ME standard itself does not provide adequate information to allow consumers to make an informed choice, as noted in the following sixteen points:

1. NME, not ME is the level at which food components are equivalent with respect to energy balance in both human subjects and animals (see equation 3, Figs. 3–5; Agricultural Research Council, 1980; Blaxter, 1989; Livesey, 1987*a*, 1999*a*). Hence, the ME concept now has diminished value and is inadequate for food labelling.
2. Many now suggest that ME may be satisfactory only as an approximation or surrogate for NME (see Life Science Research Office, 1994), but so strong is the NME concept that it has been adopted by many working groups and authorities world wide for carbohydrates (for references, see p. 272).
3. Energy requirement estimates in human subjects are based on heat equivalents (World Health Organization, 1985) that take no account of the variation in heat production due to variation in dietary composition (Livesey, 1987*b*). At the present time only NME realistically accounts for this variation so that food energy and energy requirement estimates tessellate; this is not possible with ME.
4. Assessment of impact on the energy values of over 1000 British foods (Fig. 3) shows that differences between NME and ME values for food items are abundant and frequently so large as to indicate that food labels based on ME can no longer be thought of as providing adequately accurate declarations about a food's impact on energy balance.
5. There is evidence of concern that energy declarations on certain reduced-energy foods may be misleading (Warwick & Baines, 2000). Such concern is unfounded. The NME standard, as adopted outside the ANZFA region, makes quite clear that reduced-energy declarations are legitimately formulated with the support of scientifically-based evidence. Full adoption of the NME system should avoid such concern. ME hides the variation in energy values amongst foods (Figs. 3–5).
6. Scientifically supportable pressure arises from food ingredient manufacturers for adoption of NME, particularly for low-energy ingredients. The application of NME would meet this trade need, and those needs that arise from consumers for functionally reduced-energy products.
7. Fat is more fattening than an equal amount of ME from dietary protein, but this factor is not yet recognised in nutrition labelling, while low-energy carbohydrate that is less fattening than equal ME from available carbohydrate is recognised. The solution to this anomaly is to avoid the approximations inherent in ME and adopt the most scientifically sound and sustainable evaluation system, NME.
8. Users of ME for low-energy carbohydrates will cause disharmony between domestic and other national food standards; this situation is because of the widespread use of NME for carbohydrate ingredients.
9. Owing to the widespread acceptance of NME for carbohydrates, non-adoption of NME for low-energy carbohydrates by a regulatory authority would now introduce a barrier to cross-border trade, and so contravene legally-binding objectives (for example, see Australia New Zealand Food Authority, 1998).
10. There is a substantial growth in the prevalence of obesity, a public health issue (Department of Health, 1995; Food and Agriculture Organization, 1998). Food regulatory authorities contribute to the protection of public health; NME is more functional than ME in this regard.
11. Since the ME standard incorporates avoidable approximations, it is now a weakened basis on which to enforce adequate accuracy in food energy declarations. The NME convention indicates that approximations are as great as 25 % (Fig. 3). Equitable proof of fraud and deception will gradually become more difficult under the ME system than under the NME system.
12. Many authors of research papers subscribe to the NME concept with respect to improved food energy values, as evidenced in papers reviewed by the various authorities and experts mentioned. Regulators not adopting the NME concept would effectively be rejecting a considerable body of modern science. After adoption, those researchers working on energy requirements would be able to move forward in the knowledge that energy requirement estimates are practically independent of food composition (as this factor affects thermogenesis) by use of a conversion factor ($ME_{diet} = 1.05 \times NME_{sum\ foods}$; see p. 282).

With this simple factor, all requirement estimates (World Health Organization, 1985) remain just as valid under the NME standard as they are under the ME standard. Thus the adoption of correct food energy values should not be limited by impact on the usage of energy requirement estimates.

13. NME gives focus to a necessary understanding of the conduct of experimental studies. Examples include: (a) Over-reliance on thermogenic studies of short duration; (b) unnecessary controversy about the efficiency of alcohol as fuel in humans subjects. Recently this controversy was resolved by Prentice (1995, 1996), while earlier it was resolved by expert conference (Life Science Research Office, 1967) and 100 years ago knowledge was consistent with that at present; (c) appreciation of the sources of avoidable approximations in food energy values, with implications for studies on appetite. Bulky low-ME-density foods appear to limit ME intake (Poppitt, 1995; Stubbs *et al.* 1995b). Low-ME-density foods are frequently much lower in NME (Fig. 3) and so the impact of bulk on energy intake has been under-emphasised. Low-NME foods are also associated with a greater heat production (dHE = ME − NME), which also suppresses food ingestion (Kleiber, 1975); (d) An FAO/WHO background paper (Wolever, 1997) indicating that NME is applicable to fully-fermentable carbohydrate, e.g. fructo-oligosaccharides in human subjects (Roberfroid *et al.* 1993; Mollis *et al.* 1996). The Food and Agriculture Organization (1998) also recommends methodologies consistent with NME and for energy values refer to Livesey & Elia (1995) and Roberfroid *et al.* (1993). NME adds focus to studies with novel substrates.

14. Adoption of the NME system would promote education and understanding in energy utilisation by reference to relevant research findings during the past century since the ME concept was elaborated by Atwater & Bryant (1900).

15. The energy losses due to dHE are substantial and increase the energy loss ×1 for available carbohydrate, ×1·4 for fermentable unavailable carbohydrate, ×1·5 for protein, ×1·4 for fat and ×5 for alcohol (assuming 2 % losses as volatile substances in breath and urine; Merrill & Watt, 1973). Hence, dHE is a major contributor to energy losses. If these quantities are unimportant, so too are urinary and faecal energy losses. 'To be accurate, the assessment of food energy should take account of the site of energy conversion' (Merrill and Watt 1973). NME but not ME takes this into account.

16. Recognition that NME is important comes not just from agreements to adopt NME factors (see p. 272), but also from the suggestions that the issue can be dealt with as part of a health package (Warwick & Baines, 2000) and possibly as a claim on foods labels (Australia New Zealand Food Authority, 1999b). A claim on food labels would be inappropriate for two reasons. First, energy claims are already made through low-energy food regulations, which require recognition of the energy loss in the energy value, as it is in NME but not

in ME. Second, an additional statement on the label might be seen as noting the presence of some active ingredient, and so be misleading.

Implications of extending the use of net metabolisable energy

The NME system is in use for carbohydrates in most regions of the world. Here consideration is given to its more extensive use, with findings contrary to those of Warwick & Baines (2000).

Consistency with public health and safety

No acute public health and safety issues arise from the adoption of NME. Declarations of a food's impact on energy balance for equal intake are more relevant with NME than ME, and obesity is a growing public health concern (Department of Health, 1995).

Consistency with consumer needs

The Food and Agriculture Organization (1998) indicate that 'the main aim of food labels is to inform the consumer… and to assist in the selection of a healthy diet'. Indeed, this approach should be given more prominence than heretofore. Except for carbohydrates, the consumer is not yet informed that the ME system is an approximation of energy supply and that for some foods the approximations are very large (Figs. 2–5). The consumer can and ought to be better informed.

Consistency with previous food energy agreements

In Europe and/or North America, energy factors that would remain unchanged and may be considered as NME are those for available carbohydrate, fat, olestra, salatrim, caprenin, polydextrose, inulin, fructo-oligosaccharides, hydrogenated oligosaccharides, xylitol, sorbitol, maltitol, isomalt, lactitol, tagatose and (coming soon) dietary fibre in North America. Only two factors need to change to have a full NME system: those for protein and alcohol. Warwick & Baines (2000) effectively recommend more changes (to all the previous list except available carbohydrate, fat, caprenin and olestra). Global adoption of proposals from Warwick & Baines (2000) and Australia New Zealand Food Authority (1999a,b,c) will break more food energy agreements globally than will full adoption of the NME standard. Considerable numbers of such agreements exist, as they are made region-by-region.

Consistency with trade needs

There are three considerations. First, in both Europe and the ANZFA region, changes to the definition of carbohydrates and assignment of an energy factor to dietary fibre will cause food labels to change, and so there are negligible cost implications of adopting NME. Second, guidance to industry on making energy declaration is required. The greatest burden rests on ingredient manufacturers who supply novel ingredients, yet these suppliers already

universally welcome the NME system. Third, it helps local and world trade to have energy factors that are consistent across regulatory regions. Further adoption of NME for carbohydrates (as in the USA, Canada, Europe and Japan) would facilitate such trade. Protein and alcohol are not trade issues at present; there are no protein substitutes as there are fat or carbohydrates substitutes.

Comparability of food and ingredient energy values

The ME system is claimed to provide a consistent approach to energy evaluation, and hence it is claimed that energy values for different foods and ingredients are comparable (Warwick & Baines, 2000). However, consistent definition does not guarantee equivalents. It is erroneous to claim that comparability between foods or ingredients can result from use of a consistent definition, ME. Comparability under the ME system is an illusion achieved by hiding those approximations made explicit at present (see Figs. 2–5). Far more important than pedantry over a definition is avoidance of those approximations that are predictable and cause bias, as is achieved with NME (Fig. 3).

Comparability with intake and requirement estimates

One myth needs to be dispelled because it clouds understanding and impedes the implementation of greater accuracy and comparability in food energy labelling. Food energy can be predicted (Merrill & Watt, 1973; Livesey, 1991a) more precisely than food intake can be measured (Bingham, 1991) or energy requirements can be estimated (World Health Organization, 1985). It is sometimes thought that these facts mean that little is to be gained by improved accuracy in food energy evaluation. However, such imprecisions neither limit the accuracy and adequacy with which food energy declarations describe a food, nor impact on a food's contribution to an individual's energy requirement. Such imprecisions mean, by contrast, that no one need be concerned about improved energy values when matching calculated dietary intakes to energy requirement estimates, as practised by professional nutritionists and dieticians. The primary purpose of accuracy in food energy values is for comparability between foods and food ingredients at equal intakes for their impacts on energy balance. This factor has increased in importance because food labelling has become more prominent during the past 20 years.

Meeting energy requirement estimates

A secondary use of energy factors is in dietetic practices where food supply is calculated to meet estimates of energy requirement, and can be addressed simply:

$$\text{ME (mixed diet)} = 1.05 \text{ NME (sum food energy).}$$
$$(19)$$

The general conversion factor (1·05) was derived assuming a diet comprising 15 % ME as protein, 45 % ME as available carbohydrates, 38 % ME as fat and 2 % ME as unavailable carbohydrate. The factor varies little with diet composition and remains at 1·05 even after dilution with 5 % alcohol.

This approach (equation 19) offers advantages: (a) current energy requirements do not account for variation in 24-h thermogenesis due to variation in the composition of diets (dHE), yet the simple equation (equation 19) would account for this variation to the full extent that it is practically feasible. This objective is achieved while (b) food energy values are more exact and representative of their impact on energy balance for the same intake. There is no need to modify any documents on energy requirements other than for the sake of completeness, and then only to make this inter-conversion known.

The general factor (1·05) is sufficient because of the inherent imprecisions of energy requirement and food intake estimates. Thus, there is an approximately 20 % uncertainty in energy requirement estimates of individuals (2 SD; World Health Organization, 1985). Added to this uncertainty is more error from requirement prediction equations at the junction of life stages (up to 17 %) and this error is before even considering inaccuracies in estimating energy expenditure on physical activity. There can be no ground for restricting the presentation of more accurate information to the consumer in order to satisfy consistency of definitions with such imprecise energy requirement estimates.

Consistency with advice given by nutritionists and dietitians: precedent

In 1985 the FAO/WHO/UNU (World Health Organization, 1985) were without an appropriate energy value for dietary fibre, and recommended that users of the requirements document adjust the energy value of diets to account for dietary fibre content. FAO/WHO (Food and Agriculture Organization, 1998) gave an energy value to make this adjustment for fermentable carbohydrate so that such adjustments became unnecessary after adoption into food tables and labels of a dietary fibre energy value. This approach set a modern precedent for applying energy factors to calculate food energy values rather than leaving nutritionists and dietitians to make adjustments. This precedent should hold also for other improvements to food energy evaluation, as it did before the modern era. Leaving adjustments to professionals is not consistent with providing adequate information to the consumer as required in food labelling regulations.

Comparability with food tables

Food tables are records, not determinants, of energy factors and declared food energy values. Tables should not therefore prevent significant improvements to energy factors. Energy declarations in food tables will change in many regions as energy factors are updated for dietary fibre. The cost of additional change is negligible. To be informative, computerised tables could include gross energy, digestible energy, ME and NME values.

Sources of potential confusion in the literature

Metabolisable energy

ME has been defined as 'the amount of energy available for total (whole-body) heat production and for body gain' (Warwick & Baines, 2000), from Allison & Senti (1983) who attributed this to Atwater & Bryant (1900). This is just a general description that predates the NME and ME concepts. Critically also, 'protein gain' in this ME definition is digestible protein energy which differs from metabolisable protein energy. Digestible protein energy $(kJ/g) = ME_{protein} + 5 \cdot 2 \times$ digestible protein (Merrill & Watt, 1973). ME is better defined as 'the amount of energy available for total (whole-body) heat production at nitrogen and energy balance'.

True metabolisable energy

True ME has been used to mean ME less the heat of fermentation (Bär, 1990; Bernier & Pascal, 1990) and was central to the proposed nomenclature for the Australia New Zealand Food Authority (1999b). However, true ME is unsuitable for food labelling as it has a previous and more complex meaning (National Research Council, 1981).

Net energy

NE and NME differ (equation 8). NE is understood only by the context of its use, e.g. for maintenance, or egg or milk production (National Research Council, 1981), while this situation is not so for NME. An NE system of food energy evaluation has been described for BMR and work but has never been validated in human subjects (Life Science Research Office, 1967; Merrill & Watt, 1973; or since). The claim by Warwick & Baines (2000) that such NE is more valid than NME for the purpose of human food energy evaluation is totally unfounded.

Heat wastage

Use of this phrase has been questioned (Warwick & Baines, 2000) in reference to Brown & Livesey (1994), who observed a lack of energy retention as body fat compared with expectations from the ME definition. The discrepancy was presumed to be due to heat loss or 'heat wastage', a term that has an earlier origin (Life Science Research Office, 1967) and later usage (Prentice, 1995). 'Heat waste' is an appropriate term when heat requirement is less than the ME requirement (Kleiber, 1975).

Dietary and cold thermogenesis

Thermogenesis as defined by Warwick & Baines (2000) is energy expenditure that cannot be attributed to basal metabolism or to physical activity, citing food and cold as stimuli. An energy cost of physical activity on cold defensive posture also appears to be important (Brown et al. 1991). By definition, heat increment of food (H_iE) does not compensate for ongoing thermogenic processes, otherwise it would be neither observed nor predictable (Figs. 4 and 5).

Some concern exists about the interaction of cold and H_iE (Warwick & Baines, 2000). However, studies by Valencia et al. (1992) indicate that non-shivering cold thermogenesis in human subjects is additional to H_iE in response to a mixed diet. Duancey's (1981) study indicates that H_iE is similar at 28°C in human subjects to that in the mild cold (21°C). In fact, this similarity has been under-emphasised (Livesey, 1999b) as it can be shown that H_iE at 21°C is 95 (SE 3) % of that at 28°C. Thus H_iE of food is not affected by mild cold to a practical extent. Neither is H_iE affected by shivering cold for short periods (at 10°C compared with 26°C); thus Buskirk et al. (1960) showed in human subjects consuming a high-protein diet that H_iE at the lower temperature was slightly higher that at the upper temperature, and suggested that H_iE and shivering thermogenesis must operate additively and by different mechanisms. This finding was confirmed for a short period (2 h) at 7°C compared with 25°C with steak being the test meal (Rochelle & Horvath, 1969). Observations from Buskirk et al. (1960), Rochelle & Horvath (1969), Dauncey (1981) and Valencia et al. (1992) showed that for all practical purposes diet and cold thermogenesis in human subjects are additive. It is of truly academic proportions that any interaction exists.

The difference observed in H_iE at 21°C compared with 28°C suggests that the efficiency with which internally-generated heat is used to compensate for cold is just 5 (SE 3) %. Physical activity also poorly compensates for mild-cold thermogenesis, just 8 (SE 3) % (G Livesey, unpublished results; based on Dauncey, 1981). It can be calculated that to meet the needs of mild-cold thermogenesis fully by the heat increment of protein, one would have to eat protein at a rate of 5 kg/d! This factor emphasises the point that cold thermogenesis is of no practical significance to H_iE and NME.

To add emphasis, if H_iE compensated to any practical extent for cold thermogenesis in the 21–30°C range, such cold would neither elevate energy expenditure nor elevate an individual's food intake to meet the increased energy requirement. However, both occur and to a similar extent. Thus, in studies of Dauncey (1981), Valencia et al. (1992) and Warwick & Busby (1990), whole-body heat conductance (i.e. change in energy expenditure per degree change in environmental temperature) was 70 (SD between studies 15) kJ/°C. This value is almost as much as the increase in voluntary food intake as ME in individuals operating over similar environmental temperatures, 120 kJ/°C (Johnson & Kark, 1947).

The practical lack of influence of cold on H_iE occurs under conditions representative of the sustained cooler temperatures and intermittent colder temperatures to which human subjects are subjected from time to time. Animal studies also indicate that NME is valid at below the thermal neutral temperature (Livesey, 1991b; Brown & Livesey, 1994; Smith et al. 1998), and that temperature differences in the 21–28°C range have no effect on NME (Smith et al. 1998).

Even had an interaction occurred between cold-induced thermogenesis and H_iE, it would have been irrelevant to NME: (a) because human subjects attempt to live in thermal neutral temperatures or facilitate this situation

(incompletely perhaps) with housing and clothing; (b) because free energy equivalents of substrates are independent of environmental temperature; (c) because the heat requirement of cold is an issue for heat energy requirements not for food energy evaluation.

The mixed metabolisable energy – net metabolisable energy system

Current food regulations include both NME and ME factors, which is justified by ME being an approximate surrogate for the more accurate and representative NME. It is nevertheless preferable to remove such approximations from all food components. An advantage of NME is that low-energy food claims signify that real differences in fat accretion in the body (or energy expenditure) are evident. Traditional food components have not usually been subject to such scrutiny, but when they are (see Figs. 4 and 5), the ME system is found lacking.

Variation in thermogenesis between individuals

Variance for glucose is well known, small (about 3 % NME) and dependent on insulin sensitivity. There is little or no variation in the thermogenic response to protein between individuals (Tappy et al. 1993), likewise for fructose (Schwartz et al. 1989) and sucrose, although the latter may need to be re-examined (Raben et al. 1997). Such variation as found is: (a) small in terms of the need for specific energy factors as guided by the International Life Sciences Institute (see Livesey et al. 2000); (b) small relative to variation in heat of combustion of different types of carbohydrate (Livesey & Elia, 1995); (c) no greater than the variation in the prediction of the energy values of foods by the two best methods known (see legend of Fig. 2). Such variation as found for carbohydrates would support a view that there is no need for specific NME factors for individual carbohydrates within the proximate group of available carbohydrates.

Foods, not diets, are sold, bought and regulated

Nutrition labelling applies to food items, not diets. Whenever an error in a food energy factor has little impact on total energy in a diet, it should not be considered of little importance; it might be significant for a food item and even more significant for an ingredient. Even greater significance occurs when attempting to assess whether a low-energy food complies with a low-energy food regulation (for example, see Codex, 1991; Australia New Zealand Food Authority, 1999a). And of course, every unit of energy can have a significant impact on an individual consumer's choice, when the energy declaration is the decisive factor. There is a considerable need to focus on foods and ingredients, not diets, and to eliminate the mentioned sources of bias and variance.

There are no limits to physiological significance; limits are regulated by standards

Small differences in energy intake may be important, affecting either intake or health or both (Livesey, 1995b).

There is not a limit below which an error can be shown to have no physiological significance, but claims of reduced energy do have a threshold set in food regulations, usually a percentage of the traditional food's energy value. Thus, it is critically important to low-energy regulations (Codex, 1991; Australia New Zealand Food Authority, 1999a) that energy factors for traditional foods are: (a) as free as possible from approximations; (b) comparable with reduced energy foods; (c) relevant with respect to impact on energy balance. All three can be achieved by NME, but not by ME.

Conclusions

The NME system is valid, simple and more representative than any other food energy evaluation system known. It has been achieved by detailed study and removal from ME of substantial and importantly predictable biases. NME is important to diets but more important to informing about individual foods. NME also holds the key to making food energy requirement estimates free from variation due to food compositional effects on heat production. By contrast, the ME system supported by Warwick & Baines (2000) is demonstrably flawed, and may be regarded at best as an approximate surrogate of NME. Having databases that give each energy level for a food would facilitate adoption of NME, thus gross energy, digestible energy, ME and NME are possible in computerised food tables. This approach has already been achieved in a working version of the computerised McCance & Widdowson (1991) values for 1189 foods, with gross energy being calculated at present. No case has been found in the scientific literature, including the report of Warwick & Baines (2000), for ignoring the opinion of over twenty articles to date comprising the recommendations of expert panels, reviewing authors, and regulatory and legislative documents that recognise NME. Obstacles to implementation suggested by Warwick & Baines (2000) appear to be subjective and minor. Consistent with this conclusion, ANZFA appears to accepts that 'in the future, a system of assigning energy factors based on NME for all food components may provide a means to make the best estimate of energy content of foods for the consumer' (Australia New Zealand Food Authority, 1999c). ANZFA indicate that it is a matter of timing, such factors being applied when all that are needed are available rather than as they become available. Sufficient information is available now for full implementation.

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