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Methods for correcting the metabolizable energy intakes of ruminants measured at the production level of feeding to that measured at the maintenance level

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ABSTRACT

Respiration chamber estimates of metabolizable energy intakes and diet metabolizability for ruminants cannot be used directly to check existing metabolizable energy requirements, because of the definition of ME concentrations of feeds used in the ARC (1980) energy requirement models. These were constructed so that the amounts of net energy available for the synthesis of milk or body tissue was predicted from ME intake as defined. Reversal of the calculations requires that both metabolizability measured at the maintenance plane and feeding level as a multiple of maintenance requirement, which is also a function of diet metabolizability, are available, which is not usually the case with calorimetry studies. In the case of dairy cows, two functions were derived, both quadratic in nature, which were solved to give the required estimates of ME intake measured at the maintenance level of feeding. Use of either of the quadratic functions on test data showed the procedures to be accurate. Mean differences in ME requirement of the order of 25 MJ/d above current standards were found with the first procedure. The second procedure developed was sensitive to the estimate of fasting metabolism adopted. Using recent estimates of the latter, the mean value for ME intake measured at the maintenance level of feeding obtained indicated that no level of feeding correction was necessary to get an accurate fit of the model to the test data. Also, that the 5% safety margin adopted in AFRC (1993) was not required.

The exponential energy retention model for growing beef cattle of ARC (1980) cannot be reversed; it generates a transcendental equation with no algebraic solution. The linear model of ARC

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(1965), with a feeding level correction dependent upon diet metabolizability is shown to be a good fit to the exponential model, and its use is suggested if estimates of depressions in diet metabolizability by growing beef cattle are required. The derived equation was cubic in nature. The Newton-Raphson method was used to obtain solutions numerically, using suitable test calorimetry data. Testing of the solutions obtained showed the equation derived was reliable, and that the AFRC (1993) ME requirements for growing beef cattle are accurate.

KEY WORDS: dairy cow, beef cattle, metabolizable energy requirement, feeding level, maintenance, production, efficiency factors

INTRODUCTION

The metabolizable energy (ME) requirements for ruminants currently adopted in the UK are given in AFRC (1993), based on the recommendations of ARC (1980) and a subsequent report (AFRC, 1990), which tested the ARC (1980) recommendations and made some adjustments thereto. As a bias was found between measured ME intakes (from summated feed ME values) and the ME requirement, a 5% safety margin was adopted in calculating the tables of energy requirements in AFRC (1993). Only a few calorimetric studies of ME requirements for dairy cows (e.g. Yan et al., 1997a, b) have been reported since current energy requirements were published in 1980, which relied on the work with dairy cows of Moe et al. (1972) and Van Es (1975) for estimates of maintenance ME requirements and efficiencies of ME utilization.

The current UK energy requirement models for ruminants give estimates of ME requirements to achieve defined animal production targets, using diets of defined ME concentration. They can also be used to predict performance from measured or estimated ME intakes, with the exception that the dairy cow model does not partition ME available for production, ME_p, between milk and tissue gain or loss. The ME values of feeds, $[ME_m]$, used in the models are defined as those measured at the maintenance level of feeding with wether sheep, as originally suggested by Blaxter (1962) and adopted by ARC (1965) and ARC (1980). Estimates of intakes of ME, MEI_m, are made by summating weights of feed dry matter and ME densities ($[ME_m]$, MJ/kg DM) obtained from standard tables of values (MAFF 1992).

As there are differences in the digestive efficiency, methane and urine production between lactating cows fed at 2 to 5 times maintenance, beef cattle fed at 2 times maintenance, and wether sheep fed at maintenance, ARC (1965) introduced a feeding level correction, C_L, to MEI_m. Feeding level, L, is defined as multiples of the ME requirement for maintenance, M_m, which is a function of the net energy requirements for fasting metabolism, F, activity, A, and the efficiency of utilization of ME for maintenance, k_m.

Efficiency factors for the efficiency of utilization of ME for maintenance, k_m, lactation, k_l, and growth, k_g, are predicted with a set of linear equations (AFRC, 1993), which depend upon the diet metabolizability, q_m. The ME available for production, ME_p, is calculated by the difference of MEI_m and M_m and the net energies required for milk synthesis, E_l, and growth, E_g, which are unaffected by plane of nutrition in the model, are then used to calculate the dietary ME requirement as measured at the maintenance feeding level.

Large animal calorimeters installed at the Agricultural Research Institute of Northern Ireland, Hillsborough and the Centre for Dairy Research (CEDAR), Department of Agriculture, The University of Reading have now generated a large amount of data on the energy utilization of dairy and beef cattle, enabling some reappraisal of current energy standards. Ideally, all diets fed to animals placed in these calorimeters should also have been fed to wether sheep at the maintenance level of feeding, to give the standard baseline [ME_m] values for the diets fed. When this has not been done, there is therefore a problem in establishing what the diet [ME_m] values at maintenance are, when only the calorimeter data for production levels of feeding are available.

Definition of the problem

Respiration calorimeters measure the amounts of oxygen consumed, and carbon dioxide and methane produced by the animals being studied. Together with the amount of nitrogen (g/d) excreted in the urine, this enables calculation of the daily heat production of the cow, using the formula of Brouwer (1965). When associated with measurement of the gross energy intake, GEI, of the feed, using [GE] measured by adiabatic bomb calorimeter and dry matter (DM) intake, the collection of milk (if lactating), faeces and urine at the same time, whose energy content is also determined, the ME available to the animal, ME_a, the actual diet metabolizability at the production level, q_a (= ME_a/GEI), the net energy partitioned to milk, E_l, and the energy balance going into or out of body reserves, E_g, can be calculated. The values for the net energy requirement of fasting metabolism, F, and activity, A, can be calculated from liveweight, W, as AFRC (1993), but adjusted for reduced activity of cattle placed in respiration chambers.

Comparison of calorimetric results with the ME requirement standards of AFRC (1993) requires that the feeding level correction, C_L, (dependent upon the maintenance ME requirement, M_m) is calculated for the experimental feeding level used, in order to calculate a value for MEI_m as required by the energy model, i.e. carry out the calculations in reverse. Unfortunately, M_m is dependent upon not only on both F and A, which are simply functions of liveweight, but on the value of q_m (= MEI_m/GEI), which is usually given at the start of the forward calculations, but is not normally a part of the protocol for experiments in respiration calorimeters with productive animals. The measured diet metabolizability, q_a, which is available, should not be used in the relevant efficiency equations, which were derived and published using values for q_m, as this can introduce a significant error in the calculated values for k_m and k_l. Whilst GE intake is known, and unaffected by level of feeding, MEI_m is the parameter to be calculated from ME_a, but this also requires a value for C_L, itself a function of M_m and MEI_m.

MATERIAL AND METHODS

Suitable calorimetric test data for dairy cows were obtained from an experiment conducted at CEDAR (Cammell et al., 2000). Six multiparous Holstein-Friesian cows were used for repeated respiration chamber measurements at 6 weekly intervals throughout lactation. The data for period 2, week 12 of lactation were chosen for this exercise, to define and test the methodology developed. The cows were fed *ad libitum* a total mixed ration, consisting of the following amounts on a DM basis (kg/t): maize silage, 410; grass silage, 140; concentrates, 280; soda grain, 110; molasses, 60, plus minerals and vitamins at 2.5 kg/t fresh weight. For growing cattle, suitable test data was obtained from Thorp (1995), who used Friesian steers of about 500 kg liveweight, fed 4 diets based on grass silage, fed either alone *ad libitum* (CO) or with the addition of 20, 40 or 60% of concentrates (C20, C40, C60, respectively).

The terms and symbols used in this paper are those adopted in AFRC (1993) and are given in Table 1. The mathematical procedures developed for dairy cows and growing cattle differ in form, as outlined below.

The metabolizable energy requirement model for dairy cows of ARC (1980)

Procedure I. The forward sequence of the calculations is as follows, when the dietary ME/GE concentration, q_m, is given:

$$k_m = 0.35\,q_m + 0.503 \quad (1)$$

$$k_{l0} = 0.35q_m + 0.420 \quad (2)$$

$$k_g = 0.95k_l = 0.33q_m + 0.400 \quad (3)$$

$$F = 0.53(W/1.08)^{0.67} \quad (4)$$

$$A = 0.008W \quad (5)$$

$$M_m = (F + A)/k_m \quad (6)$$

$$L = MEI_m/M_m \quad (7)$$

$$C_L = 1 + \gamma(L - 1) \quad (8)$$

$$\text{Available ME, } ME_a = MEI_m/C_L \quad (9)$$

$$\text{Production ME, } ME_p = ME_a - M_m \quad (10)$$

$$\text{Milk net energy available, } E_l = ME_p \times k_{l0} \quad (11)$$

where γ is the feeding level correction per unit increase in feeding level, set at 0.018 here as in ARC (1980), and the activity allowance, A, (MJ/d) was reduced from 0.0092W to 0.008W, since the cattle housed in calorimeters did not walk the 500 m/d assumed in the standard calculation of A in AFRC (1993).

It can be seen that q_m appears in equations (1), (2) and (3), and terms derived from these appear in equations (6) and (11). The whole forward calculation se-

TABLE 1

Terms, symbols and units, after AFRC (1993)

Symbol	Term	Units
A	Activity allowance	MJ/d
C_L	Feeding level correction	-
E_g	Net energy for gain	MJ/d
E_l	Net energy for milk	MJ/d
E_{l0}	Net energy for milk corrected for tissue energy gain or loss	MJ/d
F	Fasting metabolism	MJ/d
[GE]	Gross energy in feed dry matter	MJ/kg DM
GEI	Gross energy intake	MJ/d
I	Gross energy intake scaled by fasting metabolism	-
k_f	Efficiency of ME utilization for liveweight gain in growing cattle	-
k_g	Efficiency of ME utilization for liveweight gain in lactating cows	-
k_l	Efficiency of ME utilization for milk synthesis	-
k_{l0}	Efficiency of ME utilization for milk synthesis measured at zero energy balance	-
k_m	Efficiency of ME utilization for maintenance	-
L	Feeding level as multiples of maintenance ME intake	-
M_m	ME requirement for maintenance	MJ/d
ME_a	Total ME available to the animal as measured in a calorimeter	MJ/d
ME_l	ME available for milk synthesis	MJ/d
$[ME_m]$	Metabolizable energy of a feed measured at maintenance	MJ/kg DM
ME_p	ME available for production (milk or tissue gain)	MJ/d
MEI_m	ME intake measured at the maintenance level of feeding	MJ/d
MER	ME requirement	MJ/d
q_m	Metabolizability of a diet, $[ME_m]/[GE]$	-
q_a	Metabolizability of a diet, ME_a/GEI, measured in a calorimeter	-
R	Energy retention, E_g, scaled by fasting metabolism	-
W	Liveweight	kg

quence depends upon the metabolizability of the diet, q_m, being given. These equations can be re-arranged to reverse the calculations, with each term being expanded where it is dependent upon q_m, as follows:

$$\begin{aligned} MEI_m &= ME_a \times C_L \\ &= ME_a[1 + \gamma(L - 1)] \\ &= ME_a\{1 + \gamma[(MEI_m/M_m) - 1]\} \\ &= ME_a\{1 + \gamma[(MEI_m/((F + A)/k_m)) - 1]\} \\ &= ME_a\{1 + \gamma[MEI_m/(F + A)\times(0.35q_m + 0.503) - 1]\} \end{aligned}$$

Finally,

$$MEI_m = ME_a\{1 + \gamma[MEI_m/(F + A)\ (0.35(MEI_m/GE) + 0.503) - 1]\} \quad (12)$$

where the values for ME_a, F, A and GE are known and the equation is to be solved for MEI_m. Equation (12) can be re-arranged to give:

$$MEI_m^2 + (GE/0.35)[0.503 - (F + A)/(\gamma ME_a)]MEI_m + [GE(F + A)/0.35](1/\gamma - 1) = 0 \quad (13)$$

which is a quadratic equation in the usual form:

$$MEI_m^2 + \alpha MEI_m + \beta = 0 \quad (14)$$

where:

$$\alpha = (GE/0.35)\ [0.503 - (F + A)/(\gamma ME_a)] \quad (15)$$

$$\beta = [GE(F + A)/0.35]\ [(1/\gamma) - 1] \quad (16)$$

Equation (13) therefore has the usual two roots of a quadratic, provided that $\alpha^2 > 4\beta$:

$$\text{Root 1} = 0.5[-\alpha - \sqrt{(\alpha^2 - 4\beta)}] \quad (17)$$

$$\text{Root 2} = 0.5[-\alpha + \sqrt{(\alpha^2 - 4\beta)}] \quad (18)$$

Root 1 gives the biologically sensible value of MEI_m required for comparison with tabulated ME requirement values for dairy cows as AFRC (1993), using $\gamma = 0.018$ per multiple of M_m above maintenance. The form of equations (15) and (16) enable other values of γ to be inserted and tested if required.

Procedure II. This procedure includes the milk synthesis section of the ARC (1980) dairy cow model, i.e. it uses both efficiency of ME use terms, namely maintenance, k_m, and that for milk synthesis at zero body energy balance, k_{l0}, not just the maintenance and feeding level correction components used in Procedure I. It requires the addition of the corrected milk net energy, E_{l0}, data calculated as ARC (1980), and solves a function for the metabolizability of the diet estimated at maintenance, q_m, which fits the test data. As GEI is known, the corrected ME intake, MEI_m, can then be calculated without resort to assuming a feeding level correction, since the latter is now one of the results of the calculations. The key equations are:

$$E_{l0} = E_l + E_g(+ve) - 0.84E_g\ (-ve) \tag{19}$$

$$E_{l0} = k_{l0} \times ME_p \tag{20}$$

and

$$ME_p = ME_a - M_m \tag{21}$$

Substituting for ME_p in equation (20):

$$E_{l0} = k_{l0}(ME_a - M_m) \tag{22}$$

Substituting for M_m in equation (22) using equation (6), and rearranging:

$$ME_a \times k_{l0} \times k_m - k_{l0}(F + A) - k_m \times E_{l0} = 0 \tag{23}$$

Substituting for k_m and k_{l0} as defined by equations (1) and (2) earlier:

$$ME_a[(0.35q_m + 0.420)(0.35q_m + 0.503)] - [(F + A)(0.35q_m + 0.420)] - E_{l0}(0.35q_m + 0.503) = 0 \tag{24}$$

On writing q_m as MEI_m/GEI, equation (24) can be rearranged to give:

$$MEI_m^2 + \{[0.3231ME_a - 0.35(F + A + E_{l0})]/(0.1225ME_a)\}GEI \times MEI_m - \{[0.42(F + A) + 0.503E_{l0} - 0.2113ME_a]/(0.1225ME_a)\}GEI^2 = 0 \tag{25}$$

which is a quadratic in MEI_m, with the usual roots, (equations 17 and 18), but where now Root 2 (the positive square root) gives the only biologically sensible solution, where:

$$\alpha = \{[0.3231ME_a - 0.35(F + A + E_{l0})]/(0.1225ME_a)\}GEI \tag{26}$$

$$\beta = \{[0.2113ME_a - 0.42(F + A) - 0.503E_{l0}]/(0.1225ME_a)\}\ GEI^2 \tag{27}$$

The metabolizable energy requirement model for growing beef cattle of ARC (1980)

Procedure III. A similar but more complex problem of reverse calculation also exists in the ARC (1980) model for the energy requirements of growing cattle. The exponential equation of Blaxter and Boyne (1970) was used by ARC (1980) to predict jointly the decline in the metabolizability of the diet (feeding level correction) and the effects of metabolizability on energy retention, scaled by fasting metabolism, R. ARC (1980) also stated that the exponential function was only accurate for a feeding level, L, of two times maintenance. The forward sequence of calculation when q_m, MEI_m and W are known is as follows:

$$B = k_m/(k_m - k_f) \tag{28}$$

$$k = k_m [\ln(k_m/k_f)] \tag{29}$$

$$R = B[1 - \exp(-kI)] - 1 \tag{30}$$

where:

$$I = MEI_m/F \tag{31}$$

$$R = E_g/F \tag{32}$$

The reverse sequence of calculation requires a solution be found for scaled ME intake, I, given by equation (30), to enable the calculation of MEI_m and q_m, when only GEI, net energy retention, E_g, and liveweight, W, are known. ME_a, the measured ME intake at the production level is not needed as an input to the equation, but the calculated MEI_m does give information about the depression in ME at the production level. Equation (30) can be re-arranged to give:

$$\exp(-kI) = 1 - (R + 1)/B \tag{33}$$

whilst equations (32) and (28) can be expanded, using equations (1), (4) and:

$$k_f = 0.78q_m + 0.006 \tag{34}$$

giving:

$$R = E_g/[0.53(W/1.08)^{0.67}]$$
$$B = (0.35q_m + 0.503)/[(0.35q_m + 0.503) - (0.78q_m + 0.006)]$$
$$= (0.35q_m + 0.503)/(0.497 - 0.43q_m)$$

Substituting these expressions for R and B in equation (33) yields:

$$\exp(-kI) = 1 - \{[E_g/(0.53(W/1.08)^{0.67})] + 1\}/\{[0.35q_m + 0.503]/[0.497 - 0.43q_m]\} \tag{35}$$

Consider equation (29). Substituting for k_m and k_f in equation (29) using equations (1) and (34) gives:

$$k = [0.35q_m + 0.503]\times\ln[(0.35q_m + 0.503)/(0.78q_m + 0.006)]$$

As scaled ME intake, I (equation 31), can be expanded to:

$$I = MEI_m/[0.53(W/1.08)^{0.67}]$$

we have:

$$\exp(-kI) = \exp\{-[0.35q_m + 0.503]\times\ln[(0.35q_m + 0.503)/(0.78q_m + 0.006)] \times MEI_m/[0.53(W/1.08)^{0.67}]\} \tag{36}$$

Finally, equating equations (36) and (35) and writing q_m as MEI_m/GEI:

$$\exp\{-[0.35MEI_m/GEI + 0.503]\times\ln[(0.35MEI_m + 0.503GEI)/(0.78MEI_m + 0.006GEI)] \times[MEI_m/(0.53(W/1.08)^{0.67})]\} = 1 - \{[E_g/(0.53(W/1.08)^{0.67})] + 1\} /\{[0.35MEI_m + 0.503GEI]/[0.497GEI - 0.43MEI_m]\} \tag{37}$$

As all the factors in equation (37) other than MEI_m are known, i.e. GEI, W and E_g, it might be possible to solve the equation algebraically, by re-arrangement to give q_m in those terms. However, the presence of both logarithmic and exponential functions make this a transcendental equation, not amenable to algebraic solution. This equation therefore has to be solved using a numerical method such as the Newton-Raphson method (Conte and de Boor, 1981).

Procedure IV. The exponential model of Blaxter and Boyne (1970) was probably formulated as a replacement for the original bi-linear energy retention model of ARC (1965), which has a separate feeding level correction equation, as did ARC (1980) (although not adopted in the final model). These two equations are:

$$\text{ARC (1965), p. 209: } C_L = 1 + (L - 1)(0.095 - 0.11q_m) \quad (38)$$

$$\text{ARC (1980), p. 77: } C_L = 1 + (L - 1)[0.2(q_m - 0.623)] \quad (39)$$

It is clear that equation (38) predicts consistent reduction in ME depression as q_m increases in value, reducing from 0.040 when q_m is 0.5 to 0.018 per unit increase in L when $q_m = 0.7$, and reaching zero for $q_m = 0.864$. Equation (39) reverses for values of q_m above 0.623 and predicts an increase in metabolizability of 0.015 when q_m is 0.7. For diets of metabolizability around 0.623, a depression of about 0.02 per unit increase in L would be predicted by equation (38), which may explain the adoption of a constant reduction of 0.018 per unit increase in L by ARC (1980) for dairy cows, following the recommendations of Van Es (1975). Equation (39) was not incorporated in any of the final dairy cow, beef cattle or sheep energy requirement models of ARC (1980).

Comparisons of predicted net energy for gain, E_g, for 200-600 kg liveweight, diet q_m values ranging from 0.5 to 0.7 and ME intakes, MEI_m, from 40 to 120 MJ/d gave the following relationships between the exponential model of ARC (1980) and the original bi-linear models, using equations (38) and (39) for feeding level correction:

$$\text{ARC (1965) Bent stick } E_g = 1.04(\text{ARC, 1980})E_g - 1.4 \qquad r^2 = 0.993 \quad (40)$$

$$\text{ARC (1980) Bent stick } E_g = 1.13(\text{ARC, 1980})E_g - 1.91 \qquad r^2 = 0.987 \quad (41)$$

The mean difference in predicted E_g between the exponential model and the ARC (1965) bi-linear model using equation (40) was 0.69 MJ/d, ranging from -1.44 to +2.41 MJ/d, which seems acceptable, particularly as the slope of the regression is nearly 1.0 and the intercept quite small at 1.4 MJ/d. It would appear that the simpler algebraic model of ARC (1965) could be used to reverse energy retention calculations using measurements made on beef cattle in the calorimeter, to give estimates of ME intake corrected to the maintenance plane and correct values for q_m as originally defined.

The sequence of equations is as for Procedure I for dairy cattle with equation (8) for C_L replaced by equation (38) above, i.e. replacing γ by the term 0.095-$0.11q_m$ as follows:

$$\begin{aligned} MEI_m &= ME_a \times C_L \\ &= ME_a \times [1 + (0.095 - 0.11q_m) \times (L - 1)] \\ &= ME_a \times \{1 + (0.095 - 0.11q_m) \times [(MEI_m/M_m) - 1]\} \\ &= ME_a \times \{1 + (0.095 - 0.11q_m) \\ &\qquad \times [MEI_m/((F + A)/(0.35q_m + 0.503)) - 1]\} \end{aligned} \quad (42)$$

On writing q_m as MEI_m/GEI, equation (42) can be rearranged to give:

$$\begin{aligned} &(0.0385/GEI^2)MEI_m^3 + (0.0221/GEI)MEI_m^2 + [(F + A)(1/ME_a - 0.11/GEI) \\ &\qquad - 0.0478]MEI_m - 0.0905(F + A) = 0 \end{aligned} \quad (43)$$

where the values for GEI, F, A and ME_a are known and equation (43) is to be solved for MEI_m. Equation (43) can be written as a cubic in MEI_m, in the usual form:

$$MEI_m^3 + \alpha MEI_m^2 + \beta MEI_m + \gamma = 0 \quad (44)$$

where:

$$\alpha = 0.574GEI \quad (45)$$

$$\beta = (26.0/ME_a - 1.24)GEI^2 - 2.86GEI \quad (46)$$

$$\gamma = -23.5(F + A)GEI^2 \quad (47)$$

This cubic equation can be solved algebraically, but the solution is very cumbersome. Consequently, the use of a numerical technique such as the Newton-Raphson method is preferred to obtain solutions to equation (43).

RESULTS

Dairy Cattle

Procedure I. The results obtained from the quadratic equation (13) using the calorimetry test data of Cammell et al. (2000) are shown in Table 2. The solutions obtained gave a mean value for MEI_m of 273.2 MJ/d. The values calculated for MEI_m imply that existing ME requirements as AFRC (1993) are low on average by about 25 MJ/d (varying from 15 to 35 MJ/d), as found by Yan et al. (1997a). The calculated mean feeding level correction of 1.066 (L = 4.67) is of the same size as the bias between requirement and actual ME intake of dairy cows found by AFRC (1990). The estimated ME intake as defined by the ARC (1980) model is 17.5 MJ/d (equivalent to over 3 kg milk/d) higher than the measured ME supply

TABLE 2

Calculation of the ME intakes of dairy cows in terms of ME at the maintenance feeding level from measurements made at the production feeding level using Procedure I (Symbols and units are given in Table 1)

W	F	A*	GEI	ME_a	q_a	E_l	E_g	MEI_m[†]	C_L[†]	MER[§]
643	38.3	5.1	441.5	276.1	0.625	107.5	15.0	296.1	1.070	279.4
624	37.6	5.0	383.5	240.7	0.628	77.1	16.0	255.5	1.060	225.7
627	37.7	5.0	398.4	242.4	0.608	111.4	-15.0	257.2	1.060	236.6
567	35.2	4.5	414.2	256.0	0.618	111.9	-10.0	274.8	1.071	240.8
609	37.0	4.9	386.8	246.5	0.637	109.5	-10.0	262.7	1.064	236.2
617	37.3	4.9	416.1	272.3	0.654	116.8	-5.0	292.9	1.073	255.5
Mean	37.2	4.9	406.8	255.7	0.628	105.7	-1.5	273.2	1.066	245.7

* a set at 0.008W MJ/d, not 0.0092W as AFRC (1993), because the cows did not walk 500 m/d whilst in the calorimeter

† calculated using Root 1, equation (17)

§ values from AFRC (1993)

and the mean value for the metabolizability of the diet is raised from 0.628 (q_a) to 0.672 (q_m).

This increase in metabolizability also raises the predicted values for k_m and k_{l0} used in the ARC (1980) energy model from 0.723 to 0.738 and from 0.640 to 0.655 respectively, a smaller proportional increase, due to the large constant term and small coefficient of 0.35 on q_m in both equations (1) and (2) of AFRC (1993). The predicted increased efficiency of ME utilization for both maintenance and lactation will reduce the calculated ME requirement proportionately by about 0.02, from that obtained without calculating a correct value for q_m.

Procedure II. Solutions obtained from quadratic equation (25) using the same dairy cow test data as previously are shown in Table 3. The initial results, using the standard values from ARC (1980) for fasting metabolism, F, and the slightly reduced activity allowance, A, gave a low mean value of 0.413 for q_m; a value typical for cereal straw, not a maize silage and concentrate based diet. The mean values for k_{l0} and k_m from which q_m had been calculated were also about 0.9 of values for normal dairy cow diets. A possible reason for the low estimate of q_m obtained is its sensitivity to small changes in k_m and k_{l0}, because of the large constant terms in equations (1) and (2). These two equations also constrain k_m to be 0.083 greater than k_{l0}. An explanation for this predicted low value for q_m was therefore sought.

The net energy for maintenance term (F + A) appears in both equations (26) and (27) for α and β, where F is defined by equation (4) earlier, with a coefficient of 0.53 for the $(W/1.08)^{0.67}$ term. The estimated efficiencies of ME utilization for

TABLE 3

Results of applying Procedure II using the calorimetry test data (Symbols and units are given in Table 1)

F coefficient*	M_m	q_m	k_{l0}	k_m	ME_m	L	C_{Lc}†	γ§
0.53	65.4	0.413	0.565	0.648	162.8	2.489	0.661	-0.228
0.60	71.1	0.465	0.583	0.666	183.3	2.580	0.774	-0.162
0.70	78.5	0.541	0.609	0.692	213.3	2.717	0.865	-0.079
0.80	85.5	0.616	0.636	0.719	242.9	2.842	0.985	-0.008
0.81	86.1	0.624	0.638	0.721	246.0	2.857	0.998	-0.001
0.83	87.4	0.639	0.644	0.727	251.9	2.881	1.022	0.012
0.85	88.7	0.654	0.649	0.732	257.8	2.906	1.046	0.024
0.90	91.8	0.693	0.663	0.746	273.2	2.975	1.108	0.055
1.00	97.8	0.770	0.690	0.773	303.6	3.105	1.231	0.110

* coefficient for the term $(W/1.08)^{0.67}$

† implied feeding level correction

§ implied coefficient on (L - 1) in equation (8)

milk have been found to be dependent upon the dimensions of the maintenance intercept of the fitted regression line, low maintenance intercepts being associated with lower estimated efficiencies, and vice versa. Yan et al. (1997b) found the fasting metabolism of dairy cows to be 0.453 MJ/kg $W^{0.75}$/d not 0.321 MJ/kg $W^{0.75}$/d, which is the equivalent of the ARC (1980) estimate, using 520 kg liveweight in equation (4), but expressing the result on a metabolic body weight, $W^{0.75}$, basis. For the mean liveweight, W, of 620 kg in the test data, the estimates of Yan et al. (1997b) are F = 56.28, F + A = 61.24 and M_m = 84.85 MJ/d. To achieve an equivalent value for (F + A), the coefficient on $(W/1.08)^{0.67}$ in the ARC (1980) function for F has to be increased from 0.53 to 0.81. Sensitivity testing of this coefficient showed it to be the dominant factor in the results obtained for q_m (Table 3).

Figure 1 shows a plot of the calorimetry test data used and the fitted regression line, which has a slope, k_{l0}, of 0.625 and an x-axis intercept of 0.665 MJ ME/kg $W^{0.75}$/d, similar to the mean result of Yan et al. (1997b) not the ARC (1980) equivalent of 0.475 MJ ME/kg $W^{0.75}$/d. If a line is drawn through the mean of these data points and the ARC (1980) maintenance estimate, the slope is reduced to 0.56, in good agreement with the slope 0.565 found in Table 3 when F was set at 0.53. If a maintenance intercept appropriate to the test data set is used, i.e. setting the F coefficient to 0.81, then q_m is found to be 0.624, which agrees closely with the observed value q_a. Consequently, the corrected ME intake, ME_m, is calculated to be 246.0 MJ/d, 0.998 times the measured production ME_a of 246.5 MJ/d, implying a negligible level of feeding correction, C_L, at 4 times maintenance, not the value of 1.054 derived from equation (9). Other values calculated were k_{l0} = 0.638, k_m = 0.721 and M_m = 86.1 MJ/d. Insertion of these values into equations (10) and (11) gives M_p = 160.3 MJ/d, and E_l = 102.3 MJ/d compared to 105.7 MJ/d given.

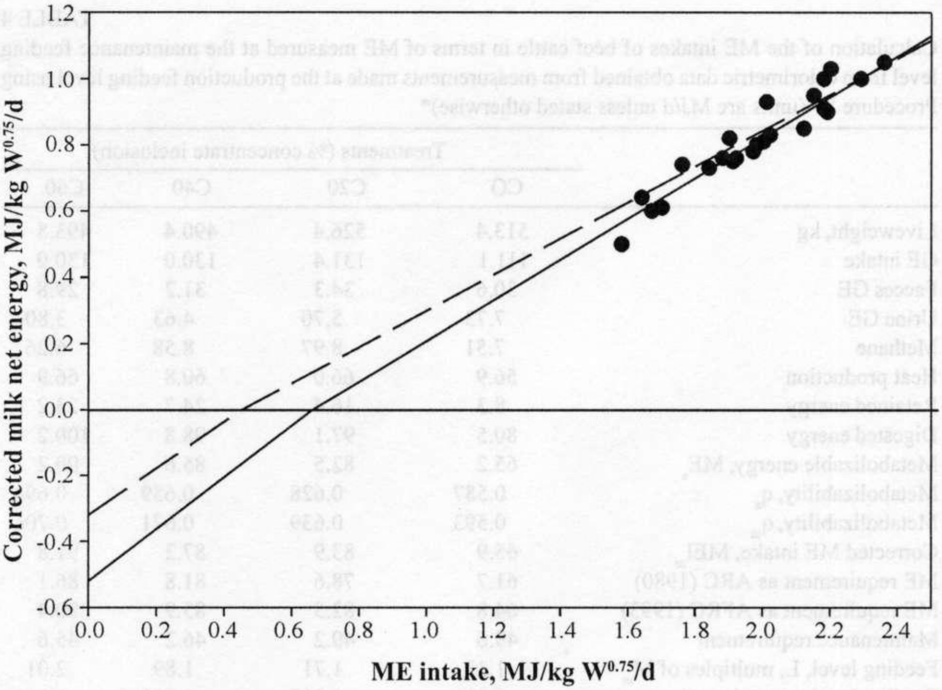

Figure 1. Corrected milk net energies in relation to measured ME supply for the data of Cammell et al. (2000). Lines are fitted regression (solid line) and drawn (broken line)

Beef Cattle

Procedure III. Results are unavailable owing to the death of the senior author.

Procedure IV. Suitable calorimetry test data on growing beef cattle were obtained from Thorp (1995) and are shown in Table 4.

The mean of the corrected ME intake, MEI_m, values (82.2 MJ/d) agrees closely with the requirements calculated for these beef animals according to AFRC (1993) (80.9 MJ/d), with a mean difference of only +1.3 MJ/d. The feeding level corrections, C_L, reported in Table 4 may appear small, because of the lower planes of nutrition used, but when expressed per unit increase in feeding level, L, show the expected decrease as diet metabolizability, q_m, increases with increased levels of concentrate inclusion as predicted from equation (43). The size (0.033) of the correction for the all-forage diet per unit increase in feeding level, L, is significantly greater than the value of 0.018 adopted for dairy cows, but reaches that value with 60% concentrate inclusion, when q_m reaches 0.706.

TABLE 4

Calculation of the ME intakes of beef cattle in terms of ME measured at the maintenance feeding level from calorimetric data obtained from measurements made at the production feeding level using Procedure IV (units are MJ/d unless stated otherwise)*

	Treatments (% concentrate inclusion)			
	CO	C20	C40	C60
Liveweight, kg	513.4	526.4	490.4	493.8
GE intake	111.1	131.4	130.0	130.0
Faeces GE	30.6	34.3	31.2	29.8
Urine GE	7.73	5.70	4.63	3.80
Methane	7.51	8.97	8.58	6.26
Heat production	56.9	66.0	60.8	66.9
Retained energy	8.3	16.4	24.7	23.2
Digested energy	80.5	97.1	98.8	100.2
Metabolizable energy, ME_a	65.2	82.5	85.6	90.2
Metabolizability, q_a	0.587	0.628	0.659	0.694
Metabolizability, q_m	0.593	0.639	0.671	0.706
Corrected ME intake, MEI_m	65.9	83.9	87.2	91.8
ME requirement as ARC (1980)	61.7	78.6	81.8	86.1
ME requirement as AFRC (1993)	64.8	82.5	85.9	90.4
Maintenance requirement	49.6	49.2	46.2	45.6
Feeding level, L, multiples of M_m	1.33	1.71	1.89	2.01
Feeding level correction, C_L	1.011	1.017	1.019	1.018
Correction per unit increase in L	0.033	0.024	0.021	0.018

* A set at 0.0066W MJ/d, not 0.007W as AFRC (1993), because the steers did not walk 500 m/d whilst in the calorimeter

DISCUSSION

It is not always the case that the theoretically correct definitions of ME inputs, MEI_m, and values for diet metabolizability, q_m, are used when reporting comparisons of calorimetric data with the energy standards of ARC (1980) and AFRC (1993); see Yan et al. (1997a). This is especially the case when no measurement of diet ME concentration measured at maintenance has been reported, as it was not part of the experiment protocol. The required corrected ME intake values can be calculated from the experimental data, as shown above, by assuming that the chosen energy model is correct, and by using various mathematical manipulations. The feeding level corrections involved may appear small, but they can have the same magnitude as previously reported biases (AFRC, 1990) and the safety margin of 5% implemented in AFRC (1993) based on their findings. With high genetic merit dairy cows, predicted feeding level corrections to diet metabolizability can exceed 1.05, equivalent to 15 MJ ME/d, or 3 kg milk/d, which is quite significant economically.

The performance prediction equation sequence of the dairy cow energy model of ARC (1980) can be reversed by solving either of two quadratic equations in MEI_m (equations 13 and 25). Measurements of production level ME intake are thereby corrected for the current estimates of feeding level depressions of metabolizability in ARC (1980), enabling comparison with existing ME requirements of dairy cows (AFRC, 1993). The quadratic equation for Procedure I has the decline of metabolizability with feeding level, γ, as a constant in it, so that the latter could be modified in a revised model to fit the new calorimetric data if required.

Procedure II, whilst still relying on the ARC (1980) energy model, starts from the measured milk net energy, corrected for tissue energy balance, and is also a quadratic equation in corrected ME intake, MEI_m. For the selected test data, the values found for the ARC (1980) efficiency of ME utilization terms, k_{l0} and k_m, predicted milk net energy outputs which were an accurate fit to the mean of the test data, provided recently reported estimates of dairy cow fasting metabolism and maintenance ME requirements (Yan et al., 1997b) are used, not those of ARC (1980). Also that the feeding level correction, γ, of 0.018 per unit increase in L is omitted or is set equal to zero. It is also interesting to note that equation (39) above, from ARC (1980), for the metabolizability of the test diet (0.628) would predict a value for C_L of 1.0007 compared to the value of 0.998 calculated when q_m is 0.624, as shown in Table 3. It also showed that the 5% safety margin used in AFRC (1993) ME requirement tables is not needed either. It would appear that both the latter adjustments were needed to correct for the low estimates of the maintenance requirements used in the original factorial dairy cow model of ARC (1980) as illustrated in Figure 1. These adjustments do not bring the existing ME requirements of AFRC (1993) into line with the selected test data, except at the mean. It can be concluded that several components of the ARC (1980) dairy cow energy model require revision or omission, but that the core efficiency of ME utilization terms for maintenance and milk synthesis are still accurate.

This analysis does not deal with the question as to whether there is a systematic bias between $[ME_m]$ diet values measured with wether sheep fed at maintenance and the derived estimates of $[ME_m]$ for dairy cows which are a good fit to the original ARC (1980) efficiency of ME utilization equations, as there is no data available on the test diets studied. It should be noted however, that the ratio ME:digestible energy for the dairy cow test diet fed (Cammell et al., 2000) yielded a mean value of 0.877, in agreement with Moe et al. (1972), whereas the value for wether sheep is given as 0.82 by ARC (1980). Thus with dairy cows, there appears to be significant compensation, for any reductions in digestibility caused by higher rates of passage though the rumen and associated lower retention times in the rumen, resulting in reduced methane production. However the latter will be influenced by the proportion of cell walls in the diets fed, which in the selected test diet was about 400 g/kg volatile corrected DM.

The ARC (1980) exponential equation used to predict the performance of beef cattle can be reversed, but it becomes a transcendental equation with no algebraic solution (equation 37). The linear model of ARC (1965), which is a close fit to the later exponential model of ARC (1980), includes a function for feeding level correction of metabolizability, γ, which is itself dependent upon diet metabolizability. When reversed, this model generates a cubic equation (equation 43). The Newton-Raphson method was used to solve the cubic and to find values for corrected ME intake to the data and thence derive accurate estimates of diet metabolizability at maintenance, q_m, as defined by the simpler bi-linear model of ARC (1965). The results show that the ME requirements of AFRC (1993) are in close agreement with those calculated, with mean values of 80.9 and 82.2 MJ/d respectively, confirming the need for a 5% safety margin to be added to the ARC (1980) mean ME requirement value of 77.1 MJ/d. This also raises the question as to whether upwards revision of the estimates of fasting metabolism of steers, as recently found for dairy cows by Yan et al. (1997b), would remove the necessity for the inclusion of a safety margin in the beef model, which is an empirical and clumsy method of correcting such energy models.

If significant progress in the revision of the feeding level component of current UK ruminant energy requirement models is to be made, the routine measurement of diet metabolizability with wether sheep at the maintenance plane ought to be an essential component of the protocol of all respiration chamber work with beef and dairy cattle.

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STRESZCZENIE

Sposoby korekty pobrania energii metabolicznej przez przeżuwacze, oznaczanego przy produkcyjnym poziomie żywienia w porównaniu z określanym przy bytowym poziomie żywienia

Dane dotyczące pobrania energii metabolicznej (EM) oraz metaboliczności dawki dla przeżuwaczy, otrzymane w komorach respiracyjnych, nie mogą być bezpośrednio zastosowane do oszacowania rzeczywistego zapotrzebowania na energię metaboliczną, z powodu przyjętej definicji dotyczącej koncentracji EM w paszy w modelu zapotrzebowania energii ARC (1980). W modelu tym zakłada się, że ilość energii netto dostępnej do syntezy mleka lub tkanek ciała jest określana na podstawie pobrania EM. W przeciwieństwie do potrzebnych wyliczeń, zarówno metaboliczność dawki, oznaczana przy bytowym poziomie żywienia, jak i poziom żywienia, jako wielokrotność zapotrzebowania bytowego, które jest także funkcją metaboliczności diety, są potrzebne, a które zazwyczaj nie są oznaczane w badaniach kalorymetrycznych. W przypadku krów mlecznych opracowano dwie potęgowe funkcje, na podstawie których oblicza się zapotrzebowanie w oparciu o ilość pobranej EM przy bytowym poziomie żywienia. Otrzymane tym sposobem dane są dokładne. Według pierwszego sposobu obliczania średnie różnice w zapotrzebowaniu EM wynosiły około 25 MJ/dzień powyżej przy-

jętych standardów. Druga metoda była precyzyjna do oznaczania przemiany głodowej. Stosując oznaczone tą metodą dane do wyliczeń, średnie wartości pobrania EM przy bytowym poziomie żywienia wskazują, że nie jest potrzebne wprowadzenie poprawki na poziom żywienia dla otrzymania dokładnego modelu do badanych danych. Nie jest też potrzebny 5% margines bezpieczeństwa przyjęty w AFRC (1993).

Wykładniczy model retencji energii ARC (1980) dla rosnącego bydła nie może być zwrotny; tworzy on transcedentne równanie bez algebraicznego rozwiązania. Liniowy model ARC (1965), z poprawką na poziom żywienia, zależny od metaboliczności dawki, jest dobrze przystosowany do modelu wykładniczego, i proponuje się jego zastosowanie wówczas, gdy potrzebne jest oznaczenie obniżenia metaboliczności diety dla rosnącego bydła ras mięsnych. Jest to równanie trzeciego rzędu. Metodę Newtona-Raphsona zastosowano dla rozwiązań liczbowych, stosując odpowiednie dane z badań kalorymetrycznych. Sprawdzając otrzymane rozwiązania wykazano, że otrzymane równanie jest wiarogodne, oraz że zapotrzebowanie na EM przez rosnące bydło ras mięsnych podane w AFRC (1993) jest dokładne.