



Maintenance energy requirements of goats: predictions based on observations of heat and recovered energy

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Abstract

A database including 80 treatment means, based on energy balance publications, was constructed and analyzed to estimate fasting heat production (FHP) and ME required for maintenance (ME_m) of goats. Experiments entailed comparative slaughter, respiration calorimetry or CO_2 entry rate techniques. Goats were of eight breeds and five physiological states (preweaning; growing; mature and non-lactating; early and mid-pregnancy; and lactating). Assuming that heat increment was 40% of total heat energy, unweighted, and weighted (number of observations per treatment mean) log–log regressions ($n = 74$ following removal of observations to increase explained variation) of FHP against BW resulted in FHP (kJ) = $299 \times BW^{0.762}$ ($R^2 = 0.82$) and $244 \times BW^{0.826}$ ($R^2 = 0.75$), respectively. The 0.762 and 0.826 BW scaling factors did not differ ($P < 0.17$) from 0.75. The slope and intercept of a regression of recovered energy (RE) against ME intake (MEI) for preweaning goats differed ($P < 0.01$) from those for other physiological states. A linear regression analysis of RE on MEI (both kJ/kg $BW^{0.75}$) was conducted with the remaining 71 observations, after removing two observations with SD greater than 2.5 residual SD. The resultant equation was: $RE = -298.0$ (SE = 22.38) + $(0.691$ (SE = 0.028) \times MEI) [$n = 69$; $R^2 = 0.90$]. These estimates of FHP and efficiency of ME use yielded an estimate of ME_m of 431 kJ/kg $BW^{0.75}$. In summary, FHP and ME_m of 298 and 431 kJ/kg $BW^{0.75}$, respectively, appear appropriate as general descriptors of the maintenance energy requirement of goats consuming diets at, near or above maintenance.

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1. Introduction

Factorial approaches often are used to estimate energy requirements of livestock (Kirkland and Gordon,

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1999), even though energy metabolism is not a segmented process. One very large component of energy metabolism is the energy requirement for maintenance. ME for maintenance (ME_m) can be viewed as the amount of energy used in basal metabolism and lost as heat when an animal fasts (fasting heat production, FHP, or net energy for maintenance, NE_m) plus the heat of activity (H_jE) and the additional energy lost when an animal consumes enough feed to maintain a static body energy content (e.g., heat increment, H_iE), i.e., $ME_m = FHP + H_jE + H_iE$. Maintenance energy requirements, typically, are measured using mature animals even though values are frequently employed when calculating energy requirements for BW gain or growth (Ferrell, 1988b).

Energy requirements of ruminants have been studied via respiration calorimetry and comparative slaughter. For respiration calorimetry, FHP is determined directly, and ME_m is the ME intake (MEI) when equal to total heat production (HE). With higher energy intakes, the rate of increase in HE above ME_m or in recovered or retained energy (RE), determined as the difference between MEI and HE, is used to calculate the efficiency of ME use for gain. Though less common than respiration calorimetry, the carbon dioxide entry rate technique (CERT), similar in principle to respiration calorimetry, has been employed to assess energy needs of livestock. With comparative slaughter, change in body energy content is measured at several levels of MEI. Through extrapolation, maintenance energy requirements and efficiencies of ME use can be calculated. With energy metabolism experiments, the number of observations in any given experiment usually is inadequate for developing accurate requirement estimates that are applicable across classes of animals within a species.

Maintenance energy requirements of goats have not been well defined. Several energy metabolism studies have been conducted with goats, but ME_m estimates vary widely. Sauvants (1981) concluded that variability in published estimates of FHP or NE_m could not be explained by conditions such as biological type, physiological state or the particular measurement techniques employed. Consequently, simple means of FHP estimates and ME_m of a number of studies were calculated by AFRC (1998). NRC (1981) proposed a ME_m derived by averaging values from 10 publications between 1950 and 1980. We included results of addi-

tional studies and additional statistical procedures in an attempt to re-evaluate the maintenance energy requirements of goats. Our objectives were to estimate FHP and ME_m of goats from a database constructed from available publications where MEI and HE or RE were measured with goats.

2. Materials and methods

2.1. Database

The database that we assembled included 80 treatment means, representing 466 individual animals from 16 publications involving dairy, meat, Angora, and indigenous (e.g., mixed-purpose native goats) breeds of goats at various physiological conditions (Appendix A). Physiological states of animals included preweaning; weaning to one year of age; mature wethers and dry does; early and mid-pregnancy; and lactating. Eight publications and 36 treatment means involved respiration calorimetry techniques with direct measurement of HE and RE as the difference between MEI and HE. Five publications with 26 treatment mean observations used CERT to calculate HE. Three publications and 18 treatment mean observations entailed comparative slaughter, with direct measurement of RE and HE calculated as the difference between MEI and RE. Nine of 18 treatment mean observations from comparative slaughter experiments were with pre-weaning goats. Table 1 outlines conditions of the experiments of the database and Table 2 summarizes most important variables.

Johnson (1986) discussed factors responsible for differences in partial efficiencies between respiration calorimetry and comparative slaughter; calorimetry usually results in higher efficiencies of energy use and comparative slaughter frequently over-estimates ME_m because of low efficiency of ME use at high intakes. However, for purposes of this study, maximizing the number of observations was deemed of greater importance than attempting to adjust for variation imposed by different measurement techniques.

2.2. BW function

To investigate the function or power of BW by which maintenance energy requirements can be ex-

Table 1
Summary of references used in the database

Method ^a	Biotype	Breed	Country ^b	BW ^c (kg)	Goats ^d	Treatments ^e	PS ^f	Forage ^g (%)	Source ^h
CERT	Indigenous	Spanish	USA	32.4	12	2	DRY	100.0	(E) Herselman et al. (1999)
	Indigenous	Etawah	Indonesia	20.0	20	4	LAC	55.1	(J) Kiranadi et al. (1994)
	Indigenous	Etawah	Indonesia	21.5	20	4	LAC	55.5	(O) Sastradipradja et al. (1994)
	Indigenous	Etawah	Indonesia	28.5	81	9	DRY, PR ⁱ	13.0	(H) Katipana and Sastradipradja (1994)
	Indigenous	Etawah	Indonesia	13.8	20	5	GR		(C) Astuti et al. (1997)
CS	Mohair	Angora	USA	30.4	12	2	DRY	100.0	(E) Herselman et al. (1999)
	Dairy	Saanen	Germany	18.6	16	4	GR	16.7	(K) Negesse et al. (2001)
	Dairy	Granadina	Spain	4.6	12	6	PW	0.0	(N) Sanz Sampelayo et al. (1988)
RC	Indigenous	Carpatian	Romania	18.8	24	8	PW, GR ^j		(P) Voicu et al. (1991)
	Dairy	Saanen	Japan	44.1	9	3	DRY	91.5	(I) Khan et al. (1998)
	Dairy	Saanen	Italy	55.2	24	6	LAC	13.8	(M) Rapetti et al. (2001)
	Dairy	Granadina	Spain	28.2	32	4	DRY	79.0	(L) Prieto et al. (1990)
	Dairy	Granadina	Spain	38.6	70	6	LAC		(A) Aguilera et al. (1988)
	Dairy	Granadina	Spain	38.9	70	6	LAC	39.7	(B) Aguilera et al. (1990)
	Indigenous	Cheghu	India	27.8	8	2	DRY	88.9	(D) Haque et al. (1998)
	Indigenous	Native	Japan	25.9	16	4	DRY	63.9	(F) Islam et al. (2000)
	Indigenous	Native	Japan	29.5	20	5	DRY	79.9	(G) Islam et al. (2001)

^a CERT: carbon dioxide entry rate technique; CS: comparative slaughter; RC: respiration calorimetry.

^b Country where the experiment was conducted.

^c Mean body weight of goats for all treatments.

^d Number of goats in the experiment.

^e Number of treatments in the experiment.

^f PW: preweaning; GR: growing, weaning to 1 year of age; DRY: mature wethers and dry non-pregnant does; PR: early and mid-pregnancy; LAC: lactating.

^g When not listed, sufficient information on dietary forage percentage was not reported.

^h Letters assigned to each reference were used in figures.

ⁱ Six of nine treatments in this experiment were with PR goats.

^j Five of eight treatments in this experiment were with GR goats.

pressed, H_iE was assumed to be 40% of HE (Crampton and Harris, 1969; McDonald et al., 1977). Although the ratio of H_iE to HE might not be constant, differences among observations in this study probably were not marked. For example, FHP or NE_m is thought to decrease with increasing stage of maturity (Tolkamp and Ketelaars, 1992; Freetly et al., 1995), but HE decreases as animals mature and energy intake nears that required for maintenance (Graham and Searle, 1972). Likewise, as HE increases with increasing MEI, energy used for maintenance functions (e.g., splanchnic tissue metabolism) also rises (Ferrell, 1988a).

The relationship between FHP and BW, typically, has been described as a power equation ($Y = a \times BW^b$) based on the work of Brody (1945).

The power equation was converted into linear form by log(10) transformation; both unweighted and weighted log–log regressions of FHP on BW were conducted. Regressions were performed using PROC REG of SAS (1990). Preceding any regression analysis, analysis of covariance, using Proc GLM of SAS (1990), was employed to compare slopes and intercepts of regression equations for the different physiological states (Snedecor and Cochran, 1978). For this and other regressions, the residual (difference between actual and predicted values) of each observation was compared with various multiples of residual S.D. (3S.D., 2.5S.D., 2S.D., 1.5S.D.). Individual observations with differences greater than selected residual S.D. were deleted and changes in

Table 2

Summary of the database used to estimate fasting heat production (FHP) and maintenance ME requirements (ME_m)

Item	Database					Data subset ^a				
	<i>n</i>	Mean	S.D.	Min ^b	Max ^c	<i>n</i>	Mean	S.D.	Min	Max
Mean BW (kg)	80	27.7	12.96	4.0	61.5	71	30.41	11.02	12.1	61.5
Forage (%)	69	40.2	35.37	0	100	60	46.17	34.04	0	100
DM intake (g/day)	74	818	625.8	69	2946	65	902	620.1	258	2946
ME intake (MJ/day)	80	9.18	7.479	1.60	33.79	71	9.89	7.631	2.40	3.379
ME intake (kJ/kg BW ^{0.75} /day)	80	747	380.7	261	1821	71	726	387.8	261	1821
Energy digestibility (%)	46	67.3	11.40	45.6	90.6	46	67.3	11.40	45.6	90.6
Fecal energy (MJ/day)	60	5.06	3.98	0.75	20.98	57	5.25	3.99	1.19	20.98
Urine energy (kJ/day)	55	540	490.9	38	1943	57	544	502.2	38	1943
Heat energy (MJ/day)	80	6.44	3.62	1.33	18.20	71	6.91	3.538	2.65	18.20
Fasting heat production (MJ/day) ^d	80	3.86	2.17	0.80	10.928					
Recovered energy (MJ/day)	80	2.76	4.41	-2.86	16.30	71	3.00	4.623	-2.86	16.30
Recovered energy (kJ/kg BW ^{0.75} /day)	80	208	277.7	-217	1071	71	205	292.7	-217	1071

^a Excluding pre-weaning observations; consisting of observations for weaning to 1 year of age, mature wethers and dry goats, early and mid-pregnancy and lactating.

^b Minimum.

^c Maximum.

^d Calculated value with the assumption that heat increment was 40% of heat energy.

regression R^2 and root mean square error (RMSE) were viewed. The residual S.D. that was used to identify observations for omission yielded an appreciable increase in explained variability but maximized the number of observations used. Observations removed from dataset were examined in detail for each computation (Chatterjee et al., 2000). The *t*-test was used to compare the difference between the calculated exponent (e.g., slope of the regression) and reference power of 0.75 (Draper and Smith, 1966).

2.3. FHP or NE_m and efficiencies of ME utilization

RE (kJ/kg BW^{0.75}) was regressed against MEI (kJ/kg BW^{0.75}), with the intercept describing FHP or NE_m and the slope efficiency of ME use for maintenance and energy accretion (k_{m+p}). The intercept and slope for preweaning observations differed ($P < 0.01$) from other intercepts and slopes and, thus, these observations were omitted. A separate equation for pre-weaning goats was not presented because the number of observations was limited (only 9). Intercepts and slopes for the other physiological states were similar; hence, regressions were with pooled data. The data subset with 71 treatment means representing 445 goats is described in Table 1.

3. Results

3.1. Regression of FHP on BW of goats

In comparing metabolism of animals of different sizes, FHP or basal metabolism can be related to BW by using the power equation of $Y = aX^b$; the value of exponent b provides an estimate of the rate at which metabolism changes with increasing body size. Regressions of log(FHP) against log(BW) for each physiological state of goats yielded similar ($P > 0.10$) slopes and intercepts. Therefore, all observations in the database were used. The resulting log–log regression, with calculated FHP in kJ and BW in kg, was:

$$\begin{aligned} \log \text{FHP} = & 2.507(\text{SE} = 0.073) \\ & + (0.739(\text{SE} = 0.052) \times \log \text{BW}) \\ & [n = 80; R^2 = 0.72] \quad (1) \end{aligned}$$

There were six observations with residuals greater than 2 S.D., for which there were no obvious reasons for deviation, such as distinctive nutritional or genetic factors. After deleting these observations (8% of the database), the modified regression was:

$$\begin{aligned} \log \text{FHP} = & 2.476(\text{SE} = 0.060) \\ & + (0.762(\text{SE} = 0.043) \times \log \text{BW}) \\ & [n = 74; R^2 = 0.82] \quad (2) \end{aligned}$$

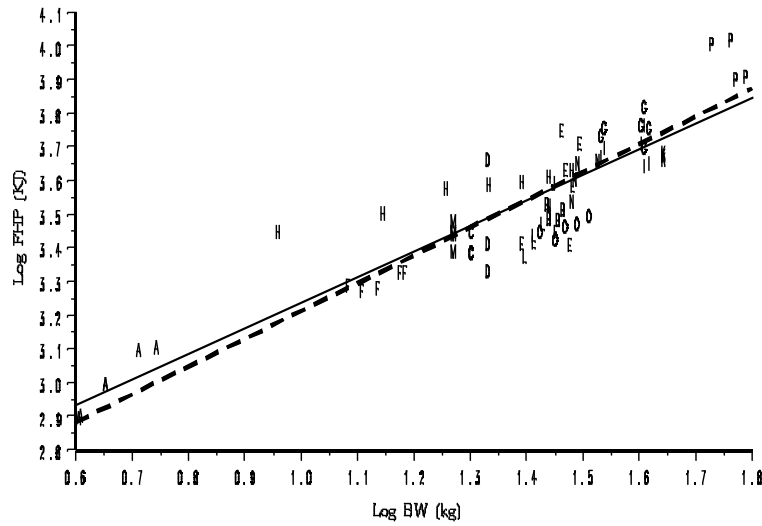


Fig. 1. The relationship between the log of fasting heat production (FHP) and the log of BW for all goats in the database. Letters represent the reference shown in Appendix 1. The dashed line describes the weighted equation: $\log \text{FHP} = 2.387 \text{ (SE} = 0.081) + (0.826 \text{ (SE} = 0.055) \times \log \text{BW)}$ [$n = 74; R^2 = 0.75$]; the solid line describes the unweighted equation: $\log \text{FHP} = 2.476 \text{ (SE} = 0.060) + (0.762 \text{ (SE} = 0.043) \times \log \text{BW)}$ [$n = 74; R^2 = 0.82$]. $\text{MBW} = \text{kg BW}^{0.75}$.

The regression line and Eq. (2) are presented in Fig. 1. The antilog of the intercept of Eq. (2) resulted in a prediction equation of $\text{FHP (kJ)} = 299 \times \text{BW}^{0.762}$. The exponent for BW was not different from 0.75 ($P > 0.10$), the factor that is routinely used for nutrient requirement assessments. In this regard, the power equation from Eq. (2) was converted to: $\text{FHP (kJ)} = 311 \times \text{BW}^{0.75}$, based on the mean BW of 27.7 kg in the database. With the same data used for Eq. (2), the regression with a fixed exponent of 0.75 produced the equation: $\text{FHP (kJ)} = 330 \times \text{BW}^{0.75}$ ($R^2 = 0.95$). The greater regression coefficient can be attributed to forcing the regression line through the origin.

Because of differences in the number of observations per treatment mean, a weighted log–log regression was also conducted with the same observations used in regression Eq. (2):

$$\begin{aligned} \text{FHP} &= 2.387(\text{SE} = 0.081) \\ &+ 0.826(\text{SE} = 0.055) \times \text{BW} \\ &[n = 74; R^2 = 0.75] \end{aligned} \quad (3)$$

The regression line and Eq. (3) are also presented in Fig. 1. The resulting power equation of Eq. (3) was: $\text{FHP (kJ)} = 244 \times \text{BW}^{0.826}$, again, with no significant difference between the exponent (i.e., 0.826) and 0.75

($P > 0.10$). The power equation from Eq. (3) was converted to: $\text{FHP (kJ)} = 314 \times \text{BW}^{0.75}$ based on mean BW. With the same data used for Eq. (2), the regression with a fixed exponent of 0.75 yielded the equation: $\text{FHP (kJ)} = 332 \times \text{BW}^{0.75}$ ($R^2 = 0.96$).

3.2. Linear regression of RE on MEI

Using the subset of the database, with pre-weaning observations removed, RE ($\text{kJ/BW}^{0.75}$) was regressed against MEI ($\text{kJ/BW}^{0.75}$). Linear, quadratic, and cubic effects of MEI were tested. Quadratic and cubic effects were non-significant ($P > 0.10$), and R^2 for regressions with linear, quadratic, and cubic functions (0.894) and with linear and quadratic functions (0.890) were not different from that of the simple linear regression of RE against MEI:

$$\begin{aligned} \text{RE} &= -312.1(\text{SE} = 24.84) \\ &+ 0.712(\text{SE} = 0.030) \times \text{MEI} \\ &[n = 71; R^2 = 0.89] \end{aligned} \quad (4)$$

In the examination of the plot of residuals against MEI, two observations with residuals greater than 2.5 S.D. were identified and removed from regression analysis. Both observations were with lactating goats of

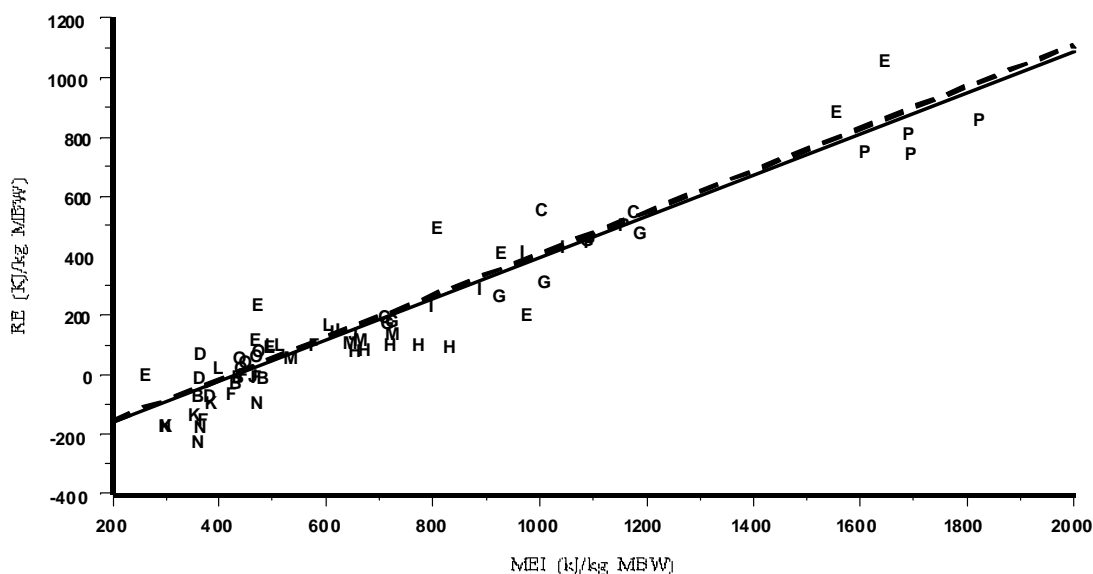


Fig. 2. The relationship between recovered energy (RE) and ME intake (MEI) for goats, excluding preweaning observations. Letters represent the reference shown in Appendix A. The dashed line describes the weighted equation: $RE = -297.0$ (SE = 24.70) + 0.703 (SE = 0.030) \times MEI [$n = 69$; $R^2 = 0.89$]; the solid line describes the unweighted regression equation: $RE = -298.0$ (SE = 22.38) + (0.691 (SE = 0.028) \times log BW) [$n = 71$; $R^2 = 0.90$]. MBW = kg BW^{0.75}.

an indigenous breed, but no reason was apparent for their high residuals. Further deletion of observations with residuals greater than 2 S.D. or 1.5 S.D. did not, markedly, improve the fit of the model with respect to R^2 and RMSE. Therefore, the regression equation with exclusion of the two observations noted earlier was considered most appropriate:

$$RE = -298.0(\text{SE} = 22.38) + 0.691(\text{SE} = 0.028) \times \text{MEI} \quad [n = 69; R^2 = 0.90] \quad (5)$$

The equation with weighting by the number of animals per treatment mean with the same observations used for Eq. (5) was:

$$RE = -297.0(\text{SE} = 24.70) + 0.703(\text{SE} = 0.030) \times \text{MEI} \quad [n = 69; R^2 = 0.89] \quad (6)$$

Eqs. (5) and (6) were almost identical; however, the unweighted regression (Eq. (5)) was selected as most appropriate because of slightly smaller SE of the intercept and slope. The regression lines of Eqs. (5) and

(6) are presented in Fig. 2. FHP, determined as the intercept, was 298 kJ/kg BW^{0.75}, and the slope of the equation represents a k_{m+p} of 0.691. Dividing FHP by k_{m+p} yielded a ME_m of 431 kJ/kg BW^{0.75}.

4. Discussion

4.1. BW power for basal metabolism of goats

Using extensive data on many animal species, Brody (1945) proposed the equation FHP (kcal) = $70.5 \times \text{kg BW}^{0.734}$ to describe the relationship between basal metabolism or FHP and BW, with BW^{0.734} being the reference base for energy metabolism. Later, Blaxter (1967) proposed the 0.75 exponent of BW. However, Brody (1945) suggested that BW powers should be determined with actual data from the species of interest. In this regard, b values determined in this study with goats of 0.762 and 0.826 from unweighted and weighted log–log regressions, respectively, were close to and did not significantly differ from 0.75. Therefore, 0.75 remains suitable as an appropriate exponent of BW for the expression

of basal metabolism or FHP of goats. Similarly, Luo et al. (2004) found that $BW^{0.75}$ could be used as a basis to express endogenous urinary N of goats.

4.2. Estimates of FHP of goats

FHP of goats has been previously studied in feeding trials with non-lactating (Devendra and Burns, 1983; Akinsoyinu et al., 1975; Morand-Fehr, 1981) and lactating goats (Armstrong and Blaxter, 1965), with estimates ranging from 212 to 402 kJ/kg $BW^{0.75}$ (AFRC, 1998). This wide range may be attributed partly to differences in mathematical models and accuracy of measurements. Respiration calorimetry experiments (Fujihara et al., 1973; Roy-Smith, 1980; Prieto et al., 1990) have yielded less variable estimates (324–357 kJ/kg $BW^{0.75}$). The AFRC (1998) recommendation of 315 kJ/kg $BW^{0.75}$ for FHP of goats, based on 9 studies from 1906 to 1990, is slightly greater than 298 kJ/kg $BW^{0.75}$ from the regression of RE against MEI.

Even though the FHP estimate from our study is in accordance with that recommended by AFRC (1998), our database included goats in widely different physiological states, each with a limited number of observations and under diverse experimental or production conditions. FHP is thought to decrease with advancing age (McDonald et al., 1977; ARC, 1980; Tolkamp and Ketelaars, 1992), increase with increasing level of feed intake (Armstrong and Blaxter, 1984), and differ among genders (McDonald et al., 1977). Furthermore, differences among cattle breeds in FHP (Ferrell and Jenkins, 1985) suggest that FHP of various goat breeds also might be unique. Hence, future experiments with direct measurements, or investigations with larger compiled databases, could result in FHP estimates that are more accurate for specific goat feeding applications.

4.3. Estimates of ME_m value of goats

As noted for FHP, the ME_m estimate of 431 kJ/kg $BW^{0.75}$ is in close accordance with that estimated by AFRC (1998; 438 kJ/kg $BW^{0.75}$), which was derived by averaging ME_m values of 17 studies using different methods from 1868 to 1990. The NRC (1981) estimate of 421 kJ/kg $BW^{0.75}$, obtained by averaging ME_m values of 10 studies during the 1950s and 1980s,

also is similar. Comparable values (i.e., 421–456 kJ/kg $BW^{0.75}$) have been observed in specific experiments (Rajpoot et al., 1980; Mohammed and Owen, 1981; Prieto et al., 1990; Aguilera et al., 1991; Sauvant and Morand-Fehr, 1991). However, in other experiments greater [(i.e., 460–672 kJ/kg $BW^{0.75}$) Majumdar, 1960; Singh and Sengar, 1978; Haenlein, 1980; Kurar and Mudgal, 1981; Sengar, 1980; Kurar, 1983; Singh and Mudgal, 1985; Abate, 1989; Haque et al., 1998] and lower [(365–401 kJ/kg $BW^{0.75}$) Devendra, 1967; Itoh et al., 1978; Aguilera et al., 1990] values were estimated. Greater variability in estimates of ME_m versus FHP are expected given higher levels of feeding for direct determination of ME_m and greater differences among diets in efficiency of ME use for gain than for maintenance (NRC, 1984). Likewise, a large range in MEI is necessary for accurate estimation of ME_m via regression of RE against MEI, particularly in the distance from the lowest MEI to that with 0 RE. In the present study, MEI ranged from less than FHP (i.e., 261 kJ/kg $BW^{0.75}$) to 1821 kJ/kg $BW^{0.75}$.

Similar to the FHP estimate, the ME_m value of this study seems appropriate as a general descriptor of ME necessary to maintain constant body energy in goats consuming diets at, near or above maintenance. But, in specific experimental or production settings, actual ME_m may differ from this estimate. However, differences in ME_m among genotypes or as a result of selection appear to be primarily dependent on variation in FHP rather than efficiency of ME use for maintenance (k_m ; Ferrell and Jenkins, 1985; Rompala et al., 1991), although dietary characteristics may impact both k_m (NRC, 1984) and FHP (Webster, 1980; Reynolds et al., 1991). Inadequate data were available to address potential differences among genotypes in FHP or ME_m . Also, these estimates would not be directly applicable to goats on a low plane of nutrition, which decreases FHP (NRC, 2000). In this regard, Silanikove (2000) stated that differences among goat genotypes in potential magnitude of adaptation (i.e., change in fasting heat production) to fluctuating energy intake are appreciable. Thus, effects of nutrient restriction on energy use by goats deserve research attention.

4.4. Estimates of k_{m+p} value

The combined efficiency of ME use for maintenance and productive functions, k_{m+p} , was slightly greater

than reported for goats by Aguilera et al. (1990; i.e., 0.67), but less than the values of Prieto et al. (1990; i.e., 0.73) and Katipana and Sastradipradja (1994; i.e., 0.74). Nonetheless, k_{m+p} of the present study was of primary importance only to calculate ME_m because goats of a number of physiological states and with a wide range of feed intakes were employed.

5. Conclusion

Regressions of treatment mean observations from energy balance publications indicate that $BW^{0.75}$ is an

appropriate scaler of goat energy requirements. FHP and ME_m estimates of 298 and 431 kJ/kg $BW^{0.75}$, respectively, appear useful as general descriptors of maintenance energy needs of goats continuously consuming diets at, near or above maintenance. Further study is necessary to develop energy requirement expressions for goats more appropriate for specific production or experimental conditions.

Acknowledgements

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Appendix A

Letters preceding reference are shown in Fig. 1.

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