

ENERGY SOURCES AND REQUIREMENTS OF THE EXERCISING HORSE

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ABSTRACT

This review outlines the energy sources available to the horse, from its diet and from its body stores, at rest and while exercising. It looks at the current ways of describing the energy potential of diets fed to horses and discusses the relative advantages and disadvantages of the digestible energy and net energy systems. The more empirical net energy system for calculating the energy available for maintenance and work is compared with a more physiological partitioning system. Finally, the energy requirements for maintenance and exercise are discussed, together with how they may be practically determined and achieved through different diets.

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BACKGROUND

Since it was first domesticated, around 4000–5000 B.C., the horse's role in society has varied according to man's requirements, but it has always been based on the animal's ability to run and jump, pull and carry. Initially the horse was kept for its flesh and milk, but it soon became used for transport. The first record of a man on horseback is believed to be the bone engraving of the Susa horseman (2800 B.C.). By the eighth century B.C., horses had become essential to the skilled-horseman-turned-warrior. In parallel with horse riding, horse racing developed. There were races on horseback being held in Greece as early as 648 B.C., although initially they were not as popular as the chariot races. The very popular Roman chariot races evolved into modern-day racing.

In developed countries today the horse is used mainly for pleasure, and a variety of contests have evolved that provide a competitive angle. These sporting activities vary not only in the intensity and duration of the exercise undertaken but also in the degree of skill and aptitude needed by horse and rider. Flat racing is at one end of the duration/intensity spectrum, with American quarter horses racing at speeds of up to 20 m/s for over 400 m. At the other end of the spectrum are endurance rides, which may take place over several days at speeds of ~5–6 m/s (on average). The show jumper may only have 3-min competition bouts, but this can include a number of fences, each of which could be 5 ft or more in height and spread. Many believe the three-day-event competition to be one of the most demanding equestrian activities because it involves a number of phases, including dressage, steeplechasing, endurance, and show jumping as well as cross-country jumping, all within a relatively short time period (Table 1).

Ponies of 200-kg mature weight or less, horses up to 700 kg or more, as well as miniature horses around 150-kg body weight are used for competition/sporting purposes. A variety of types and/or breeds are used in the different activities, although one or two types/breeds may dominate each equestrian discipline. In addition, many horses and ponies are not used for competition purposes but are kept as pets or as breeding animals or for hacking/general purposes.

Any discussion of energy requirements of the horse must take into consideration the great variety of body sizes and uses of this animal. In this review, the energy requirements for growth, pregnancy, lactation, and breeding in general

Table 1 Estimated energy expenditure for a 500-kg horse competing in the four phases of the cross-country day of a three-day event (43)

Phase	Description	Time (min)	Speed (m/s)	Jumps	Average metabolic power (kW; excluding jumps)	Energy expenditure rate [kJ/min including 15% allowance for rider (75 kg)]	Total energy expenditure (kJ)	Allowance for jumps ^a
A	Roads and tracks	23	3.7	No	5	345	7935	7935
B	Steeplechase	4.5	11.5	Yes	20	1380	6210	6406 (+3.2%)
C	Roads and tracks	50	3.7	No	5	345	17250	17250
D	Cross country	13	9.5	Yes	15	1035	13455	14560 (+8.3%)

^aAllowing 9.81 J of mechanical energy to lift each kilogram of mass an elevation of 1 m (excluding horizontal translation) with a 20–25% efficiency of conversion (i.e. 49 J/kg/jump). No allowance for rider.

are not considered; the chapter concentrates on the energy requirements for maintenance and exercise.

DEFINITION OF ENERGY

A typical dictionary definition of the term energy is “Physics a. The capacity of a body or system to do work. b. A measure of this capacity measured in joules (Système International) units.” Energy per se is not a nutrient, and the precise definition of it, especially in a nutritional sense, is complex, involving enthalpy and entropy (4, 46). In effect, certain nutrients in a horse’s diet ultimately provide it with energy intake following conversion of their chemical energy to other forms of chemical energy, mechanical energy, and heat.

ENERGY SOURCES

The horse can be described as a monogastric or nonruminant herbivore that is suited to digesting and utilizing high-fiber diets as a result of continual microbial fermentation within the hindgut (cecum and colon).

Dietary energy is provided to the horse by four principle energy sources: (a) hydrolyzable carbohydrates, e.g. starch; (b) cellulose, pectins, hemicelluloses, etc (i.e. nonstarch polysaccharides: a component of dietary fiber); (c) fats; and (d) proteins. In general, a high proportion of the starch ingested is degraded to glucose before absorption. However, a proportion of the starch and, depending on the extent of lignification, a varying proportion of the dietary fiber will be subjected to microbial fermentation, primarily in the large intestine, producing predominantly short-chain or volatile fatty acids. The extent to which cereal starch provides glucose or volatile fatty acids as the end result of digestion will depend on its prececal and even its pre-ileal digestibility, which in turn will vary according to the feedstuff under consideration and the extent and nature of the processing it has been subjected to (17, 19, 45).

Horses, like most animals, rely mainly on stored energy when exercising. It is not known how quantitatively important protein is as an energy source in horses during exercise, although there is some evidence to suggest that protein catabolism may represent a potential source of energy (47, 66). As in other mammals, therefore, the main fuel sources available for energy production by the horse both at rest and during exercise are carbohydrate in the form of muscle glycogen or blood glucose; fat in the form of muscle or plasma triglyceride, plasma free fatty acids, or ketones; and muscle stores of ATP and phosphocreatine. [The ketone pathway is believed to be relatively unimportant in the horse (78).] Various estimates as to the amount of fuel (excluding proteins) stored by a horse have been made. For example, a 500-kg horse has about 640,000 kJ of available energy stored as triglyceride, 75,300 kJ stored as glycogen, 188 kJ stored as phosphocreatine, and 38 kJ stored as endogenous muscle ATP (55). An alternative estimate (66) for a 450-kg horse in grams of stored energy is 1400–2800 g as muscle triglyceride, 40,000 g as adipose triglyceride, 3150–4095 g as muscle glycogen, and 90–220 g as liver glycogen. Regardless of the method for describing the stored energy, fat is by far the largest store. The actual percentage of body fat may be lower in the horse [~ 1.1 – 2.0% (25)] than in man [5 – 15% (52, 95)], although other studies have reported values more comparable to man [10 – 25% (44, 94)]. This may reflect the animals used in the studies and the methods of analysis employed. The horse, however, particularly the thoroughbred, does have considerably larger muscle and liver glycogen stores compared with man (14, 59, 69, 84) and therefore, in theory, a greater potential for carbohydrate utilization.

A number of factors affect the proportion of energy that can be derived from each potential energy source during different energy bouts, including the intensity and duration of exercise, the muscle fiber composition of the horse, and the diet and fitness (coupled with the training regimen) of the horse (18, 19, 34, 47, 49, 66). The various pathways by which the chemical energy sources (ultimately originating from the diet) provide the energy required for mechanical energy are not discussed in detail here, as they tend to be common to many mammals and have been described in great detail elsewhere (9, 38, 47, 79, 87).

Carbohydrate

In general it is believed that as the intensity of exercise increases, the relative contribution of fat to total energy production decreases. So during very high-intensity exercise, the catabolism of carbohydrate accounts for the majority of energy used. The majority of this carbohydrate will come from muscle glycogen (47, 69). During short-term intense exercise, muscle glycogen stores may be depleted by 20 – 35% (29, 50, 60). Even with the low rate of glycogen utilization during submaximal exercise, if this exercise is sufficiently long-term,

muscle glycogen stores may be depleted by more than 50–75% (85). During the cross-country phase of a three-day event, the muscle glycogen content may be reduced by up to 75% of a horse's resting level (35). This confirms the importance of muscle glycogen stores in both short-term intense and long-term submaximal exercise. Blood glucose levels per se may also be an important source of energy, especially in submaximal exercise (47).

Fat

Plasma free fatty acids have been suggested as quantitatively the most important energy source (especially during submaximal exercise) in the horse, as it is in other mammals (47). Endogenous, intramuscular triglycerides are also likely to play an important role, especially in the trained fit animal. The contribution of circulating triglycerides to energy production in the exercising horse is not fully understood, and although several studies have shown that horses can digest and utilize different types of dietary fat (36, 76), there is little information available as to lipid metabolism in the horse. It is known that, in the adult horse, the transport of the various lipoprotein fractions is dissimilar to that in other mammals, because an adult horse does not appear to have any chylomicron lipoproteins (91). The activity of lipoprotein lipase (assessed following administration of heparin) appears to be lower than that in man (92), and triglyceride infused into horses has a far longer half-life than when infused into other animal species (58). The horse also appears to have far lower carnitine palmitoyl transferase activities than man does (79a).

A consensus as to the benefits of feeding supplementary fat to exercising horses is not currently available. Feeding fat-supplemented diets to horses has resulted in variable effects on a range of physiological parameters as well as on athletic performance. These variations may, in part, arise from the fact that the various studies carried out to date have used horses that differed in breed, age, body condition, and training regimens, as well as in diet. In addition, the duration of the studies and the exercise protocols used, etc, have varied, making comparisons difficult. It is important to note that the diets often referred to as high fat in the equine literature are based on the lower-fat diet typical for a horse rather than on diets typical of dogs or humans. The increased interest in fat supplementation developed following work (83) that suggested that horses fed a diet containing 12% fat (9% added corn oil) and ridden 67 km over mountainous terrain for 8–10 hours performed better and had higher blood glucose levels at the end of the ride than did horses fed the control diet (3% fat). In another study (26), diets containing 4%, 8%, 12%, or 16% fat (soybean) were fed to horses trotting 67 km in 6 hours. The horses fed the highest percentage of fat had the highest blood glucose concentrations after exercise, which suggested that fat might have a glucose-sparing effect and that horses fed fat might show increased mobilization of free fatty acids. Since then, numerous studies have

investigated the potential of feeding fat-supplemented diets to performance horses. According to these studies, fat-supplemented diets (a) lower muscle glycogen concentration (e.g. 24, 69); (b) have no effect on muscle glycogen levels (e.g. 11, 13); (c) have a sparing or enhancing glycogen storage effect (e.g. 27, 41, 42, 57, 63, 64, 80); (d) have no effect on postexercise muscle glycogen (37, 42, 64, 81); (e) have an effect on glycogen utilization (37, 42, 63, 80); (f) do not have an effect on glycogen utilization (27); (g) lower the digestible energy requirements of certain horses in hot weather (77); (h) improve cutting and racing performance (27, 93); (i) increase high-intensity exercise capacity and maximum accumulated oxygen debt during intense treadmill exercise with no effect on aerobic exercise capacity (11); (j) have an effect on hormonal and glycemic responses to exercise but no significant effect on heart rate or lactate responses (58a, 68); and (k) have an effect on lactate responses (6, 16, 24, 72). (For additional references, see also 76, 18, 19). The variations in findings outlined above explain the difficulties in stating a unified view as to the role of fat supplementation in performance horses. However, in my opinion, it is likely that, in certain circumstances, fat supplementation will have a beneficial effect on performance.

Volatile Fatty Acids

The fermentation processes that occur predominantly in the hind gut produce a number of short-chain or volatile fatty acids (VFAs), in particular acetic, propionic, and butyric acids, which are transported and metabolized differently than dietary fat. These acids represent a further potential energy source to the horse. The percentage of VFAs produced depends to some extent on the type of feed, with the percentage of acetate decreasing and propionate increasing as grain replaces hay in the diet (33). Acetate tends to be used for energy or for fatty acid synthesis. Propionate can be used for energy or, because of its glucogenic properties, the maintenance of blood glucose levels. Up to 61% of available blood glucose may be derived from propionate in resting ponies on a mainly roughage-based diet (82). Acetate may contribute ~21% (on a grain and forage diet) to 32% (on a 100% roughage diet) of hind limb oxidation at rest (74), and VFA production may meet more than 30% of a horse's energy requirement at rest (22, 47). Obviously the efficiency of energy production from the diet via the VFA pathway will be less than if the energy was directly obtained from carbohydrate in the diet via glucose (4, 46).

ASSESSING THE ENERGY CONTENT OF FEEDSTUFFS

Domestication, and an increasing demand for horses to perform under circumstances that require energy intakes greater than that provided by their more natural diet of fresh forage, have resulted in the inclusion, in particular, of

cereal grains and their by-products, as well as of supplemental fat in many horse diets. Such additions may be made in the form of the raw material or processed raw material or a manufactured compound feed.

As with other animals, the energy value of any feedstuff, as well as of the total diet, for the horse will depend on the relative amounts of hydrolyzable and fermentable substrates it contains (51). Determination of a feed's energy value using *in vivo* methods, especially in the horse, tends to be time consuming, labor intensive, costly, and often highly impractical. Therefore, as with many other animals, effort has concentrated on finding methods for assessing the energy values of feeds by using prediction equations. At the moment these tend to be based on the chemical composition of the feed, which may not truly reflect its functional aspects. In the future it is hoped that these may take into account more fully the content of hydrolyzable as well as fermentable components, but currently accurate ways of determining the relative content of these in horse feeds have not been established. The use of *in vitro* digestibility techniques may become increasingly prevalent in the future.

Currently there are three main ways used to describe the energy potential of a horse feed: total digestible nutrients (TDN), digestible energy (DE) or metabolizable energy (ME), and net energy (NE). Each of these has been determined in a number of ways over the years (e.g. 56, 65), with TDN becoming less popular recently. Further confusion results from the fact that two units of energy are in common use in the horse industry: the joule (J), predominant in Europe; and the calorie (cal), used in the United States (4.184 J equals 1 cal).

Total Digestible Nutrients

Conversion factors have been used to convert TDN values to today's more commonly used DE values. These may not be appropriate. The most frequently used factor is based on work in ruminants, which resulted in an average conversion factor of 2000 kcal of DE being equivalent to 1 lb of TDN or 4.41 Mcal of DE/kg of TDN (61, 62). However, subsequent work in ruminants suggested that this conversion factor was strongly influenced by the level of digestible protein. In the horse, limited work in this area has been carried out, but in one study of five pony stallions, the DE-to-TDN relationship was found to be 4.648 Mcal/kg for a hay diet and 4.624 Mcal/kg for a hay and concentrate diet with similar crude protein levels (2), suggesting that the 4.41 conversion factor could result in substantial errors.

Digestible Energy

Using standard digestibility balance studies, the DE content of a ration can be estimated *in vivo*. This does not provide a truly accurate measurement, because fecal energy includes energy originating from endogenous sources as well as from undigested feed and bacteria. It is, nevertheless, a useful practical guide.

Table 2 Digestible energy values (in megajoules per kilogram) quoted for typical horse feed stuffs^a

Feedstuff	Maturity	A	B	C	D
Alfalfa hay ^b	Early	10.4	9.2	10.0	—
	Mid bloom	9.54	8.4	6.42	7.6
	Full bloom	9.1	7.5	—	—
Timothy hay ^b	Early head	8.6	8.4	10.6	—
	Head	8.3	8.0	10.4	—
	Over ripe	7.5	6.7	—	—
Barley		15.4	13.8	—	12.8
Corn		10.1	14.7	—	14.2
Oats	Light		11.7	—	
	Heavy	14.1	13.4	—	
	General	13.4		—	10.9–12.1
Wheat		16.2	14.6	—	14.1
Wheat bran		13.8	11.3	—	10.8

^aA, 100% dry matter (62); B, unknown dry matter (31); C, in vivo studies, 100% dry matter (7); D, 88–89% dry matter (17).

^bOne of the major factors affecting energy content of preserved forage is the stage of maturity at which the plant is cut. Older plants have increased fiber content, lower percentage of leaves, and reduced digestibility (7).

However, for the reasons stated above, prediction equations are increasingly being used to provide a guide to the likely energy content of a particular feedstuff or composite feed. A number of equations to estimate DE content of feedstuffs have been quoted in the literature (e.g. 8, 56, 65), and continual modifications are being proposed to improve the predictive nature of these equations and to take into account the different classes of feedstuffs. Examples of typical DE values for horse food given in the literature are shown in Table 2.

Net Energy System

The DE system tends to overestimate the energy potential of a high-fiber feed compared with a highly hydrolyzable carbohydrate feed, as fiber predominantly produces VFAs that are not used as efficiently as glucose (46). The French NE system was therefore developed to allow for the differences in utilization of the ME available from different feeds, depending on the proportion of the end products of digestion produced and the biochemical pathways used by these end products to produce mechanical energy. It has primarily been developed by the Institut National de la Recherche Agronomique (INRA). The French horse NE system is based on (a) the DE content of feeds as measured in horses; (b) the ratio between ME and DE as measured in horses; and (c) the efficiency of ME

utilization for maintenance (K_m) calculated from the assumed proportions of absorbed energy supplied by the various nutrients and the various K_m values of the main nutrients (54, 89).

It uses the horse feed unit (HFU) or, in French, l'unité fouragère cheval (UFC). The UFC corresponds to the NE value (2250 kcal) of 1 kg of standard barley (87% dry matter) in a horse at maintenance. The UFC value of a particular feed is calculated by dividing its NE content in kilocalories by that of barley, i.e. 2250. The NE UFC per kilogram in dry matter for corn, barley, oats, maize silage, hay, and straw is 1.35, 1.16, 1.01, 0.88, 0.40–0.67, and 0.28, respectively. Comparing this system (54) with the DE/ME system, the energy value of straw, for example, has been reported to be 41% using DE values, 37% using ME values, and 29% that of barley using NE values (UFC). The discrepancies of the actual energy values to the horse between different feeds as calculated by these various methods increase as the cell wall contents of the feed increases.

The UFC of forages or concentrates (raw materials), it is suggested, can be predicted directly from their chemical composition, although these predictive values are more accurate if the DE is known (54), e.g. for forages,

$$\text{UFC} = 0.0557 + 0.0006 \text{ CC} + 0.2489 \text{ DE} (r^2 = 0.996),$$

$$\text{UFC} = 0.825 - 0.0011 \text{ CF} + 0.0006 \text{ CP} (r^2 = 0.69),$$

and for concentrates-raw materials,

$$\begin{aligned} \text{UFC} = & -0.134 + 0.0003 \text{ CF} - 0.0004 \text{ CP} \\ & + 0.0003 \text{ CC} + 0.3160 \text{ DE} (r^2 = 0.99), \end{aligned}$$

where CC is cytoplasmic carbohydrate, CF is crude fiber, and CP is crude protein. It should be noted, however, that an additional correction has been recommended for high-fat diets (54). For compound feeds it has been suggested that the UFC value can also be predicted (54) from chemical composition by using a number of equations. The difference between the values obtained using a composite equation and that obtained by addition of the UFC values of individual feed components is said to be between 0.2 and 1.3 UFC/100 kg of organic matter.

The NE system has a number of potential advantages, but at the moment an English version of all the tables and factors used is not readily available; most countries use the DE system, and DE values for horse feedstuffs are more routinely available. The NE system relies on the fact that maintenance requirements for energy account for the largest part of the total energy requirement, which may not be true for certain performance animals. It also assumes that the UFC value for a particular feed is the same for maintenance as for work, which

because of the increased heat production associated with work may not be a valid assumption (see below). The use of a NE system also implies among other things that the NE requirements of the horse have been accurately described (32) (see below). Certain of the equations used to predict ME and therefore the NE values of feeds, etc, appear to have very low correlation values, whereas others—as illustrated above—are very high (54) and at present full justification of their use does not appear to be available. However, it is possible, as more information becomes available, that this system will become more generally applicable and widely used.

ENERGY AVAILABLE

A number of methods or models have been used to estimate the energy partitioning of a diet and, therefore, the energy available. Most of these rely on a mixture of calculated, determined, and assumed efficiency factors and have not been validated fully under field conditions. However, they provide at the moment the most reliable way of determining the true energy or NE available.

The French NE system (an empirical system) for calculation is illustrated in Figure 1 and can be compared with a partitioning model (a more physiological system), as illustrated in Figure 2, for determining NE, ME, and DE values (46). The NE values can be directly compared only for maintenance, not for work, as explained below. Similar values for the NE available for maintenance, from a 100% typical timothy hay diet, can be obtained by using one of the composite equations suggested by the INRA for forages (54), or the system outline in Figure 1 or the partitioning system as described by Kronfeld (46). Further comparisons need to be made both theoretically and in the field before conclusions can be made as to which system provides an overall advantage.

Unfortunately, accurate digestibility data for the various different energy sources within different feeds is not currently available, and the effect of different feed types and processing techniques on energy availability are not fully understood. Therefore, the amount of energy each nutrient type within a particular ration will really provide to an individual animal cannot be accurately determined. The differing analytical methods and terminology used also add to the confusion. Both systems, as illustrated in Figure 1 and Figure 2, therefore can only provide a guide to the energy content of a diet.

In even more general terms it has been suggested that the DE values of common horse feeds of average quality are ~60–70% of the gross energy, depending on fiber content; the higher the fiber content, the lower the percentage. ME is taken as ~85–94% of DE (48). Where data for horses are not available, conversion factors have been applied to ruminant data. The degree of accuracy

Gross Energy (GE)

Forages

- Predicted from the CP content
- Conversion factor will vary according to type of hay

Concentrates

$$GE = 5.72 \text{ CP} + 9.5 \text{ EE} + 4.79 \text{ CF} + 4.17 \text{ NFE} + \Delta'$$

The ' Δ ' values depend on the kind of feed cereals



Digestible Energy (DE)

- Predicted from GE and the digestibility of energy (dE) efficiency factor

$$dE = 0.0340 + \Delta' + 0.9477 \times \text{digestible organic matter}$$

' Δ ' = +1.1 for concentrates: -1.1 for forages.

dOM can be predicted from crude fibre content for forages to some degree

dOM for concentrates need to be drawn from tables

$$DE = \frac{GE \times dE}{100}$$



Metabolisable energy (ME)

For all feeds :

$$100 \text{ (ME/DE)} = 84.07 + 0.165 \text{ CF} - 0.276 \text{ CP} + 0.184 \text{ CC} \text{ (} r^2 = 0.45 \text{)}$$

For protein rich feeds $\geq 30\%$ CP on DM basis :

$$100 \text{ (ME/DE)} = 94.36 + 0.110 \text{ CF} - 0.275 \text{ CP} \text{ (} r^2 = 0.17 \text{)}$$

For beet pulp : $100 \text{ (ME/DE)} = 89$ (ref. 90)

ME/DE \approx 0.78 - 0.8 for oil meals : 0.91 for wheat straw : 0.84 - 0.88 for hays
0.90 - 0.95 for cereals

$$\therefore \text{ for feedstuff} \quad ME = (\text{ME/DE ratio for that feedstuff}) \times DE \text{ value}$$



Net Energy (NE)

(Continued)

$$\text{NE} = \text{ME} \times \text{efficiency of ME utilisation [k}_m\text{]} = X$$

$$\text{NE (UFC)} = \frac{X}{2250}$$

k_m varies with feed composition and is predicted from the chemical composition, e.g.

Forages

$$100k_m = 71.64 - 0.0289\text{CF} + 0.0148 \text{ CP } (r^2 = 0.878)$$

Cereal - by-products

$$100k_m = 94.41 - 0.0237 \text{ OM} - 0.0022 \text{ CP} + 0.0121 \text{ CC } (r^2 = 0.887)$$

Example for Barley

$$\text{GE} = 3854 \text{ Kcal/kg}$$

$$\text{dOM} = 0.83 \text{ (from Tables) } \therefore \text{dE} = 0.8 \text{ DE} = 3076 \text{ Kcal/kg}$$

$$\text{ME/DE} = 0.93 \therefore \text{ME} = 2864 \text{ Kcal/kg}$$

$$k_m = 0.785 \therefore \text{NE} = 2250 \text{ Kcal/kg}$$

$$1 \text{ UFC} = 2250 \text{ Kcal NE} = \text{net energy content of one Kg of standard barley}$$

CP = Crude protein, EE = Ether extract, CF = Crude fibre, NFE = Nitrogen free extract, CC = Cytoplasmic Carbohydrates, dOM = Digestible Organic Matter

OM = Organic Matter

Figure 1 System for determining the NE of a diet using the French NE system devised by INRA [based on Martin-Rosset et al (54)]. Examples only of the various equations available are given.

of such general conversion figures is currently unknown, and they should not, therefore, be taken as anything more than a very approximate guide.

ENERGY REQUIREMENTS FOR MAINTENANCE

Definitions of the energy requirements for maintenance include “the amount of DE required for zero body weight change plus normal activity of non working horses” (62) and the daily food intake that maintains constant body weight and body composition of a healthy adult horse with zero energy retention at a defined level of activity in comfortable surroundings [adapted from Kronfeld (46)].

Studies looking into maintenance requirements have been ongoing since the end of the last century (23,96) and have principally involved feeding trials and indirect calorimetry trials. Since 1986, many in the United States and United Kingdom who work with horses have quit basing energy requirements on metabolic body size, following studies that suggested maintenance energy requirements varied linearly with bodyweight and not with $W^{0.75}$. Nevertheless,

Gross Energy/Intake Energy (IE)

- Calculated from the relative proportion of fat, carbohydrate and protein using conversion factors (enthalpies or heats of combustion) of 38.9, 17.5, and 23.7 KJ/g, respectively (4)

**Digestible Energy (DE)**

- Using estimated apparent digestibility factors ($K_d = DE/IE$) - various estimates from other experiments
- Factors will vary according to nature of diet
 - Factors of 0.74 and 0.65 x IE for protein and fat respectively for a diet without supplemental fat
 - Factors of 0.61 and 0.82 x IE for protein and fat respectively for diet with supplemental fat
 - Factors of 0.8 x IE for non structural carbohydrate (NSC)
 - Factors of 1.0 x IE for hydrolysable carbohydrate (CHO-H) ie. where $CHO-H = NSC \times 0.8$
 - Factors of 0.25 - 0.5 x IE for fermentable carbohydrate (CHO-F) ie. where $CHO-F = NDF + 0.2 \times NSC$

**Metabolisable Energy (ME)**

- Takes into account energy loss in gas produced during fermentation as well as via urea in the urine
 - 0.78 x DE for protein (loss of energy as urea)
 - 0.95 x DE for fermentable carbohydrate (loss of energy as methane)

**Net Energy Available for Maintenance (NE_m)**

- Uses estimated efficiency factors (K_m)
- K_m : 0.7; 0.89; 0.85 and 0.63 x ME for amino acids, long chain fatty acids, glucose, short chain fatty acids respectively



NB. Amount of energy available for the work of maintenance or exercise will depend on the exercise undertaken and the heat produced ie. K_w may not be the same as K_m .

**Net Energy Available for Work (NE_w)**

- Uses estimated efficiency factors (K_w)
- K_w : 0.228 for glucose oxidation : 0.245 for long chain fatty acid oxidation

Figure 2 System for determining the NE available from a certain diet (in megajoules) for maintenance, based on a physiological partitioning system [based on Kronfeld (46)].

the best fit between energy intake and energy balance in one of the studies was $W^{0.88}$. These studies were only carried out in a small number of animals (10, 70). Potential problems with using $W^{1.0}$ include overestimations for small ponies and large horses. Allowances for the larger horse (>600 kg), however, have been recommended (62, 75), especially if they have a lower voluntary activity level than the lighter horse has. But little absolute data are available on the energy needs of these heavier horses or on the voluntary activity level relationship between breed, size, and individual. More work is needed in this area. Many mainland European researchers and nutritionists continue to use metabolic body weight (i.e. $W^{0.75}$ kg) for the horse (54, 56), which again adds to the confusion in the literature.

Several equations for estimating maintenance energy requirements have been derived over the years. The values obtained using these equations are often fairly consistent, although the equations themselves may differ considerably (Table 3).

It is appreciated that a number of factors—including the individual animal, body composition, gender, environmental temperature, whether the animal is in work or not, age, breed, temperament, and season—may affect the actual maintenance energy requirements (18, 47, 53, 54, 62). Individual variability for ME requirements for maintenance and zero weight gain was found, for example,

Table 3 Equations used to estimate maintenance DE and NE requirements (adapted where appropriate)^a

1. For horses 600 kg or less (62, 70):
DE = $1.4 + 0.03 \times W$ (Mcal/day)
2. For horses over 600 kg (62):
DE = $1.82 + (0.0383 \times W) - (0.000015 \times W^2)$ (Mcal/day)
3. For New Forest and Welsh Ponies (12):
DE = $111 W^{0.75}$ (kcal/day) and DE = $465 W^{0.75}$ (kJ/day)
4. General:
DE = $155 W^{0.75}$ (kcal/day) (61)
DE = $140 W^{0.75}$ (kcal/day) (54)
DE = $92 W^{0.75}$ (stall confined; kcal/day) (46)
ME = $120 W^{0.75}$ (kcal/day) (54)
5. NE ^b = $84 W^{0.75}$ (kcal/day) (54) or
NE ^b = $0.038 W^{0.75}$ (UFC/day)

^aDE, Digestible energy; NE, net energy; W, body weight (in kilograms); ME, metabolizable energy; UFC, l'unité fouragère cheval (French horse feed unit).

^b+10–20% for stallions and +5–15% for working horses, to take into account the rise in overall energy metabolism (54).

to be 8% in one study (53). Each of the equations in Table 3, should therefore be considered a guide, and recommendations should be tailored to the individual animal and its circumstances.

ENERGY REQUIREMENTS FOR EXERCISE

Many factors also influence the additional requirements for exercise, including the weight of the rider, the weight of the tack, the ability of the rider, the degree of the animal's fatigue, the condition and training of the animal, diet composition, and environmental conditions, in addition to the exercise itself, which will vary according to its intensity, duration, and contour (terrain).

Energy Expenditure

Exercise requires the expenditure of metabolically derived energy in the form of ATP. At certain speeds, under steady state conditions, the ATP used can be regenerated by oxidative phosphorylation or aerobic metabolism. For short periods of non-steady state work at high exercise intensities, ATP can be regenerated by net anaerobic metabolism with accumulation of lactate in muscle and blood. During sprinting, the thoroughbred horse produces and accumulates a large amount of lactic acid in skeletal muscles and the circulating plasma (30), but it has a greater capacity for protein buffering than man has, which might be linked to the high carnosine content of horse skeletal muscle (28, 82). The efficiency of the conversion of chemical energy (derived ultimately from the diet) to mechanical work (work efficiency or K_w) is only about 20–25%. Most of the energy released appears as heat. It has been stated (43) that the amount of heat a horse produces during exercise is the sum of its standard metabolism, the additional metabolism required for the generation of ATP for the generation of muscular force, its efficiency in converting metabolic energy into useful mechanical work, and a small amount of heat generated by friction within and against its body during exercise. Ways of reducing the heat load of competing horses, especially under adverse environmental conditions, has recently been the focus of a number of research groups.

Although the total energetic cost of running a given distance for both bipedal and quadrupedal homeothermic animals has been considered to be independent of speed, the energetic cost for the horse has been suggested to increase when it gallops (3, 15, 88). The rate at which metabolic energy is used and metabolic heat is produced during exercise has been stated to depend on the horse's size, its running speed, the weight it carries, and the gradient up or down the terrain on which it is running (88).

The rate of energy expenditure at rest and during submaximal steady state exercise can be estimated from the rate of oxygen consumption, as ~ 20.1 J

or 4.8 kcal of energy is liberated for every ml (STPD) of O_2 consumed in aerobic metabolism. The rate of oxygen consumption of horses exercising at a number of speeds, at various degrees of incline, and carrying various loads has been determined (see 43). However, at speeds that approach aerobic capacity, estimations become more complex because the accumulation of lactate represents net metabolic energy usage and heat production that would not be reflected in estimates based purely on O_2 consumption figures.

The three-day event and in particular the cross-country day is one of the most demanding equestrian sports and provides an indication of the energetic load of horses working at different speeds. Using a number of assumptions and theoretical calculations (43), the energy requirements of the various stages of the cross-country day have been estimated (Table 1). These calculations assume a direct relationship between weight carried, force generated by working muscles, and metabolic cost. They also assume that the mechanics of locomotion on the treadmill and ground are similar. Overall, it was estimated that the total energy expenditure (ME) was 44,850 kJ if no allowance for jumps was made and 46,151 kJ if such an allowance was made. In reality (43), the expenditure in the field is likely to be higher than that predicted, because additional energy will be required to overcome wind resistance, raise and lower the center of mass with the terrain, allow for periods of deceleration and acceleration, allow for horizontal translation over a jump, and so on. Such allowances would need to be made if more accurate estimates are to be established, but these estimations provide very good baseline data.

Energy expenditure for an individual animal can, therefore, be calculated based on heart rate/ VO_2 max, which is averaged/measured/calculated and determined over a period of exercise (as outlined above) or on a minute-by-minute basis and then added up (Table 4). Using Table 4, and the speeds and durations

Table 4 Energy expenditure in addition to maintenance requirements (54) based on 560-kg horses carrying a load of 100 kg (rider, tack, etc)

Determinant	Energy expenditure ^a	Maintenance requirements (No. of times)
Walking (110 m/min)	50 (7.58)	~5
Trotting slowly (200 m/min)	110 (16.67)	10
Trotting normally (300 m/min)	160 (24.24)	15
Trotting fast (500 m/min)	350 (53.03)	35
Cantering (350 m/min)	210 (31.82)	20
Galloping (600 m/min)	420 (63.64)	40
Maximum speed	600 (90.91)	60

^aParentheses indicate energy expenditures in kilocalories per minute per 100 kg total weight.

given in Table 1, the estimated energy expenditure would have been around 58 MJ ($5.75 \times 18 \times 23 + 5.75 \times 70 \times 4.5 + 5.75 \times 18 \times 50 + 5.75 \times 60 \times 13$ kcal, for phases A to D, respectively) rather than 45 MJ. Both of these methods provide an indication of the energy expenditure (including heat production), which has then to be related back to energy requirements.

Net Energy Requirements

Using the same cross-country phase example as above, it has been suggested that if the 44.85 MJ of ME was used with 20% efficiency (i.e. $K_w = 0.2$), it would mean that 8.97 MJ of energy had been available for work (i.e. NE), the remainder being lost in heat production (43). If higher K_w values are used, then obviously a greater percentage would have been used for work (46).

Estimated NE requirements needed, in addition to the daily maintenance NE requirements, for a number of types of work, based on work by INRA, are shown in Table 5. It does not seem possible to directly compare these NE requirements with those derived based on the partitioning system described above (46), because the French NE system appears to assume the same efficiency for work as for maintenance, i.e. $K_w \sim K_m$, whereas in the partitioning system (Figure 3), K_w (~ 0.2 – 0.25) is taken to be much lower than K_m (~ 0.7 – 0.8). Because the requirements are estimated by using the same assumptions, those made under the French NE system appear far higher than those estimated by using the partitioning system: For example, based on the partitioning system, a 575-kg (total weight plus rider) horse in the three-day event requires about 25 MJ of NE for all activity apart from maintenance (46) (Figure 3), whereas in the

Table 5 Estimated net energy requirements needed to be added to the daily maintenance requirement based on a 560-kg horse carrying a 100-kg load (39)

Type of work ^a	Net energy requirements (Mcal/hr)
Very light ($\cong 50\%$ walk/ 50% trot)	0.45–1.125
Light lesson ($\cong 50\%$ walk/ 40% trot/ 10% canter)	2.25–3.375
Moderate lesson ($\cong 20\%$ walk/ 10% canter/ 10% jumping/ 60% trot)	3.375–4.5
Hard lesson	5.625–6.75
Light hack, >3 hr/day ($\cong 90\%$ walk/ 10% trot)	1.125
Light short ride, 1–2 hr/day ($\cong 50\%$ walk/ 45% trot/ 5% canter)	3.375
Moderate outdoor training ($\cong 20\%$ walk/ 10% jumping/ 15% canter/ 45% trot)	4.5–5.625
Intense training/competition ($\cong 10\%$ walk/ 15% canter/ 15% jumping/ 40% trot)	5.625–7.895

^aGuide to type of work being carried out.

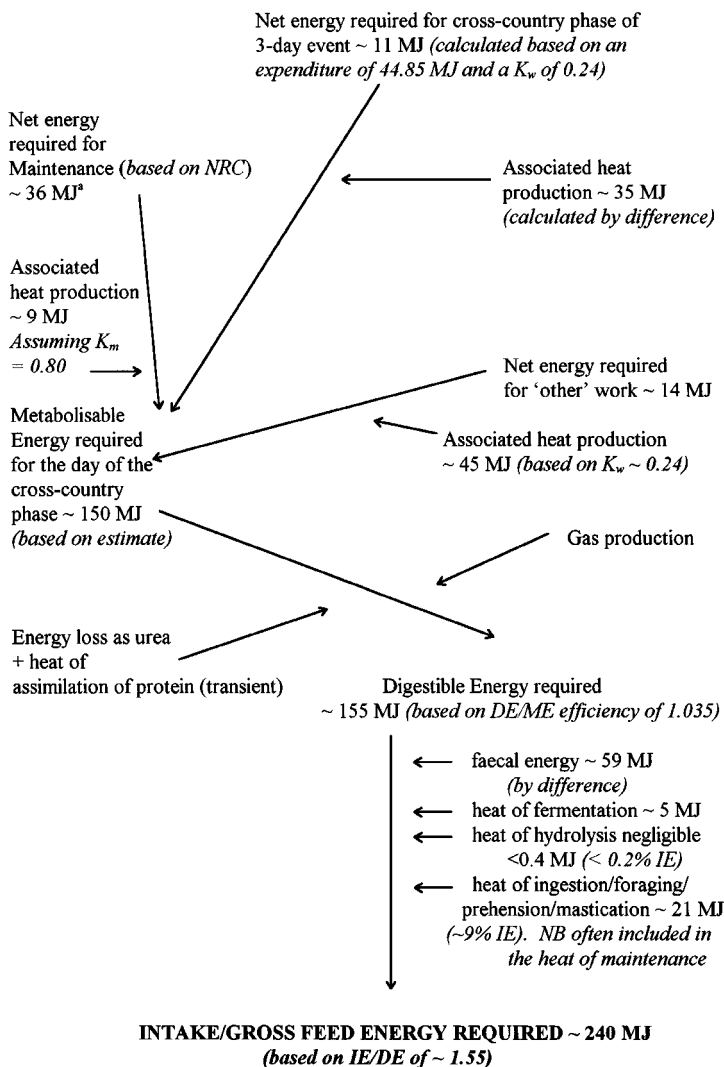


Figure 3 Schematic picture to illustrate how the amount of gross energy required from a particular diet can be determined if the net energy requirements for work and maintenance are known or can be calculated. Based (46) on a 500-kg horse competing in the cross-country phase of a three-day event being fed a diet of 45% Timothy hay, 45% oats, and 10% vegetable oil.^a Probably underestimated, as the maintenance requirements of exercising horses may be higher than those of sedentary animals. DE, Digestible energy; ME, metabolizable energy; IE, intake energy.

Table 6 Additional daily energy requirements needed above that for maintenance requirements for exercise based on 560-kg horses carrying loads of 100 kg (rider, tack, etc) (48)

Pace	Speed (m/min)	Mcal/hr	kcal/min ^a
Slow walk	60	1.12	18.7–26.2
Fast walk	100	1.65	27.7–38.8
Slow trot	200	3.96	66.0–92.4
Medium trot	250	6.6	110–154
Fast trot	300	8.58	143–200.2
Cantering	350–400	13.2	220–308
Fast work	500–1000	25.74	429–600.6

^aSuggested by Lewis (48) that may be up to 40% greater than requirements per hour for shorter-duration work and for horses in poor physical condition.

French NE system (Table 6), a similar-sized horse undertaking 90 min of work at a moderately intense level has NE requirements of around 38 MJ (assuming that this includes the allowance for the warmup period, recovery period, etc). Daily NE requirements—using the French NE system—of around 6.9 UFCs or 20.25 MCal or 84.7 MJ/day for a 500-kg horse undertaking 2–4 hours of outside exercise have been reported (40). Such NE intakes would be difficult to achieve unless the NE values of feeds for work are considered to be equivalent to those for maintenance, which is the case for the French NE system but not for the partitioning system described by Kronfeld (46). Therefore, currently, each system must be used in isolation, which may cause confusion.

Digestible Energy Requirements

DE requirements can be worked back from the energy expenditures (46). Alternatively, guidelines have been given for directly determining the DE requirements for different types of physical activity on a minute-by-minute basis, as shown in Table 6. Even more general empirical equations for estimating DE requirements have been suggested in the literature. The following equation, for example (1), was produced for horses whose work load (kilograms times kilometers) was not greater than 3560 (i.e. not applicable to endurance horses) and whose body weight was maintained. This therefore assumes that this body weight was desirable:

$$\text{DE (MCal/day)} = 5.97 + 0.021W + 5.03X - 0.48X^2,$$

where W is body weight in kilograms, X is Z times the distance traveled in kilometers times 10^{-3} , and Z is the weight of horse, rider, and tack in kilograms. Such an equation makes no allowance for speed, which may be important in the horse, as mentioned above. A different equation was therefore proposed (71),

Table 7 Total digestible energy requirements for 200- to 600-kg ponies/horses based on maintenance requirements from the National Research Council (62)^a

Exercise	Times maintenance DE
Light (e.g. pleasure riding, bridle path riding, etc)	1.25
Moderate (e.g. ranch work, jumping, etc)	1.5
Intense (e.g. racing, polo, etc)	2.0

^aMaintenance daily energy requirements are taken to be $1.4 + 0.03$ body weight Mcal/day. DE, Digestible energy.

which does take into account speed and can be used for horses traveling up to 350 m/min.

DE requirement above maintenance in kilocalories per kilogram (of horse, rider, and tack) per hour is

$$\{[e^{(3.02+0.0065Y)} - 13.92] \times 0.06\} / 0.57,$$

where Y is the speed (in meters per minute). This is useful for horses exercising on level ground and an even surface, but it is not useful when velocity is not the sole determinant of intensity. It also relies on knowing the speed at each phase of the exercise. In most cases, precise details of the number of minutes spent at the various gaits or the speed/distance traveled cannot be determined, and therefore, even more general activity guidelines tend to be given (Table 7). These estimates have been supported in general terms by surveys in the field, at least for intense work. The calculated actual energy intakes apparently needed to maintain body weight in the field tend to be similar or slightly higher than those estimated by using such general guidelines (20, 21, 86). These very general guidelines do not take into account the actual time spent doing light/moderate/intense work or the other influencing factors listed above.

On a purely practical basis, it is appreciated that horses fed insufficient energy sources to meet their requirements will lose weight and a number of workers, including Hintz & Cymbaluk (34), have suggested there is relatively little advantage in spending more time and resources on further refining the energy requirement equations. Instead, it has been suggested that it would be more beneficial to carry out studies on factors that influence energy metabolism and the effects of dietary manipulation on energy utilization.

DIETARY INTAKE/COMPOSITION NEED TO MEET ENERGY REQUIREMENTS

Horses evolved to utilize high-fiber diets supplied almost continuously. The upper part of the gastrointestinal tract has a relatively small capacity, and the

horse has digestive and metabolic limitations to high-grain, high-hydrolyzable-carbohydrate diets. This has resulted in problems following domestication and the requirement for repetitive, intensive, or prolonged exercise. Large grain meals may overwhelm the digestive capacity of the stomach and small intestine, leading to the rapid fermentation of the grain carbohydrate in the hind gut. This potentially can result in one of a number of disorders, including colic, diarrhea, and laminitis (5, 17, 18, 48, 91).

When looking at the energy requirements of the horse and determining the best way of achieving these requirements via diet optimization, a balance is therefore required that provides (among others) (48): (a) sufficient soluble carbohydrate to maintain glycogen levels, and to help provide a sufficiently energy-dense ration without overloading the digestive capacity of the horse; (b) adequate fat to maintain the required energy density of the ration without adversely affecting palatability and gastrointestinal tract function; (c) heat production, which is minimized or maximized according to requirements; and (d) sufficient fiber to maintain normal gut and digestive function and to limit behavioral disturbances while maintaining the energy density of the diet in order to allow overall energy intake to meet the demands.

Energy available from the diet for work and maintenance can be estimated either from requirements backwards (as outlined below) or from intake forwards (as illustrated in Figures 1 and 2). A partition model based on the NE requirements of a 500-kg horse undergoing the cross-country phase of the three-day event, as described above (43), is illustrated in Figure 3. The values for ME, DE, and intake energy demonstrated (46) were calculated based on a NE requirement of ~ 11 MJ for the competition work and efficiency factors based on a diet comprised of 45% Timothy hay, 45% oat grain, and 10% vegetable oil (taking CP, 8.9% fat, 13.1% hydrolyzable carbohydrate, 22.3% and fermentable carbohydrate, 42%). Several assumptions were specified for the model, and efficiency factors were selected that applied to this diet. However, it is a good illustration of energy partitioning in a competition horse fed a likely competition diet. In practice, many such three-day-event horses would be fed proportionally more hydrolyzable carbohydrate and less fermentable carbohydrate. When calculations similar to those used in Figure 3 were applied to a 100% Timothy hay (CP, 8.6% fat, 2.3% hydrolyzable carbohydrate, 12.8% fermentable carbohydrate, 59.8%) diet, however, they showed that in order to provide the same NE (required for maintenance, other work, as well as the actual competition), an intake energy of 348 MJ was required from the hay. If all this energy was to be provided by the intake for that day, this would correspond to an intake of ~ 22 kg of hay or $\sim 4.5\%$ body weight. Horses would not be able to ingest as much hay as this daily, which helps to explain why hay-only diets are unsuitable for intensively exercising animals.

This example also provides support for using the French NE system, which enables different feed stuffs to be compared directly according to their ability to provide mechanical energy. As stated above, this approach relies on knowing the NE requirements for the various exercise patterns, and these are not currently readily available. In addition, it relies on both the requirements and the availabilities from the feed having been determined using the same criteria, i.e. both determined via the French NE system. Present mixing systems for determining the NE available from food or required from food for exercise is likely to cause more confusion.

CONCLUSION

Although much more work is needed before we fully understand the energy requirements of the exercising horse and how we can manipulate the diet to provide an optimal level of energy, there have been a number of useful developments in the last few years. The relative value of replacing hay with cereal grains and fats to meet the energy requirements for strenuous exercise appears to be explained, in principle, better by the French NE system or the energy partition model than by the more commonly used DE system. Work is needed to enable the NE system to be more widely applicable. In a number of other areas, a unified approach would help to minimize the confusion currently present and to maximize progress in this area.

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