Standardization of Analytical Methodology for Feeds

Proceedings of a workshop held in Ottawa, Canada, 12–14 March 1979

Editors: W.J. Pigden, C.C. Balch, and Michael Graham

IDRC-134e

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IDRC-134e

Standardization of analytical methodology for feeds : proceedings of a workshop held in Ottawa, Canada, 12-14 March 1979. Ottawa, Ont. IDRC, 1980. 128 p. : ill.

/IDRC publication/. Compilation on /animal nutrition/ /nutrition research/ applied to the /evaluation/ of energy values of /feed/s and the /standardization/ of analytical /methodology/ — discusses /biochemistry/ aspects, practical rationing systems, /nitrogen/ evaluation, /sugar cane/ feeds /classification/, /trade/ and /legal aspect/s of /technique/s. /List of participants/.

UDC: 636.085.2.001

ISBN: 0-88936-217-3

Microfiche edition available

38093

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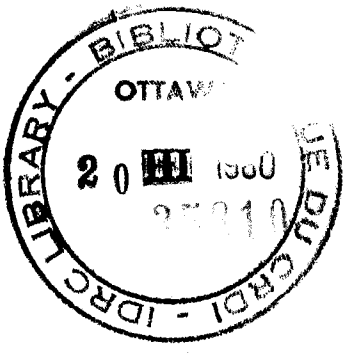

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Evaluation of the Energy Value of Feeds: Overall Appreciation

A.J.H. van Es[1]

The conversion of gross energy (GE) into metabolizable energy (ME) is discussed, with attention being paid to the digestion process and to the production of CH_4 and fermentation heat and to urinary energy losses. On average, for ruminants only about 90% of the ME of a ration is energy in a chemical form. For monogastrics with hindgut fermentation, especially when CH_4 is neglected, part of the "ME" consists of CH_4, heat, and VFA. ME utilization is discussed, for both maintenance and production, with the main emphasis being placed on the energetic efficiency of the biochemical conversions for each of the chemical components of ME. ME content is found to be the major factor influencing the value of the feedstuff for maintenance; whereas, the origin of the ME influences this value by about 20% in nonruminating animals and by less in the case of ruminants.

For nonruminants, feed evaluation according to net-energy-fattening (NEF) approximates the true feeding value of the feedstuff for both maintenance and production fairly closely, and some improvements are suggested to further improve the predictive equation. Some of the new systems for the evaluation of energy for beef and dairy cattle are also discussed. The net-energy-lactation (NEL) system for dairy cattle is well-based and is easy to use in practice, but the new systems for beef cattle still require additional work.

For feed evaluations in warm countries, it is of foremost importance to have information on the composition and digestibility of the feedstuffs. In most cases DE or ME will be sufficiently precise; however, for nonruminants a slightly improved NEF system and for ruminants a NEL system might be preferred. These systems are said to be more precise, and they are well-suited to tropical countries where maintenance metabolism accounts for a great proportion of total metabolism. They require little additional analytical information, and they are no more difficult to use.

For their maintenance and production, farm animals require sufficient quantities of (chemical) energy, amino acids, vitamins, and minerals at the tissue level. The size of the requirement for the first two is much larger than for the latter two; therefore, we shall only pay attention to energy and amino acids. As well, shortages of vitamins or minerals can easily be corrected by supplying the animals with an additional small amount of a vitamin and/or mineral mixture.

A high concentration in a ration of substances supplying energy and amino acids at the tissue level is not a guarantee that the animal's requirements will be met: for that purpose, sufficient quantities of the ration must be ingested. This means that attention should also be paid to the palatability and ingestibility of rations.

Rations are composed of one or more feedstuffs; thus to provide the animal with the required energy and amino acids at the tissue level we need information on the energy, protein, and ingestibility aspects of the separate feedstuffs. It is, therefore, necessary to study how to predict these values.

Before doing so, we must discuss a number of complications. Low ingestibility does not make a feedstuff useless; it only restricts its use in large quantities in rations where a high energy and/or protein intake is needed. It is clear that the ingestibility value of a feedstuff is not constant for all cases; it depends on the purpose for which the feedstuff is to be used. The same holds true for its protein value. Protein can be used by animals both as an amino acid and as an energy source. We might express this more clearly by saying that protein has an energy value as well as an amino acid value. It exerts its first task in all cases, its second only if there is need for amino acids. Also, those amino acids that at the tissue level are in excess of needs are used only as an energy source. Practice is taking account of this by demanding

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that rations contain a sufficient amount of energy as well as a sufficient amount of protein or N: the protein of the feedstuffs is evaluated for both energy and protein.

In warmer and more humid environments, ingestibility and protein aspects are further complicated. The high heat load may lower the animal's appetite, especially for those feedstuffs that result in a relatively high heat production on ingestion. In such environments, farm animals often have higher loads of intestinal and other parasites, which may also decrease their appetite and increase their amino acid needs. In ruminants, many of the rations grazed or fed are often low in N and considerably lignified. Low N levels result in slow microbial digestion in the rumen and reduced feed intake. Furthermore, more lignified feeds are eaten in smaller quantities and produce per kilogram less chemical energy at the tissue level, and per joule of energy more heat. Finally in warmer environments, feeds occasionally contain weeds that are toxic or that depress intake. Tannin levels of feeds can be high, which might result in lower efficiencies of N utilization.

Feed Intake

For monogastrics as well as ruminants, it is a general rule that energy requirement determines intake. There are many examples of high-producing animals eating more than non- or lower-producing ones. However, there are quite a number of exceptions where other factors overrule this general rule: high heat loads decrease feed intake (the high heat load can be due to the environment or to too high metabolic heat production per kilogram of ingested feed); voluminous feeds with low nutrient density cannot be eaten in great quantities; very fat animals have a lower intake due to reduced intestinal capacity, and maybe also due to metabolic feedback; and in ruminants low intakes of N, and also of S or P, may lower intake. On the other hand, feeds of high digestibility and high nutrient concentrations are often eaten in greater quantities than needed.

In ruminants, some of these feeds under certain circumstances may lower feed intake: for example, concentrate rations rich in easily fermentable carbohydrates when eaten in great quantities over short periods may upset rumen fermentation. In such cases, rumen pH may become low and considerably reduce the speed of microbial conversions. The lower emptying rate of the forestomachs, and possibly the low pH or the fermentation products per se, often lead to feed intake reduction, and in severe cases to "off-feed." Part of the reduction in forage intake after increasing the supply of concentrates is due to this phenomenon. Changes in microflora also occur.

Low or high intake of feed is disadvantageous to the farmer when it results in either not meeting the animal's requirements or in exceeding them. In the first case, production might be low and/or the animal's condition might deteriorate. The second case leads to unnecessary feed losses as the direct conversion of feed is physiologically more efficient than production via reserve tissues, i.e. first a conversion into reserve tissue followed by a utilization of these tissues. Nevertheless, for economic or feed availability reasons, it sometimes is necessary to make use of the animal's ability to deposit or utilize reserves.

N Metabolism

Essentially, N requirements in monogastrics consist of a need for essential and nonessential amino acids at the tissue level. Usually in a feed a few essential amino acids are limiting, and these determine the rate of production at a given feed intake level. Nonessential amino acids, although in theory synthesized by the animal, are needed when the deamination of the surplus nonlimiting amino acids and the sources for ammonia in the ration do not deliver sufficient ammonia for their synthesis from this ammonia and suitable N-free intermediates.

In monogastrics the amount of apparently digestible amino acids in most cases gives a good indication of the quantities of the various amino acids absorbed in the blood. Lysine is often the first limiting amino acid, and its apparent digestibility is usually equal to or slightly lower than that of crude protein. Therefore, lysine concentration and apparent digestibility of crude protein give quite a bit of information about the feed's N value. However, in monogastrics with a higher degree of microbial activity in the hindgut, as is the case in older pigs and in horses, apparent digestibility is not a good indicator of absorbed essential amino acids, especially lysine. The microbes in the hindgut modify the amino acid pattern in a way that is not yet well understood.

In ruminants, N metabolism is far more complicated because the proteins and amino acids that enter the small intestine are from undegraded feed protein, microbial protein, and endogenous protein. Most of these proteins (after hydrolysis) and amino acids are absorbed in the blood. Various systems exist for predicting the total amount of absorbed amino acids; unfortunately they differ considerably due to a lack of precise information. The pattern of absorbed amino acids seems to match the required pattern for maintenance and production fairly well. Thus, in ruminants it

is the total amount of absorbed amino acids (absorbed "protein") that is important rather than a given limiting amino acid in this "protein." Unfortunately, there is still a lack of precise quantitative information on the requirements for absorbed "protein" for maintenance and for milk production.

Energy Metabolism

From Gross Energy to Metabolizable Energy

The gross energy (GE) of feedstuffs, as well as of materials like feces, urine, milk, eggs, animal tissue, etc., can be measured with high precision with a bomb calorimeter. In fact, GE is due to the chemical constituents of these materials, especially carbohydrates, proteins, fats, etc.

Part of the feed is not digested. The degree of digestion, by the digestive enzymes of the animal and by the enzymes of the microbes it hosts in the gastrointestinal tract, depends on many factors of feed as well as of animal origin. Feed and animal factors, moreover, show interaction.

Feed factors determining the degree of digestion by animal and microbial enzymes are: species; growth conditions and way of conservation of the plants from which the feed originates; the part of the plant that is used as feed and its treatment prior to feeding; and its composition (protein, fat, carbohydrates-starch, sugar, cellulose, etc., degree of incrustation, tannins, etc.).

Animal factors include: animal species (symbiosis with microbes prior to or after the true stomach or not at all — in view of the host's lack of cellulase); rate of flow of digesta (in view of time available for digestion); and conditions for microbial activity and growth in forestomachs or hindgut.

It is nearly impossible to predict with a reasonable degree of precision the degree of digestion of a feedstuff by a given type of animal at a level of intake sufficient for maintenance when no in vivo digestibility results are available for that or a related feedstuff and for that or a related type of animal. For monogastrics, feeding level has little influence on this degree of digestion. For ruminants, it does. At a higher feeding level the rate of passage increases so that a shorter time is available for fermentation, which results in lower cellulose digestion. Moreover, the high feeding level is often achieved by feeding more concentrates that on the one hand may lead to lower rumen fluid pH and thus lower cellulose digestion, but which may also allow more undegraded starch and protein to pass on to the duodenum for digestion by the animal's enzymes. Whether or not rumen fluid pH decreases markedly and over a longer period after a meal also depends on the animal (speed of eating, ability to produce saliva to buffer microbial acid production); therefore, the effects may differ considerably.

Some endogenous substances (digestion fluids, gastrointestinal wall abrasions) mix with the feed digesta in the gastrointestinal tract during the digestion process and are not completely reabsorbed into the blood or lymph. The part lost with the feces is usually called the metabolic fecal fraction. Its size is related to the amount of ingested dry matter, but other factors also play a part. The fraction is mainly composed of protein and fat. Not all endogenous substances not reabsorbed in blood or lymph as amino acids, fats, and long-chain fatty acids are voided with the feces as the metabolic fecal fraction. Part of the endogenous material is converted into volatile fatty acids (VFA), methane (CH_4), ammonia (NH_3), CO_2, H_2O, and heat, and is for a large part absorbed in the blood in these forms. The greater the microbial activity in the large intestine the more such conversions occur. Part of the feed-digesta undergoes a similar fermentation. Thus, in animals with an intensive fermentation in the hindgut it is nearly impossible to distinguish between fecal matter originating from feed and fecal matter of metabolic origin. Furthermore in such an animal the apparently digested material contains digested feed as well as VFA, CH_4, NH_3, and heat.

In ruminants, most of the microbiological degradation of the feed, its fermentation, takes place prior to the true stomach. Fermentation in the forestomachs is usually far more active than in the hindgut because the feed contains more and easier degradable nutrients than the digesta entering the hindgut.

This fermentation also results in VFA, CH_4, NH_3, CO_2, H_2O, and heat, which are absorbed or eructated, and microbial matter. In the hindgut a second fermentation may take place, and its extent depends on the degradability for microbes of the remaining digesta. Due to the fermentation, the apparently digested matter of ruminants contains far less nonfermented digested feed and far more VFA, CH_4, and heat than in the case of those monogastric animals, which have little fermentation in the hindgut. Besides this, the apparently digested material of ruminants also contains amino acids, fat and higher fatty acids, and sometimes monosaccharides, all resulting from the digestion of microbial matter.

Some research workers prefer to work with truly rather than apparently digested matter. Physiologically they are right; the truly digested

material is the part of the feed that is actually absorbed into the blood. However, the process of digestion itself requires metabolic substances resulting in metabolic fecal losses. Apparently digested matter clearly is closer to the net result of the whole process than truly digested matter. Also for practical reasons, among others, the difficult separation of feed residues from endogenous material in the feces, especially from animals having considerable fermentation, apparent digestion has to be preferred.

Gross energy minus fecal energy gives (apparently) digested energy (DE). From the above discussion on digestion it is clear that the chemical and physical composition of DE may vary considerably. In ruminants, methane losses are 5–12% of GE, but are included in DE although worthless for the animal. So DE is sometimes corrected for methane energy. Very rarely is the DE also corrected for the energy of the heat resulting from fermentation, some 3–8% of GE, because it is impossible to measure this amount with reasonable precision. Methane energy losses in nonruminants are usually neglected. Indeed these losses are less than 1% of GE in poultry, veal calves fed only an artificial milk, and pigs up to 100 kg on rations without forages, but are up to 2% of GE in sows and up to 6% in horses.

Subtraction of both urinary energy and fecal and methane energy from GE gives metabolizable energy (ME), which equals ingested energy minus all energy losses other than heat. Urine contains detoxication products like urea, uric acid, hippuric acid, etc. In monogastrics, urinary energy loss is from 2 to 6% of GE, mainly depending on the excess of N that must be excreted. In ruminants, urinary energy loss is slightly higher, and the higher the content of forages in the ration the higher the loss. Because the N of absorbed amino acids is either deposited in products like tissue, milk, eggs, and hair or excreted as urea or uric acid with the urine, for the same amount of absorbed amino acids higher urinary energy losses due to N excretion occur when N retention and N production in milk and eggs are zero.

In monogastrics, the ME content of a ration is hardly influenced by feeding level. In ruminants, it is influenced to a measurable extent, although less than DE because at a higher rate of passage microbial cellulose digestion and microbial methane production decrease. This gives some compensation, but it is an incomplete one. When the feeding level is mainly increased by adding concentrates, how the concentrate affects the rumen fluid pH determines the magnitude of the decrease in the ME of the concentrate. There is a lack of information on this point, which is so important for high production levels.

Because of what has been said about urinary energy, somewhat higher ME values are found for the same ration at the same feeding level when N is deposited in the tissues or in milk or eggs than when all the N is excreted with the urine. For this reason, ME values are sometimes standardized by correcting them to the situation of zero N retention and production, or to a 30% retention and production of all the N (N corrected ME).

In ruminants part of the DE is heat; therefore the same holds true for ME. On average only about 90% of the ME of a ration is energy in a chemical form.

The Utilization of Metabolizable Energy

Maintenance

Animals use absorbed nutrients for maintenance and production. The maintenance process mainly needs ATP (for blood circulation, respiration, muscle tonus, some work, maintaining concentrations, transport, etc.) and a small quantity of chemical compounds to replace worn tissues and for the synthesis of the necessary enzymes and hormones. As to the latter aspect it concerns only a small net supply of the building blocks of these compounds because the degradation products of the worn tissues, enzymes, and hormones can partially be reutilized. The actual linking of the building blocks, and any conversions required prior to linking, again mainly require ATP. It is therefore fairly safe to assume that maintenance needs for energy consist of a need for ATP.

Because of the biochemical pathways used in the animal, ME consisting of glucose is the most valuable for the synthesis of ATP from ADP, fat-ME some 5% less, and amino acid-ME some 10–20% less. For monogastrics with fermentation in the hindgut, part of the carbohydrate and protein is fermented, which results in an absorption of VFA, CH_4, NH_3, and heat in the blood rather than monosaccharides and amino acids. It is clear that ME containing such fermentation products is less valuable for maintenance, especially because CH_4 production is often neglected (i.e. assumed not to be present). The energy in the methane and heat (at normal environmental temperatures) is of no value to the animal, and the VFA are about 10–20% less valuable as a source for ATP production than glucose-ME.

Poultry, due to their short gastrointestinal tract and because their diet is low in cellulose, have very little fermentation and produce hardly any methane. Nonruminating veal calves fed only liquid milk replacers also show hardly any meth-

ane production. Their ME can therefore be considered to be absorbed monosaccharides, amino acids, and fats. Pigs, especially when fed higher levels of byproducts or roughages, can show fermentation, with methane energy productions of less than 0.5% of GE for pigs weighing less than 50 kg and fed concentrated diets, and up to 2% for other diets when the pigs weigh 100 kg and more. Compared to pigs without fermentation, the ME of these animals, especially the 100-kg pigs, has a slightly lower value for maintenance.

It will be clear that information on the composition of the ME is of importance for a correct evaluation of the feeding value of feedstuffs for maintenance. In experiments with monogastrics with no or little fermentation most of the above-mentioned differences in the relative value of ME from different sources for maintenance have been demonstrated. Information with regard to monogastrics with considerable hindgut fermentation is still limited.

In ruminants with an active rumen fermentation the ME is some 10% less valuable than monogastric-ME as an ATP source because about 10% is lost as (fermentation) heat. Secondly, VFA and amino acids are absorbed from the gastrointestinal tract rather than glucose and fat, again making ruminant-ME less valuable as an ATP source than monogastric-ME. Because VFA and amino acids on a ME basis have about the same potential for ATP synthesis, one would not expect much difference in the value of ME originating from different feeds for maintenance. Nevertheless, in balance and other trials a small influence was found: the lower the metabolizability, q (equal to 100 ME/GE) the more ME was needed for the same purpose — about 0.5% more if q decreased by one unit. Part of this may be due to a shift in the composition of the absorbed VFA towards more acetic acid, which is a slightly poorer source of ATP than the other VFA's. A second consideration is the higher eating and digestion costs of the feed, which becomes more voluminous and more difficult to ingest and digest as its q value decreases.

For maintenance with regard to monogastrics, knowledge is needed of the ME-content of the feed, but it is also of value to have some knowledge of the separate ME-contributions due to glucose, fat, amino acids, and the rate of fermentation (from CH_4 production). For ruminants, knowing the ME content and q is sufficient. In both cases it should be stressed that it is the ME content that largely determines the maintenance value of the feed; whereas, the origin of the ME influences this value by only 20% or less in monogastrics, and even less in ruminants.

Production

Monogastrics and not yet Ruminating Ruminants

The utilization of ME for production not only differs with the origin of the ME but also with the product it is used for, and with the animal's species and physiological state.

Energetically, *fat production* from fat-ME has a high efficiency of utilization, about 90%. However, it cannot be accurately predicted how much of the fat-ME will be used for fat synthesis, i.e. direct incorporation, and how much will be broken down to acetyl CoA for later use in fat synthesis or in maintenance. Direct incorporation is more efficient than incorporation after prior partial breakdown. In general, there appears to be a fair preference for direct incorporation of absorbed fat into body or egg fat, but this is certainly not an absolute preference. Incorporation as such also depends on the fatty acid composition of the fat.

Fat-energy production from glucose-ME has a 75–80% efficiency, from amino acid-ME it is 10–20% less. For VFA-ME the efficiency is somewhat lower than that of glucose-ME. When VFA are present, it means that there was hindgut fermentation; thus some of the ME consists of VFA, CH_4, and heat (which we will call rest-ME) rather than glucose, amino acids, and fat. For fattening, this rest-ME is utilized 20–30% less efficiently than glucose.

These statements as to the utilization of fat-, glucose-, and amino acid-ME for fat production have been generally proven in experiments with monogastric animals. There is little experimental evidence of the efficiency of the utilization of the rest-ME in animals with hindgut fermentation. The size of rest-ME in monogastrics is usually small; furthermore, efficiencies derived above from biochemical considerations, in view of our knowledge obtained from energy utilization studies in the ruminant, will be close to the actual ones. The ME contribution of those feedstuffs that are high in cellulose, and that by monogastrics can only be digested to a large extent by hindgut fermentation, will consist mainly of rest-ME.

Protein deposition in eggs, milk (sows), and meat (chickens, pigs) needs building blocks, an amino acid mixture matching the amino acid pattern of the protein to be synthesized, and ATP to link the amino acids. Theoretically some 5 moles of ATP are needed for the peptide linkages of 100 g protein (2385 kJ). The 5 moles of ATP require about 400 kJ ME, so to produce 100 g protein some 2400 kJ ME of "building block"-

ME and 400 kJ ME as energy for linking are needed. This means that the theoretical efficiency of utilization is about 85%. Proof of this efficiency figure in experiments with animals is very difficult to obtain. In fact, all our attempts to derive this figure, even in the case of experiments specially planned for it, have left us with imprecise estimates. The cause of this is quite clear: energetically, protein deposition even in a rapidly growing animal or productive laying hen is only a small part of total energy metabolism. In growing chickens, pigs, and veal calves production metabolism changes with ages from 60 to 40% of total metabolism, while the protein energy percentage of the deposition of energy decreases from 60 to 20%. Total metabolism of a laying hen is seldom twice maintenance, while only 40% of the egg-energy is protein-energy. Thus, for deriving the actual ME quantity required for protein deposition, the ME needed for total metabolism, for maintenance, and for fat deposition must be known separately and very precisely (the quantity looked for being the difference of two or three large figures).

There is still another problem: precise maintenance estimates of young animals are lacking. Most of the data used for this purpose are derived from mature animals and are corrected for the difference in (metabolic) weight. It is well-known that young animals are more physically active than older ones, and that they are more easily excited, but it is not known to what extent this affects maintenance needs.

Regression calculations, using the model:

$$\text{total ME} = a \times RE_p + b \times RE_f + c \times W^{3/4}$$

in which RE_p and RE_f are retained protein and fat, $W^{3/4}$ is metabolic weight, and a, b, and c are constants, are often used to derive the efficiency of the utilization of ME for protein deposition in growing animals. Properly said, the model is incorrect for this purpose because c, related to maintenance, probably is not a constant because it changes with age. Moreover, the model is nearly always used on data for which it is not well suited: results with animals of uniform potential for protein deposition fed ad libitum or nearly so rather than results with animals showing considerable variation at all ages in protein and fat deposition due to differences in genotype and in feeding level. Even the best experiment for this purpose, that of Pullar and Webster (1977), was not completely free from bias. Nonetheless, calculations from this kind of research show a fair amount of agreement with regard to the values found for a and b: the value of b being only slightly above the one expected from biochemical considerations and experimentation with mature monogastrics. From the value of a, however, efficiencies of utilization between 50 and 70% can be derived for protein deposition, i.e. much lower than the theoretical 85%. It is not very probable that the biases of the regression are responsible for this because the low estimates of protein efficiency are so consistent. These efficiencies are therefore probably low, especially for growing animals. It has been suggested that this might be due to a higher rate of protein turnover during rapid growth. Isotope studies have indeed shown this for small animals, but unfortunately there is little evidence for large animals. As a consequence of an increase of this rate with the rate of growth, ME is needed not only for actual protein deposition but also for the higher turnover of existing protein. This is because protein synthesis requires ATP; whereas, its degradation to amino acids does not yield ATP. Such an effect could easily explain the low efficiency values. It is a great pity that we know so little about the rate of turnover of protein under various conditions, especially in farm animals. Its measurement requires isotope studies, which are not always easy to interpret; whereas, the other available technique of 3-methylhistidine excretion, which does not make use of isotopes, also has its drawbacks.

Some of the estimates of ME-requirements for *egg-protein* synthesis are not far below the theoretical estimate of 85%; some, however, are. The lack of agreement in the results of the few studies with layers is due to the above-mentioned relatively low amount of protein production and to insufficient information on the hen's maintenance needs.

Reliable studies, from which the ME required for *milk-protein* synthesis in sows may be derived, still are lacking. Sow's milk contains about 60% fat-, 25% protein-, and 15% lactose-energy. For the efficiency of *milk-fat* synthesis from ME we can use the same arguments as body-fat synthesis. The same arguments apply to milk protein, except possibly for the rate of whole body protein turnover. So far, an increased rate of whole body protein turnover has only been found during rapid growth. Clear evidence that lactation does not influence this rate of turnover is however lacking. During rapid growth an increased rate of protein synthesis can be understood to have some purpose, during lactation such a purpose, except for udder tissue, is difficult to imagine. Synthesis of *milk-lactose* from glucose is biochemically a simple process, probably requiring little additional energy. Synthesis from (glucogenic) amino acids is less efficient because it requires urea formation and excretion as well as glucogenesis. Milk-energy synthesis therefore will probably be

slightly more efficient energetically than fat synthesis from carbohydrates.

With regard to feed evaluation, the value of ME of different origins for production in nonruminating animals may be summarized as follows. The main kind of chemical energy synthesized is fat energy. This is formed most efficiently from absorbed fat, some 10–20% less efficiently from carbohydrates, and 20–30% less efficiently from amino acid- and rest-ME. Except for the fat, the relative contributions of the different kinds of ME are of the same order as for maintenance. These considerations led the research workers of the Oskar Kellner Institute in Rostock to use Net Energy Fattening (NEF), i.e. the value of a feedstuff for tissue fat deposition by a mature monogastric, as the criterion of feed evaluation for both production and maintenance. They admit, however, that feed fat does not fit completely in this theory as it is preferentially incorporated in body or egg fat with high efficiency. For a correct evaluation of the carbohydrates of the feed, NEF should not be predicted from digestible crude protein, digestible crude fat, digestible crude fibre, and digestible N-free extract. The latter two fractions do not partition the carbohydrates into valuable and less valuable sources of energy for production and maintenance. Instead, they could better be replaced by: (1) total starch plus sugar, being highly digestible; and (2) the digestible remainder, equal to digestible organic matter minus the sum of digestible protein, digestible crude fat, starch, and sugar. Some experimental evidence for this has already been found.

With regard to protein and lactose production, correct feed evaluation is more difficult. Protein synthesis, especially at high protein turnover rates, needs ATP, which is synthesized with the same efficiency as maintenance ATP from the various ME-sources. Lactose synthesis from glucose-ME is also more efficient than from protein- and especially rest-ME. Thus, the various nutrients rank in about the same order for lactose synthesis as for fat synthesis and maintenance. Therefore, the concept of the Rostock group appears well-founded. However, NEF underestimates the value of protein-ME for protein deposition: it assumes all absorbed protein to be deaminated, resulting in an energy reduction of some 20%; whereas, such an energy loss does not take place at all for the retained or deposited protein. Increasing the NEF-value for protein-ME according to the percentage of feed protein incorporated as protein in tissues, eggs, or milk seems a suitable correction.

Net energy fattening will also evaluate the feedstuffs correctly when physical work is part of production, because this, like maintenance, mainly means an ATP requirement. The same holds true for animals that must walk over long distances or are under some stress because these also usually result in a greater need for ATP.

Ruminants with Active Rumen Fermentation

The main kinds of production to be treated in this section are lactation, growth, and pregnancy. Cow's milk with 4% fat contains 50% fat-, 25% protein-, and 25% lactose-energy. Production of about 12 kg of milk requires as much ME as is needed for the maintenance of a 550-kg cow. Thus to produce 36 kg of milk such a cow has to absorb four times as much ME as for maintenance alone.

Growing cattle or sheep do not reach such high production levels; therefore, ME requirements of twice maintenance are close to the upper limit. A considerable part of the energy deposition is fat-energy, (the more so the more mature the animal and the higher its feeding level). In well-fed, early-maturing, beef cattle protein-energy deposition decreases from about 35% at 200 kg to about 15% at 500 kg, but in late-maturing breeds the decrease is much slower.

Even at the end of pregnancy, daily energy deposition (e.g. 6000 kJ for a cow) is small, but it requires, relative to other productions, an unusually large amount of ME because the efficiency of utilization is only 10–25%. Therefore, the total feed requirement near parturition is 2.0–1.5 times the ME needed for maintenance. The low efficiency suggests that the main need during pregnancy is an ATP supply, maybe because synthesis of fetal tissues is difficult and / or because the changed endocrinological state of the mother may increase her maintenance needs. Thus, with regard to feed evaluation, the value of ME from different sources, relative to each other is very probably the same for pregnancy as for maintenance.

Biochemically seen, lactose and fat synthesis in ruminants give special complications. Usually little glucose is absorbed from the gastrointestinal tract; therefore, glucose for *lactose synthesis* must be synthesized from propionic acid and glycogenic amino acids. This conversion, especially from glycogenic amino acids, requires energy because of the necessary NH_3 excretion. Only a small quantity of the ingested carbohydrates fermented in the forestomachs becomes propionic acid, so the supply of this precursor is not great. Also, the supply of the other precursor, protein, is small because the protein content of the rations is usually low; whereas, at higher protein levels, rumen microorganisms often degrade more protein to VFA and ammonia than they synthesize.

Like lactose synthesis, *fat synthesis* also requires gluconeogenesis, first a small quantity as a precursor for the necessary glycerol; and second for the NADPH supply. It still is not clear if all the NADPH is synthesized from glucose via the pentosephosphate pathway or if other pathways like an extramitochondrial NADH/NADPH exchange at the isocitrate or other steps of the citric-acid cycle also result in a substantial NADPH supply.

It is clear that especially in high-yielding dairy cattle, glucose supply for lactose and fat synthesis may be low; therefore the energetically less efficient pathway of gluconeogenesis from protein might have to be followed. On the other hand, absorption of glucose from the small intestine at high levels of intake and rapid passage rates of ingesta, may have a compensatory effect. In sheep, indeed, such changes with feeding level have often been demonstrated. There is much less evidence with cattle, however, and so far it suggests a smaller compensatory effect than in sheep.

Most results of balance trials suggest that the utilization of ME for milk production is not influenced as much by the origin of the ME as the utilization for body-fat synthesis, the main energy synthesis of growing ruminants. Within the range of the rations studied, which in the case of the dairy cow with a reasonable rate of production cannot be wide, the effect of the ME's quality (q, excess protein) on the efficiency of converting ME into milk energy is small and of the same size as for maintenance. It should be mentioned that not all studies show precisely the same effect of q on this efficiency, but in all cases it is low: at Beltsville half and at Rostock about twice the size as in Wageningen, where an increase of q by one unit improved ME utilization by 0.4%. The differences probably are not statistically significant. All studies show nearly the same small negative effect for ME resulting from protein in excess of protein needs, i.e. protein not deposited as milk or tissue protein. Dairy rations, however, seldom contain large protein excesses, so in practical feed evaluation the lower value of excess protein could be neglected.

On the other hand, many studies tend to show a much greater influence of ME quality on the efficiency of body-fat deposition. However, the evidence is still not quite clear. Although test rations with much greater variation in quality have been used than in the case of dairy cattle, the results regarding the efficiency of utilization of the ME for body-fat synthesis (k_f) are not clearcut. This is mainly caused by the fact that the maximum feeding level in beef cattle is low, not more than 2.5 times maintenance for high-quality rations and hardly above 1 times maintenance for low-quality rations. Even in the first case, accidental experimental errors decrease the precision of the measured k_f markedly, and in the second case the decrease in precision is of course enormous.

The results suggest a greater decrease in k_f when q is lowered by one unit at low levels of q than at high levels. This would agree with biochemical expectation. Rations with low q usually result in a lower percentage of propionic acid in the VFA, which might cause too little gluconeogenesis from propionic acid for NADPH synthesis and lead to less efficient production of NADPH.

During lactation there is a much greater need for glucose than during fattening; and at high milk yields, much higher feed intake levels are also needed. This is the reason why nearly all dairy rations have high q values. It appears logical that at such a q level the tendency is for k_f to be slightly lower than k_l, the efficiency of the utilization of the ME for milk-energy production. At this level, there probably is no shortage of glucose, so that milk- and body-fat synthesis will have the same efficiency. Lactose synthesis from propionic acid and milk-protein synthesis from amino acids, however, have a higher energetic efficiency than fat synthesis, thus k_l will exceed k_f. One would expect that at lower q in dairy cattle glucose shortage would occur sooner during lactation than during fattening and that k_l would decrease more markedly than k_f. As stated earlier, this appears not to be so. While trying to find an explanation for this discrepancy we have to keep in mind that it is difficult to work with such rations for dairy cattle and still maintain milk yields at a sufficient size.

Although clearly our biochemical understanding of the relationship of ME quality with k_l and with k_f is incomplete, at the present time the following procedures for feed evaluation appear fairly correct. For rations of not too extreme composition, with sufficient physical structure, and without large protein excesses, the *same* (small) effect of q on k_m and k_l may be assumed to exist (where k_m=efficiency of the utilization of ME for maintenance). This allows us to express both milk energy production and maintenance in net-energy-lactation (NEL). Because k_l averages 0.60, and taking into account the small effect of q, NEL can be computed as:

$$\text{NEL} = 0.60\ (1 + a\ (q - \bar{q})\ \text{ME}$$

in which $\bar{q} = 57$. In this equation, according to the Wageningen studies, a might be 0.004, but it

would be lower according to the Beltsville work and higher for that of Rostock. Because the equation was derived using the actual ME value found in the experiments, i.e. at the actual feeding level, ME-values corrected for feeding level have to be used rather than maintenance-ME values.

For feed evaluation for *beef cattle* the situation is more complicated. The first simplification is neglecting protein deposition, i.e. assuming that energy deposition during growth is mainly deposition of fat-energy. For animals weighing 200 kg or more, fat deposition indeed is the main energy deposition. Further, we do not have for such animals (which probably do not have increased protein turnover rates as they are no longer in their youth) any proof that ME-composition has a different effect on the efficiencies of ME-utilization for fat or protein energy deposition.

The second assumption is to use two different values for the effect of q on k_m: the first being small or even zero; the second being higher as has been found from work with mature cattle and sheep. As discussed above, our knowledge of the precise effect of q on k_f unfortunately is still limited. In this way, for any animal production level, equal to net energy for maintenance plus energy deposition divided by net energy for maintenance, the effect of q on the utilization of total ME can be derived. Such an approach clearly leads for the same ration to a greater influence of q the higher the energy retention of the animal. This means that the same ration or feedstuff may have several feeding values depending on the rate of daily gain (in lactating cattle this is not the case because the effect of q on k_l and on k_m is about the same). With the help of a computer, or of tables and graphs for a given animal production level, the correct feeding value of all feedstuffs available can be calculated to compose a least-cost ration. Most beef cattle are fattened either intensively with high quality feed or at a moderate rate on rations with much roughage. Therefore, for an easier comparison of the value of feedstuffs, the average animal production level at each of these two fattening intensities can be fixed and used to compute only two net energy values for maintenance and fattening (one applying to the high, the other to the low intensity.) This would simplify feed evaluation considerably because it permits listing of the two values for all feedstuffs. The precision gained by working with the actual animal production level (APL) rather than with one or two fixed APL's seems small compared to the large source of uncertainty due to insufficient knowledge of the effect of ration composition on k_l.

Feed Evaluation Systems for Countries with a Warm Climate

For various reasons, e.g. the high heat production of animals (especially at higher production levels of milk, meat, eggs), higher level of disease, periods with feed shortage, suboptimal management etc., production levels in countries with a warm climate are moderate to low, often even very low. As a consequence, maintenance metabolism accounts for a greater portion of an animal's total metabolism. Therefore, it seems important, while selecting suitable feed evaluation systems, to give priority to those in which the evaluation for maintenance is done as correctly as possible. Fortunately, as we have seen, feed evaluation for maintenance gives fewer problems than for production. This applies to monogastric as well as ruminating farm animals. For both groups of animals, evaluation on the basis of ME, either actually measured or predicted from digestible components or from the feedstuff's name and, possibly, composition, comes close to an evaluation for maintenance. Moreover, it is, in the case of monogastrics and lactating ruminants, also a fairly good basis for production. Thus measured or predicted ME might be a suitable basis for feed evaluation for most farm animals in countries with a warm climate.

However, in my opinion, without losing the advantage of the simplicity of such a ME system, one could do better, with regard to precision as well as to flexibility. For monogastrics we have seen that the composition of the ME, especially its protein content and its rest-carbohydrate content, influences to some degree the efficiency of utilization of the ME. The NEF equation of the Rostock group, corrected as suggested in the section on "monogastrics and not yet ruminating ruminants" takes such influences into account, while hardly increasing the necessary analytical information on the feedstuffs. Also for ruminants, the type of ME, e.g. its property q, influences its utilization for maintenance and production. So here too, a unit like NEL as described in the section on "ruminants with active rumen fermentation," even for beef cattle, would give a higher degree of precision without additional analytical work. For both groups of animals, feed evaluation in the way suggested would be more flexible, i.e. it would be easy to change one of the factors of the NEF or NEL equations slightly, when new experimental evidence made this desirable.

Even so, such energetic feeding values do not tell everything. They provide information on the energy aspect, which is very important but is not the only consideration.

In all cases, information on digestibility forms the basis of the proposed systems of energetic feed evaluation. It is this information that mainly determines the feed's value, and unfortunately for many plant products in warm countries this information is poor or imprecise. The ability to predict the digestibility of feeds is a must for animal husbandry in these countries, especially as this property also influences ingestibility.

Survey of Feed Evaluation Systems

Feed evaluation for poultry enjoys the greatest uniformity. Nearly everywhere, except in East Germany, ME is the unit on which feed evaluation is based. However, some research workers are of the opinion that the evaluation can be improved. They say that not only the amount but also the origin of the ME should be taken into account because protein-ME, fat-ME, and starch-, sugar-, and rest-carbohydrate-ME do not have the same net-energy value for the animal.

For pigs, several countries use TDN, DE-, or ME- systems, whereas the NEF-system from the Oskar Kellner Institute at Rostock is used in East Germany, and a modification of it is used in the Netherlands. Here too in those countries that use TDN, DE, or ME, attempts are being made to improve the systems for the same reasons mentioned for poultry. In the Netherlands, new research work is due to begin to try and make the present NEF system more applicable to fast-growing pigs fed rations with a greater proportion of by-products.

Until 1960 in Europe, NE systems (starch value, feed unit) were used for ruminants, while in most other parts of the world TDN was the preferred system. Two developments have changed this pattern: (1) energy metabolism was looked at in a factorial way, i.e. the utilization of the feed was studied separately for each of the various purposes like maintenance, lactation, etc.; and (2) biochemistry was used to improve the understanding of energy conversions. This led in 1965 to the new ARC system for ruminants, which was completely factorial and therefore had a very logical construction. Due to insufficient information it was weakly based as to its details and for use in practice it was too complicated. Intensive research work combined with a similar factorial and biochemical approach led in East Germany to the NEF system, at present the system practiced in that country. This system has not found much acceptance elsewhere because it is based largely on work with mature male animals. Work with dairy cattle in Beltsville and the Netherlands has led to systems, based on NEL, that have similar main principles but differ in some details. They are used to some extent in the United States and in the Netherlands, Belgium, France, and Switzerland; West Germany is to introduce a NEL system in 1980. The U.K. extension service introduced a considerably simplified NEL system in 1975. The effect of feeding level and of q on ME utilization for maintenance and lactation was neglected and k_l was put at 0.60; in other words, all ME was assumed to have the same NEL irrespective of origin. It is being used in practice to a considerable extent. Also, the 1965 ARC system for beef cattle was given a more practicable form and introduced with some success in the U.K. by the extension service. Similar systems, even more simplified, were recently introduced into practice in France, Switzerland, and the Netherlands.