A MODEL TO DESCRIBE RUMINAL METABOLISM AND INTESTINAL DIGESTION OF FATTY ACIDS

William Chalupa, Peter Moate and Ray Boston

School of Veterinary Medicine
University of Pennsylvania
Kennett Square Pa 19348

Summary

A lipid sub-model is used to illustrate ruminal metabolism and intestinal digestion of long chain fatty acids (LCFA). Ruminal lipolysis (defined as enzymatic cleavage of ester linkages and dissociation of salts of fatty acids) varies between feeds. Megalac (calcium salts of palm oil fatty acid distillate) was the only ingredient that showed appreciable protection against lipolysis. Lipolysis is a pre-requisite for ruminal biohydrogenation. Polyunsaturated fatty acids, especially C18:2, appear to have an energy independent effect on improving reproduction. However, less than 10% of the C18:3, C18:2 and C16:1 that are in the form of free fatty acids will escape biohydrogenation. C18:1t, which is associated with decreased mammary synthesis of fat, accumulates in the rumen when there is incomplete biohydrogenation to C18:0. De novo synthesis of fatty acids occurs, but as fatty acid intake increases, the extent of de novo synthesis declines as a result of increased uptake of LCFA by microbes. There is insufficient data to model the effect of rumen active fat on rumen digestion and fermentation so we suggest using the advisory of Jenkins (1997), which is based on unsaturation of LCFA and ration fiber, for the upper limit. Most of the LCFA flowing to the small intestine are free fatty acids but there are also non-lipolysed fatty acids in the form of glycerides and calcium salts and fatty acids in bacteria. In general, intestinal digestion of free fatty acids and non-lipolysed fatty acids in forages, grains, proteins, whole cottonseed, and cracked or ground soybeans and other oil-seeds are similar. Digestion of non-lipolysed fatty acids in tallow, hydrogenated tallow, grease, vegetable oils, animal/vegetable blends, whole-intact soybeans and other whole-intact oil-seeds with the exception of cottonseed is less than digestion of free fatty acids. In particular, digestion of non-lipolysed C18:0 in some feeds is zero. Digestion of non-lipolysed fatty acids in the form of calcium salts is greater than digestion of free fatty acids. To increase absorbed amounts of LCFA like C18:2 and C18:3, they must either be in a form that protects them from lipolysis or large amounts must be fed. The latter, however, can lead to accumulation of C18:1t that is associated with decreased mammary synthesis of fat.

Introduction

Fats provide more than calories! They provide specific polyunsaturated fatty acids that participate in a host of metabolic reactions that can have an impact on dairy cow metabolism (Jenkins, 2002; Sanchez and Block, 2001). This is the most exciting development in ruminant nutrition since we recognized that proteins provide amino acids.

For some years now, it has been evident that dairy cow nutrition and nutrient management models are vital to the continued success of the dairy industry. We have computer programs like CPM-Dairy (Boston et al. 2000), CNCPS (Fox et al. 2000) and NRC-Dairy (2001) that allow us to balance rations on the basis of amino acids but no dairy nutrition model describes fat correctly. For example, CPM-Dairy and CNCPS operate on ether extract and not fatty acids. Dairy-NRC (2001) estimates fatty acids empirically from ether extract. No model considers specific fatty acids. Instead, they consider dietary lipid as a single entity. In addition, they ignore the transformation processes that affect dietary fatty acids in the rumen and they generally have a very simplistic treatment of de novo production of fat within the rumen. Intestinal digestibility is also handled is a simplistic manner. In CPM-Dairy and CNCPS, absorbed fat is 95% of the ether extract entering the small intestine. The NRC-Dairy model employs different digestion coefficients for total LCFA from different sources and discounts digestibility as dry matter intake increases above maintenance. However, NRC-Dairy assumes that for diets containing 3% or less ether extract, the digestibility of total LCFA is 100%

In this report, a new lipid sub-model (Moate et al. 2000a,b,c; 2001) is used to illustrate ruminal metabolism and digestion of LCFA. The fat model focuses on the major LCFA (C12:0, C14:0, C16:0, C16:1, C18:0, C18:1cis, C18:1trans, C18:2, C18:3). Major issues of the fat sub model include:

1. intake of fatty acids
2. ruminal lipolysis of dietary fats
3. biohydrogenation of fatty acids in the rumen
4. de novo production of fatty acids in the rumen
5. effects of fat on rumen digestion and fermentation
6. intestinal digestion of fatty acids

Data used to develop this model came from 8 published experiments that reported intakes and flows of LCFA to the duodenum and to feces. Dairy cows were fed a diverse range of feeds with a wide range in intakes (mean, 878 g; range, 197 to 1339 g) of LCFA. These experiments contained 27 common dietary ingredients in 36 diets.

Acronyms used in the fat sub-model are defined in Table 1.

Intake of Fatty Acids

Fatty acids and not ether extract are the nutritional entities of importance. In dealing with this problem, NRC-Dairy (2001) advocates measuring LCFA content of feeds or using the equation: LCFA = EE-1 (Allen, 2000), and assuming that LCFA = 0 if EE is less than 1. Data in Figure 1 shows that the Allen (2000) equation predicts the LCFA content of some feeds well but it may not be accurate for lush grasses and legumes that contain high amounts of pigment that are ether extract.

Many references list fatty acid profiles but not total LCFA. Over 200 references contain information on fatty acid composition of feeds but this only includes about 40 different feeds. When the major fatty acids in feed ingredients (C16:0, C18:0, and C:18:2) account for 20% or more of the total LCFA, coefficients of variation are usually less than 20% (Moate, 2001). We

are assembling a bank of feeds that will be analyzed for fatty acids and ether extract by Dr. Tom Jenkins at Clemson University.

Ruminal Lipolysis and Biohydrogenation

Nutrients entering the rumen can only disappear from the rumen by two routes; by digestion or by passage. CPM-Dairy and CNCPS employ the model of Waldo et al. (1972) to define rumen digestibility (RD) as the specific rate (%/h) of rumen digestion (Kd) divided by the specific rate (%/h) of disappearance due to digestion and passage (Kd + Kp):

$$RD = \left(\frac{Kd}{Kd + Kp} \right)$$

Variable passage rates provide a method for estimating variations in ruminal digestibility as feed intake changes. As feed intake increases, rates of passage increase and the extent of ruminal digestion is reduced (Sniffen et al. 1992).

In this model, rate of lipolysis (Klip) and rates of biohydrogenation (Kb) of individual fatty acids replace Kd in the above equation.

Lipolysis of dietary fat. We use the term "lipolysis" to refer to the liberation in the rumen of LCFA in feed ingredients. This includes enzymatic hydrolysis of acylester linkages in triacylglycerols, phospholipids, galactosylglycerides and sterol esters and the dissociation of calcium salts of fatty acids. We define fatty acids arising from lipolysis as rumen free long chain fatty acids (RFLCFA) and fatty acids that were not lipolysed as rumen non-lipolysed long chain fatty acids (RNLCFA).

The approach of Waldo et al. (1972) was extended to describe the extent of lipolysis. The following equation calculates the amounts of LCFA in feeds that are "lipolysed."

$$RFLCFA = DIETLCFA * \left(\frac{Klip}{Klip + Kp} \right)$$

Where RFLCFA (g/d) is the amount of fatty acids in feeds that are lipolysed or converted to a free form in the rumen, DIETLCFA (g/d) is the intake of fatty acids, Klip (%/h) is the rate of lipolysis and Kp (%/h) is the rate of passage.

There is evidence that, for some lipids (tallow in particular), the rates of lipolysis may depend upon the concentration of LCFA in the rumen (Beam et al. 2000). We take account of this by using moderating factors to allow the Klip to be adjusted in response to different levels of total fatty acids from specific feeds in the total diet:

$$Klip = K * Exp(-L * DIETLCFA)$$

Where Klip (%/h) is the rate of lipolysis adjusted for LCFA in feeds, K (%/h) is the maximum rate of lipolysis, L is a lipolysis adjustment factor for the affect of DIETLCFA on lipolysis and DIETLCFA is the percentage of the total diet that is LCFA from a specific feed. When L = 0, Klip = K.

Rates of ruminal lipolysis vary depending on the feed ingredient (Table 2). Most feeds have high rates of lipolysis and are therefore extensively lipolysed in the rumen. The lipolysis rate of tallow decreased as the amount of tallow in the ration increased but even at a level of 5% of ration dry matter, 92% of tallow fatty acids are lipolysed. Megalac (calcium salts of palm oil fatty acid distillate) was the only ingredient that showed appreciable resistance to lipolysis (53%).

Biohydrogenation. The model assumes that lipolysis is a prerequisite for biohydrogenation. Thus, only rumen free unsaturated fatty acids are biohydrogenated. Unsaturated LCFA not liberated by lipolysis escape biohydrogenation.

Biohydrogenation is a complex process that involves the formation of many isomers (Jenkins, 2002). We adopted a simplified depiction of biohydrogenation of the major unsaturated RFLCFA that describes the essential features of these pathways. In our model, RFLCFA are biohydrogenated in stepwise processes: C18:3 → C18:2 → C18:1t → C18:0; C18:1c → C18:0; C16:1→ C16:0. The model considers the biohydrogenation of the RFLCFA derived from each feed separately but we assume that the biohydrogenation rates (Kb) are independent of the feeds from which the RFLCFA were derived. At each step, there is opportunity for the specific fatty acid to either pass out of the rumen or to be further biohydrogenated. In this model, the ruminal passage rates of RFLCFA are the same as the feed ingredients from which they were derived.

A model based on that of Waldo et al. (1972) was used to calculate biohydrogenation of unsaturated RFLCFA.

$$BHLCFA = RFLCFA * \left(\frac{Kb}{Kb + Kp}\right)$$

Where BHLCFA is the amount (g/d) of specific fatty acids that are produced by biohydrogenation, RFLCFA is the amount (g/d) of specific free fatty acids that are produced by lipolysis, Kb (%/h) is the rate of biohydrogenation and Kp (%/h) is the rate of passage.

After examining the flows of specific LCFA to the duodenum, we observed that the 'estimated concentration' of RFLCFA appeared to influence the rates of biohydrogenation. Therefore we again employed exponential moderating equations to allow for adjustment of biohydrogenation rates:

$$KbRFLCFA = K\,b * EXP\left(\frac{-B * RFLCFA}{DMI}\right)$$

Where KbRFLCFA (%/h) is the adjusted rate of biohydrogenation, Kb (%/h) is the theoretical maximum rate of biohydrogenation, B is the adjustment factor for the effect of RFLCFA on biohydrogenation, RFLCFA (g/d) is the amount of rumen free LCFA and DMI (kg/d) is dry matter intake.

Rates of biohydrogenation are in Figure 2. There are considerable differences in rates with C18:3>C16:1>C18:2>C18:1t>C18:1c. The amount of rumen free LCFA affected the biohydrogenation rates of C18:3, C16:1 and C18:1t but had no affect on biohydrogenation rates of C18:2 or C18:1c.

Data in Figure 3 present the extent of ruminal biohydrogenation and, by difference, the percentage of rumen free unsaturated fatty acids that will escape biohydrogenation and pass to the small intestine. Polyunsaturated fatty acids, especially C18:2, appear to have an energy independent effect on improving reproduction in the dairy cow. However, more than 90% of the rumen free C18:3, C18:2 and C16:1 will be biohydrogenated so that 10% or less will escape the rumen. Increased ruminal outflow of C18:1t appears to be associated with decreased synthesis of milk fat (Chalupa and Sniffen, 2000; Jenkins, 2002). Trans-10, cis 12 CLA rather than C18:t is probably the fatty acid that inhibits mammary synthesis of milk fat (Bauman et al. 2001) but there was insufficient data to include CLA in our model. It may be that ruminal accumulation of C18:1t is a marker for situations that lead increased amounts of trans-10, cis 12 CLA. Feeds contain little C18:1t. It is produced through biohydrogenation of C18:3 and C18:2. Because the rates and extents of biohydrogenation of C18:3 and C18:2 are greater than the rate and extent of biohydrogenation of C18:1t, it is easy to see how there will be increased absorption of C18:1t when diets contain polyunsaturated fatty acids in forms that have high rates of lipolysis. It is interesting that as the level of rumen free C18:1t increases, biohydrogenation decreases so that more C18:1t will flow to the small intestine.

De Novo Production of LCFA in the Rumen

Jenkins (1993) reviewed the literature on the factors affecting the balance of LCFA across the rumen of sheep and cattle. He concluded that the flow of LCFA to the duodenum is generally closely related to, but is usually slightly higher than the dietary LCFA intake. De novo synthesis of fatty acids occurs, but at high fatty acid intakes, the extent of de novo synthesis may decline as a result of enhanced uptake of exogenous LCFA by microbial cells.

In this model we assume that each feed containing fermentable carbohydrate has the potential to induce in the rumen, through growth of ruminal bacteria, de novo production of LCFA. The main LCFA that are produced de novo are C18:0, C16:0, C16:1 and COther. In order to take into account this negative effect of fatty acids on de novo synthesis of LCFA, we again employed exponential moderating factors to adjust the rate of de novo synthesis of LCFA in relation to the amount of the relevant RFLCFA produced in the rumen as a result of lipolysis and biohydrogenation. The generalized formula is

$$RPLCFA = LCFASYN*FTCHO * EXP\left(\frac{-LCFAUP*RFLCFA}{DMI}\right)$$

Where RPLCFA (g/d) is the de novo production of LCFA, LCFASYN is the de novo production of specific LCFA per gram of FTCHO, FTCHO (g/d) is fermentable carbohydrate in feeds, LCFAUP is the adjustment factor for the uptake of RFLCFA by microbial cells, RFLCFA (g/d) is the amount of rumen free LCFA and DMI (kg/d) is dry matter intake.

The impact of dry matter intake and level of dietary fatty acids is shown in Figure 4. As dry matter intake increases there is more FTCHO (and bacterial growth) so that de novo synthesis increases. However, as the amount of RFLCFA increases, bacteria take up more LCFA and de novo synthesis decreases.

Effects of Fatty acids on Rumen Digestion

While we can predict the level of rumen free LCFA in the rumen, there is insufficient data to model the effect of rumen active fat on rumen digestion and fermentation. We suggest using the advisory of Jenkins (1997), which is based on unsaturation of fatty acids and ration fiber, for the upper limit of rumen active fat.

$$\text{Unprotected fat (\%DM)} = (6*\text{ADF})/\text{UFA or } (4*\text{NDF})/\text{UFA}$$

Where ADF and NDF are expressed as a percentage of ration DM and UFA are unsaturated fatty acids (C18:1 + C18:2 +C18:3) expressed as a percentage of total fatty acids.

Intestinal Digestion of Fatty Acids

Most of the LCFA flowing to the small intestine are in the form of rumen free fatty acids but there are also non-lipolysed fatty acids and fatty acids in bacteria.

n general, there are strong linear relationships between the flow of LCFA to the duodenum and intestinal absorption. However, as shown in Figure 5, diets that contained hydrogenated tallow and whole-intact soybeans had lower digestibilities. It is likely that the intestinal digestibility of duodenal free fatty acids derived from different ingredients is the same but the digestibility of fatty acids that escaped ruminal lipolysis could differ.

We used optimization techniques to derive digestibilities for RFLCFA (including bacterial fatty acids) and six classes of rumen non-lipolysed LCFA: (1) forages, grains, proteins, whole cottonseed, and cracked or ground soybeans and other oil-seeds; (2) tallow, grease, vegetable oils and animal/vegetable blends; (3) hydrogenated tallow, (4) whole-intact soybeans and other whole-intact oil-seeds with the exception of cottonseed; (5) fish meal supplements and (6) calcium salts of fatty acids.

In general, the digestion coefficients (Table 3) for RFLCFA and rumen non-lipolysed LCFA in feeds in category 1 are similar. The digestion coefficients for all of the rumen non-lipolysed fatty acids from feed categories 2 to 5 are less than, and in many cases, substantially less than the corresponding coefficient for RFLCFA. In particular, the digestion coefficients for rumen non-lipolysed C18:0 in categories 2, 3 and 4 are zero. In contrast, Børsting et al. (1992) reported that when cows were fed emulsified vegetable fat protected by means of formaldehyde-casein, the digestion coefficient for C18:0 was 0.92. Thus it seems that the often

reported low digestibility of C18:0 from hydrogenated fat sources may be more likely due to low or inefficient intestinal emulsification than to an ineffective lipase system. The digestion coefficients for the major rumen non-lipolysed fatty acids in the form of calcium salts are substantially greater than the coefficients for RFLCFA. This is consistent with the findings of Enjalbert et al. (1997) and Moller (1988) where the apparent digestibilities of C16:0 and unsaturated C18 fatty acids were elevated in diets containing calcium salts of palm or rapeseed fatty acids.

Model Validation

Data used to validate the model came from 8 published experiments that reported intakes and flows to the duodenum and feces of the major LCFA (Moate, 2001). Due to the scarcity of published experiments with the requisite in vivo data, there were only two experiments with lactating Holstein*Friesian dairy cows while the remaining experiments involved steers of various ages and breeds. Thus, intakes of LCFA were less (mean, 479 g; range, 72 to 1040) than intakes in the data used to develop the model (mean, 878 g; range, 197 to 1339 g).

From data in Figure 6 and Tables 4 and 5, it is apparent that there is close concordance between measured and predicted flows of total LCFA to the duodenum (R^2=0.99; bias=5%) and measured and predicted absorption of total LCFA from the intestine (R^2=0.98; bias<1%).

Data in Table 4 show that there was a high correlation (R^2>0.91) between measured and predicted flows of C16:0, C18:0, C18:1t, C18:1c, C18:2, C18:3 and COther to the duodenum. The predicted bias was 13% or less. The low correlation (R^2=0.61) and high bias (75%) between measured and predicted flows of C16:1 probably reflects the low flow (mean flow=2 g/d) of C16:1.

Data in Table 5 show that there was a high correlation (R^2>0.86) between measured and predicted absorption of C12:0, C14:0, C16:0, C18:0, C18:1t, C18:1c, and C18:2. The predicted bias was12% of less for C12:0, C14:0, C16:0 and C18:0 and C18:2. For C18:t and C18:1c, the bias was about 20%. Absorption of C16:1, C18:3 and COther was predicted poorly. However, only small amounts (2 to 3 g/d) of C16:1 and C18:3 were absorbed and COther is a "mixed bag" of LCFA not always reported in all experiments.

Application of the Model

To demonstrate the application of the model, we fed a 650 kg cow 25 kg of a diet that contained (DM basis) 26% alfalfa silage, 26% corn silage, 22% steam-flaked corn, 14% soybean meal, 2% blood meal and 10% mineral mix/fatty acid supplement. 400 g of LCFA were provided by adjusting the proportions of mineral mix and fatty acid supplement (Table 6).

Total long chain fatty acids. The basal diet provided 500 g LCFA (2% DM basis). 400 g of each fatty acid supplement raised dietary LCFA to 3.6%.

De novo production of LCFA only occurred on the basal diet because the fatty acid supplements provide no or little fermentable carbohydrate for microbial growth. When fatty acid supplements are added to rations, bacterial cells will take some of the RFLCFA up with a concomitant decrease in de novo production.

Intestinal digestibility of Megalac and Megalac R is higher than the basal diet because rumen non-lipolysed fatty acids in the form of calcium salts have higher intestinal digestibilities than rumen non-lipolysed fatty acids in the form of glycerides.

C18:0. With the exception of Energy Booster, intakes of C18:0 are low but substantial amounts of C18:0 reach the small intestine. This reflects the intense biohydrogenation of C18:unsaturated free fatty acids in the rumen.

C18:1t. As noted before, C18:1t may not directly inhibit mammary synthesis of fat but it is associated decreased milk fat synthesis. There is little C18:1t in feeds but because of biohydrogenation of C18:3 and C18:2 to C18:1t and incomplete biohydrogenation of C18:1t to C18:0, C18:1t can accumulate in the rumen. The amounts of C18:1t absorbed from Megalac, Megalac R, Energy Booster and tallow are small. Feeding 400 g of LCFA in the form of whole cottonseed and roasted soybeans doubled the amount of C18:t absorbed.

C18:2. As noted before, C18:2 appears to have an energy independent effect on improving reproduction in the dairy cow. The basal ration in Table 6 contained 225 g C18:2, but because of extensive biohydrogenation in the rumen, only 58 g reached the duodenum with 48 g absorbed. On an energy basis, the basal ration would support production of 40 kg milk with 3.7% fat. Cow's milk contains approximately 2 to 6% of the fatty acid content as C18:2 (Sanchez and Block, 2001) so our example cow would secret 30 to 89 g C18:2 in milk. It is thus possible that today's high producing cows may be deficient in this essential fatty acid. To increase amounts absorbed, C18:2 must either be in a form that protects it from ruminal lipolysis (Megalac R) or the feed ingredient must contain high amounts of C18:2 (soybeans). With an ingredient like soybeans, however, there is also an increase in absorbed C18:1t which might lower milk fat test.

C18:3. Feeds contain C18:3 but little reaches the intestine because of rapid biohydrogenation in the rumen. As with C18:2, dietary C18:3 must either be in a form that protects it from lipolysis or large amounts must be fed to increase absorbed amounts.

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Figure 1. Relationship between ether extract and total fatty acids.

Figure 2. Effect of level of rumen-free long chain fatty acids on the rate of biohydrogenation.

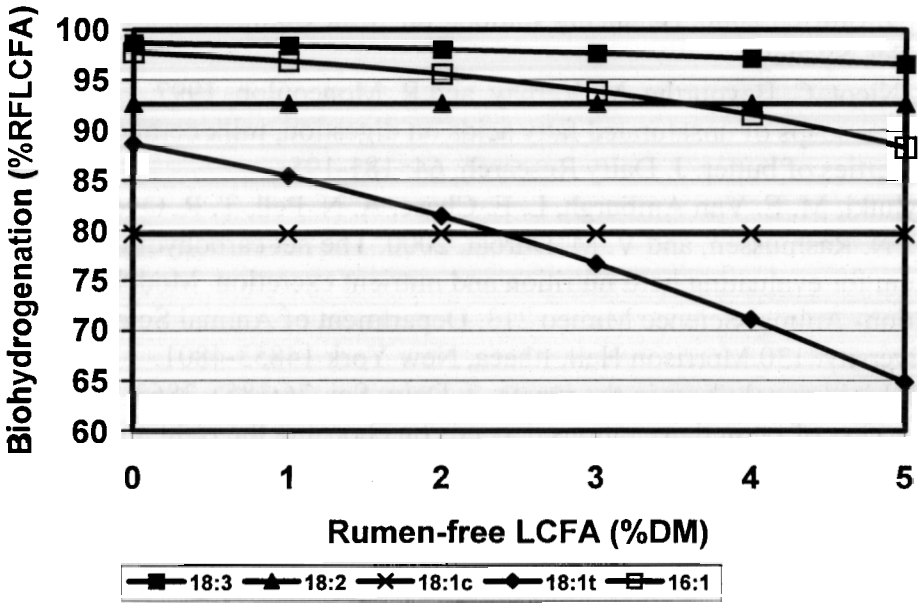

Figure 3. Effect of level of rumen-free long chain fatty acids on the extent of biohydrogenation [(Kb/(Kb+Kp))*100 where Kb is from Figure 2 and Kp = 7 %/h].
The extent of rumen escape is [100 – biohydrogenation].

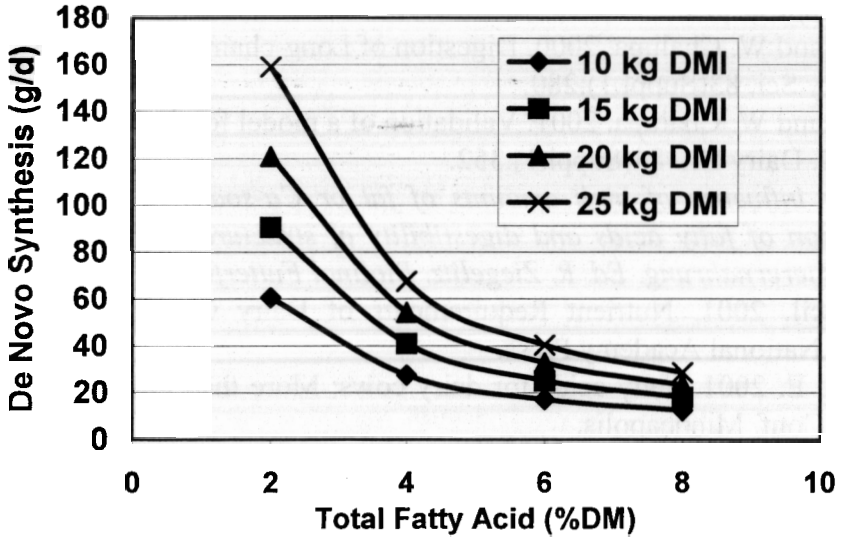

Figure 4. Effect of level of dietary fatty acids and dry matter intake on predicted de novo production of total LCFA. The diet contained (DM basis) 26%alfalfa silage, 26% corn silage, 22% steam-flaked corn, 14% soybean meal, 2% blood meal and 10% mineral mix /fatty acid supplement. The dietary concentration of total LCFA was varied by adjusting the proportions of mineral mix and fatty acid supplement.

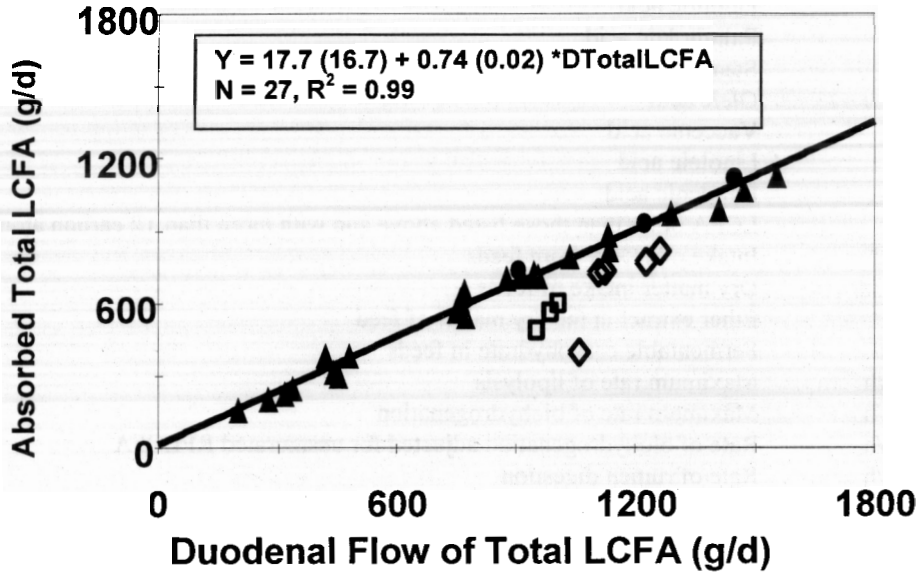

Figure 5. Relationship between duodenal flow and absorbed total LCFA. Different symbols represent different diet types: most diets (solid triangles) contained corn silage, corn and a protein source; diets (dot) contained Megalac. Diets containing hydrogenated fat (hollow diamonds) or intact soybeans (hollow squares) were excluded from the regressions.

Figure 6. Measured and predicted duodenal and absorbed total long chain fatty acids.

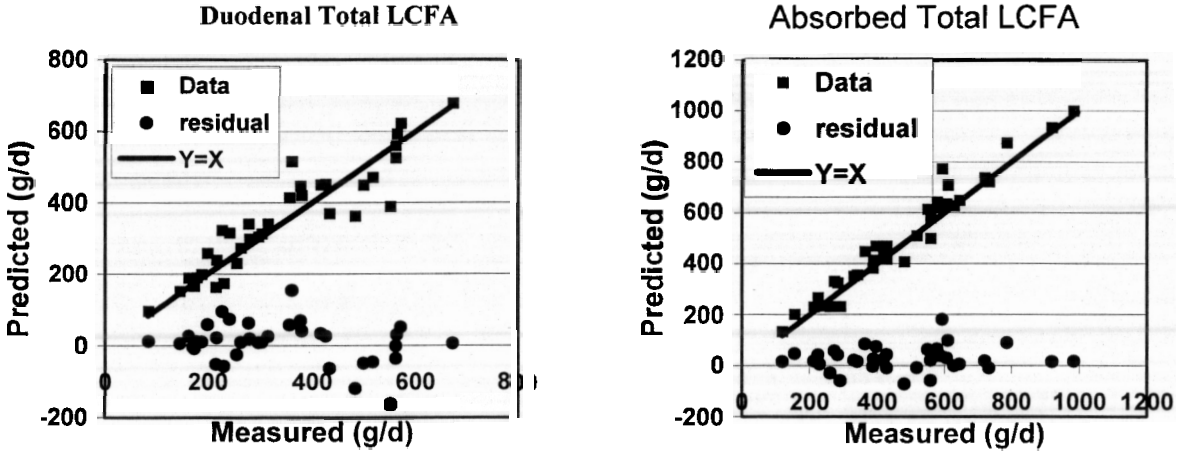

Table 1. Acronyms, their units and definitions used in the fat sub-model

Acronym	Unit	Definition
B	decimal[1]	adjustment factor for the effect of RFLCFA on biohydrogenation
BHLCFA	g/d	Amount of specific LCFA produced by biohydrogenation
C12:0		Lauric acid
C14:0		Myristic acid
C16:0		Palmitic acid
C16:1		Palmitoleic acid
C18:0		Stearic acid
C18:1c		Oleic acid
C18:1t		Vaccenic acid
C18:2		Linoleic acid
C18:3		Linolenic acid
COther		LCFA other than those listed above and with more than 12 carbon atoms.
DIETLCFA	g/d	Intake of LCFA from feeds
DMI	kg/d	Dry matter intake of feeds
EE	%	Ether extract in the dry matter of feed
FTCHO	g/d	Fermentable carbohydrate in feeds
K	%/h	Maximum rate of lipolysis
Kb	%/h	Maximum rate of biohydrogenation
KbRFLCFA	%/h	Rate of biohydrogenation adjusted for unsaturated RFLCFA
Kd	%/h	Rate of rumen digestion
Klip	%/h	Rate of lipolysis of adjusted for LCFA in feeds
Kp	%/h	Rate of passage rate feeds
L	decimal[1]	Adjustment factor for the affect of DIETLCFA on lipolysis
LCFA	g/d	Long chain fatty acid
$LCFA\%_j$	%	Percentage of the total diet that is LCFA
LCFASYN	g/d	De novo production of specific LCFA per gram of FTCHO
LCFAUP	g/d	Adjustment factor for the uptake of RFLCFA by microbial cells
RD	decimal1	Rumen digestibility of feeds
RFLCFA	g/d	Free fatty acids that are produced by lipolysis in the rumen
RNLCFA	g/d	Fatty acids that were not lipolysed in the rumen
RPLCFA	g/d	De novo production of LCFA in the rumen

Feed	Expts[1]	Diets[2]	K[3]	L[4]	Klip[5]	Lipolysis(%) [6]
Corn silage	6	28	500	0	500	99
Alfalfa silage	3	16	500	0	500	99
Alfalfa haylage	3	12	479	0	479	99
Alfalfa hay	1	5	65	0	65	93
Pasture hay	1	5	9	0	9	64
Orchardgrass hay	1	3	3	0	3	38
Corn	1	3	35	0	35	83
Corn (ground)	6	26	309	0	309	98
Barley	1	5	29	0	29	81
Soy hulls	1	4	17	0	17	77
Cottonseed (whole)	1	2	500	0	500	99
Rapeseed (crushed)	1	2	500	0	500	99
Soybean meal	4	19	500	0	500	99
Soybean (extruded)	2	2	29	0	29	81
Soy plus	2	8	15	0	15	68
Soybean (whole-intact, raw)	1	1	9	0	9	56
Soybean (whole-intact, roasted)	1	1	16	0	16	70
Soybean (cracked, roasted)	1	1	26	0	26	79
Soybean (ground, roasted)	1	1	35	0	35	83
Fish meal	1	2	23	0	23	77
Sunflower oil	1	2	52	0	52	88
Tallow	1	1	500	0.37	79-500[7]	92 - 99[7]
Animal Vegetable	2	6	392	0	392	98
Hydrogenated fat	1	1	18	0	18	77
Megalac	3	5	6	0	6	47

1. Number of experiments in data set with this feed
2. Number of diets in data set with this feed
3. K is the lipolysis rate (%/h) without correction for the effects of level of fatty acid from the ingredient
4. L is the constant that describes the effect of level of fatty acid from the ingredient on K
5. Klip (%/h) = K * Exp (-L * TLCFA%) where TLCFA% is the % of the total diet that is LCFA from the feed ingredient
6. Klip/(Klip + Kp) assuming Kp = 7%/h for concentrates and 5%/h for forages
7. Tallow fatty acids at 0.1 to 5.0% of dry matter intake

Table 3. Optimized digestion coefficients for rumen free LCFA (RFLCFA) and non-lipolysed LCFA

		Category of non-lipolysed LCFA					
		1	2	3	4	5	6
LCFA	RFLCFA	Feeds[1]	Fats[2]	Hydrogenated Tallow	Whole-intact oil-seeds[3]	Fish Meal	Megalac
C12:0	0.95	0.95	0.95	0	0	0.82	0.95
C14:0	0.75	0.45	0.47	0	0	0.40	0.78
C16:0	0.72	0.72	0.73	0	0.18	0.73	0.83
C16:1	0.64	0.64	0.64	0	0	0.60	0.95
C18:0	0.73	0.73	0	0	0	0.73	1.00
C18 :1c	0.89	0.67	0.67	0.56	0.16	0.67	0.89
C18 :1t	0.78	0	0.79	0.40	0	0	0.79
C18:2	0.83	0.78	0.83	0	0.61	0.83	1.00
C18:3	0.77	0.78	0.54	0.10	0.19	0.65	0.86
Cother	0.58	0.59	0	0	0.59	0.59	1.00

1. Non-lipolysed LCFA from forages, grains, proteins, whole cottonseed, and cracked or ground soybeans and other oil-seeds
2. Non-lipolysed LCFA from tallow, grease, vegetable oils and animal/vegetable blends
3. Non-lipolysed LCFA from whole-intact soybeans and other whole-intact oil-seeds with the exception of cottonseed

Table 4. Measured vs predicted flows of LCFA to the duodenum

LCFA	n	Mean	STD	Intercept	Coefficient	R^2	Bias(%)
Total	36	477	206	0[1]	1.05	0.99	5
C12:0		**Flow statistics not calculated because some**					
C14:0		C12:0 and C14:0 are absorbed from the rumen					
C16:0	36	97	55	0[1]	1.04	0.99	5
C16:1	16	2	1	1.8	0.86	0.61	75
C18:0	36	237	116	37.6	0.93	0.96	9
C18:1trans	8	23	14	0[1]	1.07	0.94	7
C18:1cis	8	35	14	0[1]	0.87	0.92	-13
C18:2	36	27	25	0[1]	0.91	0.95	-9
C18:3	36	5	7	0[1]	1.01	0.91	2
COther	27	36	11	0[1]	0.99	0.96	-1

1. Intercept in original regression was not significantly (P>.05) different from 0 so the subsequent regression was forced through 0

Table 5. Measured vs predicted absorption of LCFA from the intestine

LCFA	n	Mean	STD	Intercept	Coefficient	R^2	Bias (%)
Total	36	338	147	0[1]	1.00	0.98	<1
C12:0	20	4	8	0.49	0.99	0.99	10
C14:0	15	7	4	0[1]	0.89	0.98	-7
C16:0	36	71	44	0[1]	1.02	0.97	2
C16:1	16	2	1	1.3	0.78	0.43	62
C18:0	36	167	83	38.3	0.87	0.86	10
C18:1trans	8	15	8	0[1]	1.13	0.93	20
C18:1cis	8	25	6	0[1]	0.86	0.92	-22
C18:2	34	20	18	0[1]	0.89	0.91	-12
C18:3	31	3	4	1.14	0.48	0.46	-18
COther	27	24	10	14.7	0.33	0.16	-7

1. Intercept in original regression was not significantly (P>.05) different from 0 so the subsequent regression was forced through 0

Table 6. Intestinal flows and absorption of LCFA (g/d) predicted by the CPM-Dairy lipid sub-model[1]

Measurement	Basal	Megalac	Megalac R	Energy Booster	WCS	RSB	Tallow
Fat Supplement (g)	0	474	474	404	2395	2222	460
Klip (%/h)		6	6	500	500	37	277
Non-lipolysed LCFA (%Intake)		54	54	0	1	16	2
Total long chain fatty acids							
Intake	500	400	400	400	400	400	400
Duodenum	646	400	400	400	404	404	400
De novo production	**146**	**0**	**0**	**0**	**4**	**4**	**0**
Absorbed	**468**	**327**	**337**	**291**	**300**	**298**	**293**
Intestinal Digestion (%)	72	82	84	73	74	74	73
C18:0							
Intake	**16**	**16**	**14**	**163**	**10**	**4**	**72**
Duodenum	**339**	**73**	**104**	**201**	**291**	**210**	**212**
Absorbed	248	56	78	146	211	153	153
C18:1trans							
Intake	0.1	0.00	0.00	1.6	0.0	0.0	5.2
Duodenum	28.0	2.3	11.0	1.9	30.3	39.7	5.6
Absorbed	22.0	1.8	9.1	1.5	23.8	31.2	4.4
C18:2							
Intake	225	28	127	7.2	157	230	18.8
Duodenum	51	17	77	0.7	12	54	2.2
Absorbed	41	17	76	0.6	10	43	1.8
C18:3							
Intake	23.9	0.8	18.8	0.0	34.0	13.2	1.6
Duodenum	1.0	0.5	10.9	0.0	1.0	2.5	0.1
Absorbed	0.8	0.4	9.3	0.0	0.8	1.9	0.1

1. 25 kg of a diet containing (DM basis) 26% alfalfa silage, 26% corn silage, 22% steam-flaked corn, 14% soybean meal, 2% blood meal and 10% mineral mix/fatty acid supplement. 400 g of fatty acids was provided by adjusting the proportions of mineral mix and fatty acid supplement.