Milk Production, Reproductive Performance, and Fecal Excretion of Phosphorus by Dairy Cows Fed Three Amounts of Phosphorus[1]

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ABSTRACT

Milk production was measured and phosphorus (P) excretion in feces was estimated in dairy cows fed three amounts of P. A basal diet was formulated to contain 0.31% P (DM basis). Sodium monophosphate replaced corn in the basal diet to give two additional diets containing 0.40 and 0.49% P. The diets were fed to eight, nine, and nine multiparous Holsteins from the beginning to the end of lactation. Milk yields for the 308-d lactation were 10,790, 11,226, and 11,134 kg for the three treatments, respectively. The lowest milk yield resulted from decreased milk production during late lactation with the 0.31% P group. Reproductive performance of the cows was not related to dietary P content. Fecal P concentration, determined in wk 2, 4, 6, 8, 23, and 40 of lactation, increased as dietary P intake was increased. Cows fed the lowest P diet conserved P by minimizing P excretion in feces and urine, whereas cows in the other two treatments excreted more P through these routes. A reduction in dietary P from 0.49 to 0.40% reduced fecal P excretion by 23%. Apparent P digestibilities of less than 40% are indicative of surplus dietary P. Feeding 0.40% P appeared sufficient to maintain P balance and the level of milk production achieved in this experiment. An example is given which illustrates the relationship between dietary and fecal P.
(**Key words:** phosphorus requirement, minerals, dairy cows, reproduction)

INTRODUCTION

The most obvious way to reduce environmental threat from P in dairy manure is to eliminate excess P in dairy diets, thus reducing P content of manure. The NRC (29) recommends that dairy diets contain at least 0.48% P during early lactation (wk 1 to 3), 0.41% for cows milking 40 kg/d, and 0.37% for cows milking 30 kg/d. These amounts are about 10% higher than the previous NRC (28) recommendations because the assumed availability of P for uptake from the gut was lowered from 55 to 50% in the more recent NRC guidelines. Fearing that reproductive performance may suffer if P intake is low, producers tend to feed their cows even more P than recommended by the NRC, even though available literature does not support this conclusion (3, 4, 5, 6, 13, 38, 42). A survey of dairy nutritionists in the Mid-South region of the United States indicated that P was fed at about 30% above NRC guidelines (34). We conducted a telephone survey of dairy nutritionists in the United States, and the amount of P recommended by this group of nutritionists averaged 0.48% of dietary DM. It is common to see values ranging between 0.5 to 0.6% P (19, 22). Large amounts of supplemental P are required to achieve these levels because unsupplemented dairy diets typically contain between 0.33 to 0.40% P.

Recent research suggests that dietary P can be reduced from the high levels presently used to significantly lower levels without reducing animal performance. Dhiman et al. (14) reported no difference in milk yield when 0.39 or 0.65% dietary P was fed for 12 wk. Wu and Satter (42) compared an unsupplemented diet and a supplemented diet, containing 0.38 or 0.48% P over two lactations, and found no difference in milk yield or reproductive performance. These and other studies (3, 4, 13, 38, 40) have demonstrated that dietary P between 0.33 and 0.39% appear adequate for moderate to high producing cows.

Milk yield over short periods may not be a good indicator of P status due to mobilization of P from bone. Information about balance of P over a long time frame is needed to evaluate whether a given P intake is sufficient to meet requirements. When measuring P balance, however, it is important to understand that a short-term negative balance is not detrimental if corrected later in lactation (21). Loss of bone P is a normal occurrence due to mobilization of Ca in early lactation. Phosphorus from mobilized bone in early lactation should be counted as an available P source for milk

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[1]Trade names and the names of commercial companies are used in this report to provide specific information. Mention of a trade name or manufacturer does not constitute a guarantee or warranty of the product by the USDA or an endorsement over products not mentioned.

Table 1. Ingredients and nutrient content of diets (DM basis).

	Dietary phosphorus content (%)		
Item	0.31	0.40	0.49
Ingredient, %			
Alfalfa silage	30.0	30.0	30.0
Corn silage	20.0	20.0	20.0
High moisture ear corn	25.5	25.5	25.5
Soybeans, roasted	10.0	10.0	10.0
Blood meal	2.0	2.0	2.0
Molasses	5.0	5.0	5.0
Beet pulp	7.0	6.58	6.16
Salt[1]	0.4	0.4	0.4
Mineral and vitamin mix[2]	0.1	0.1	0.1
Monosodium phosphate[1]	. . .	0.42	0.84
Chemical composition			
CP, %	17.8	17.8	17.8
ADF, %	23.8	23.7	23.6
NDF, %	31.4	31.2	31.0
Ca, %[3]	0.65	0.65	0.65
P, %	0.31	0.40	0.49
NE_L, Mcal/kg[3]	1.65	1.65	1.65

[1]Added Na from NaCl and NaH_2PO_4 accounted for 0.16, 0.24, and 0.32% of the total diet DM for the 0.31, 0.40, and 0.49% P diets, respectively.

[2]Each kilogram of the mix contained 0.32 g of Se, 0.43 g of Co, 1.03 g of I, 13.35 g of Cu, 23.99 g of Fe, 51.00 g of Mn, 62.01 g of Zn, 7,000,000 IU of vitamin A, 2,222,000 IU of vitamin D, and 17,630 IU of vitamin E.

[3]Estimated using tabular values in NRC (29).

production. Thus, P status or adequacy needs to be evaluated over a long time frame. The objective of this study was to determine milk production and to obtain an estimate of P balance during a complete lactation in dairy cows fed different amounts of P.

MATERIALS AND METHODS

Twenty-six multiparous Holstein cows were used in a 308-d lactation trial approved by the Animal Care Committee of the College of Agricultural and Life Sciences, University of Wisconsin-Madison. Diets (Table 1) containing 0.31, 0.40, or 0.49% P (DM basis) were assigned to groups of eight, nine, and nine cows at parturition. Cows were balanced for mature equivalent milk yield from the previous lactation. Molasses and beet pulp were included as diet ingredients because of their low P content, and this enabled formulation of a basal diet containing 0.31% P. Treatment diets containing 0.40 and 0.49% P were obtained by adding monosodium phosphate to the basal diet.

Cows were housed in a tie-stall barn and offered a TMR once daily ad libitum (5 to 10% refusal). Actual amounts of feed offered and refused by individual animals were recorded daily to obtain net feed intake. Milking was at 0500 and 1700 h; milk yields were recorded at each milking. Cows were weighed after milking and scored for body condition early in lactation (DIM 17, SD 23) and again at the end of lactation. All cows were administered bST (Posilac; Monsanto Co., St. Louis, MO) every 2 wk beginning at wk 9 of lactation. Data related to reproduction and health were recorded.

Cows were dried off or removed from the experiment following completion of 44 wk of lactation. As a normal herd management practice, cows on occasion were dried off earlier than 44 wk to assure an 8-wk dry period before the next lactation or were removed from the experiment when they developed serious health problems. Consequently, one cow was removed from the experiment in wk 23 and 10 cows were removed during wk 38 to 44 of lactation (Table 2). To obtain 308-d lactation performance of these cows, milk yield for the missing weeks was estimated by extrapolation of the last five measures with linear regression.

Milk samples were collected biweekly from two consecutive milkings and analyzed by the AgSource Milk Analysis Laboratory (Menomonie, WI) for fat, protein, lactose, total solids, and SCC using an infrared spectrophotometer with a B filter (Fossmatic 605; Foss Technology, Eden Prairie, MN); SNF was calculated as total solids minus fat.

Alfalfa silage and corn silage were sampled daily and kept frozen to generate weekly composites. High moisture ear corn, molasses, beet pulp, blood meal, and roasted soybeans were sampled weekly. Feed refusals were sampled from individual animals but pooled by treatments on a weekly basis. All weekly samples were measured for DM by oven-drying at 60°C for 48 h. Diet formulations (as-fed) were adjusted weekly for changes in DM content of the ingredients. Dried samples were ground through a Wiley mill using a 1-mm screen (Arthur H. Thomas, Philadelphia, PA). After grinding, grain samples (high moisture ear corn, molasses, beet pulp, blood meal, and roasted soybeans) were further pooled to generate composite samples every 4 wk.

Weekly samples of the ground forage sources (corn silage and alfalfa silage) and feed refusals and the monthly samples of the grain sources were analyzed for DM (105°C), CP (LECO FP-2000 Nitrogen Analyzer, Leco Instruments, Inc., St. Joseph, MI), and NDF (heat stable α-amylase and Na_2SO_3 were used) and ADF (32); however, blood meal was not analyzed for NDF or ADF, and analysis of these fiber components in roasted soybeans were made on only one composite sample. For P analyses, 4-wk composites of forage and feed refusals and 12-wk composites of grain samples were used. These composites were processed as described by Nelson and Satter (30) and analyzed for P content using direct current plasma emission spectroscopy by adapting the procedure described by Combs and Satter (10). A certified commercial P solution (VHG Labs, Inc., Manchester, NH) was used as the calibration standard. Ac-

Table 2. Number of cows that left the experiment before completing 44 wk of lactation.

	Week of lactation							
Treatment	23	38	40	41	42	43	44	Total
0.31% P	1 (m)[1]	...	1 (d)	1 (d)	2 (d, f)	...	...	5
0.40% P	...	...	...	...	...	1 (d)	1 (d)	2
0.49% P	...	1 (f)	1 (d)	...	1 (d)	...	1 (d)	4

[1]Reason for termination: m = mastitis; d = dried off to allow for an 8-wk dry period; and f = foot rot.

curacy of the analysis was assured by referring to commercial standards (Standard Reference Material 1570a, spinach leaves, and 8436, durum wheat flour; National Institute of Standards and Technology, Gaithersburg, MD) and by interlaboratory comparison of reference samples that resulted in differences <5%. Chemical analyses were expressed on a DM basis (105°C). Dietary nutrient content was computed from analysis of the individual diet ingredients; however, content of Ca and NE_L was calculated with values for ingredients from the NRC (29).

Phosphorus balance was determined in the following 6 periods: wk 2, 4, 6, 8, 23 (22 to 24), and 40 (39 to 41) of lactation. The marker technique with Yb was employed to determine apparent digestibility of DM and P. To prepare the marker, 230.2 g of Yb_2O_3 (99% purity) (Rhodia Inc., Shelton, CT) were added to a mixture of 220 ml of water and 160 ml of concentrated hydrochloric acid. An additional 160 ml of concentrated hydrochloric acid was added, followed by mixing with heat until the solution was clear. A final solution was obtained by diluting to 5 L with water to result in a Yb concentration of 40,000 mg/L. This solution was sprayed onto beet pulp at a ratio of 1:9 (vol/wt). The marked beet pulp then was mixed into the TMR at a level of 1% (DM basis). Thus, the resultant concentration of Yb in the TMR was 40 mg/kg of DM. Samples of TMR were analyzed for Yb concentrations, showing an average of 10% lower than the calculated concentration. Considering the difficulties in preparing a uniformly marked TMR and in taking a representative sample of TMR, the calculated concentration (40 ppm) was used for estimating apparent digestibilities.

Ytterbium marker was present in the TMR continuously for the first 60 d of lactation, then for 14 d each during wk 22 to 24 and wk 39 to 41. Feces were sampled from the rectum at 0930 to 1100 and 1400 to 1530 daily for 4 d in wk 2, 4, 6, and 8, and during the last 4 d of the 14 d period when Yb was present for wk 22 to 23 and wk 39 to 41. Fecal samples were pooled across sampling times within periods for individual cows and dried at 60°C. During fecal collection, milk was sampled from two consecutive a.m. and p.m. milkings to generate a composite. A spot sample of urine also was taken.

All samples of feces, milk, and urine were analyzed for P by the same method used for feed analysis. Fecal samples also were analyzed for Yb concentration (10). From the concentration of P in milk and the average milk yield during the collection week, the amount of P secreted in milk per day was calculated. The amount of urinary P excreted was calculated from urinary P concentration multiplied by an estimated urine volume of 40 L/d, an average obtained from a separate study using the same herd and similar diets. This estimated volume was used for all the balance periods. Errors associated with the estimation would be small because of the very low concentrations of P in urine. Balance of P was calculated as the difference between P consumed and excreted or secreted in feces, urine, and milk. When the concentration of P in urine was so low that <1 g/d of urinary P resulted, 1 g/d was used in the calculation; when the amount exceeded 1 g/d, the calculated amount was used.

Blood samples were taken daily from 2 d prepartum to 5 d postpartum, once during each of the six balance periods, and periodically during early to mid lactation (DIM 91 to 117), late lactation (DIM 265 to 291), and once during the dry period. All samples (10 ml) were taken approximately 3 h after feeding from coccygeal vessels, centrifuged at $2200 \times g$ for 15 min, and analyzed for serum inorganic P and Ca concentrations by the Marshfield Laboratories (Marshfield, WI) using the molybdovanadate colorimetric procedure for P and the Lanthanum procedure for Ca (1).

Daily milk yield, milk component percentages and yields, and DMI were reduced to monthly (4 wk) means. These means and the data on blood serum P and Ca concentrations were analyzed as repeated measures in time for effects of treatment and treatment × month interaction by the mixed procedure of SAS (35); time was considered as the subplot. Other data were analyzed by the general linear models procedure of SAS (36) according to a completely randomized design. These data include 308-d milk yield, BW, BCS, reproductive measures, and those related to P balance. For both types of analysis treatment effects were tested for linear and quadratic relationships. Pooled SEM is presented for simplicity. Significance of differences was based on $P < 0.1$, unless otherwise indicated.

RESULTS AND DISCUSSION

Diet ingredients were consistent in their nutrient content during the experiment (Table 3). Dietary content of ADF and NDF was elevated some because of inclusion of beet pulp (Table 1), but fiber in beet pulp is readily fermentable. The diets contained 0.31, 0.40, and 0.49% P averaged over the lactation. Calculated Ca content was the same for all three diets. Feed refusals were higher in NDF and ADF than their corresponding diets (Table 3), most likely reflecting some animal sorting of feed ingredients. Phosphorus content of feed refusals was similar, however, to that of diets, with values of 0.33, 0.41, and 0.47%. No correction was made for differences between diets and feed refusals in P content in calculating P intake from DMI and dietary P percentages.

Days to first estrus and first AI were shorter ($P < 0.05$) for the 0.31 and 0.49% P groups than for the 0.40% P group (Table 4). Days open appeared to be shorter and more cows became pregnant at the first AI for the 0.31% P group. All cows conceived by 206 DIM, except one in each of the 0.40 and 0.49% P groups. More services ($P = 0.10$) were required per conception as dietary P was increased. Although the number of animals used in this experiment is too small to draw reliable conclusions about reproduction (42), the data do suggest that reproductive performance does not have to suffer when dietary P is reduced to 0.31%. In the literature, except for some early work that linked infertility to severe P deficiency, studies conducted in the last 30 yr relating reproductive performance to dietary P content (3, 4, 5, 6, 13, 38, 42) reveal no difference in reproductive performance when low (0.32 to 0.40% across trials) or high (0.39 to 0.55%) concentrations of dietary P are compared. These studies, along with the present study, involved a total of 785 cows and resulted in the following measures of reproductive performance for the low and high P groups, respectively: days to first estrus: 46 and 48 (SE 4.2); days to first AI: 73 and 76 (SE 3.3); days open: 96 and 100 (SE 4.9); services per conception: 1.8 and 1.9 (SE 0.2); and pregnancy rate: 0.87 and 0.86 (SE 0.02). The work conducted by Steevens et al. (38) is the only one that reported a higher rate of services per conception when a low P (0.40% P) diet was fed compared with high P diets (0.53 and 0.56% P). Some trials did not report reproductive measures, thus only part of the cows contributed to some of these measures.

More cases of foot rot were observed in cows fed the 0.31% P diet than those fed the other diets (Table 4). There was no apparent correlation between stage of lactation and the incidence of foot rot. In a previous study comparing 0.38 and 0.48% dietary P for 2 yr (42), fewer cases of foot rot were recorded for the low P group.

The DMI was very similar between treatments despite a small quadratic effect of dietary P concentration ($P < 0.01$, Table 5). Milk yield for the total lactation was not different. Overall, all groups of cows milked well, averaging 11,050 kg for the 308-d lactation. The lactation curves were unusually flat for approximately 20 wk after peaking (Figure 1), reflecting the use of bST. The interaction of treatment by lactation month was significant ($P < 0.01$), reflecting the decreased milk yield for the low P group beginning around wk 25. On average, milk production was 3.3 kg/d less for the 0.31% P group than for the other two groups during this latter part of lactation. The content of most milk components did not differ ($P > 0.10$) among treatments despite some interactions ($P < 0.01$, Table 5). No differences between treatment groups were observed for BW gain or BCS.

The above results indicate that feeding 0.40 or 0.49% P throughout the lactation did not affect feed intake, milk production, or body condition of cows; reducing dietary P to 0.31% supported comparable milk produc-

Table 3. Analyses of dietary ingredients and refusals.

Ingredient	DM	CP	NDF	ADF	P
	(%)				
Alfalfa silage					
$\bar{x}$	36.8	21.9	43.1	38.8	0.333
SD	6.4	1.9	3.9	3.4	0.021
Corn silage					
$\bar{x}$	29.9	8.4	40.7	26.4	0.225
SD	2.5	0.8	3.6	2.4	0.016
High moisture ear corn					
$\bar{x}$	69.1	9.3	13.6	5.5	0.316
SD	2.0	0.4	3.0	1.6	0.017
Soybeans, roasted					
$\bar{x}$	95.7	41.4	24.8	8.2	0.693
SD	2.7	1.0	. . .	. . .	0.041
Molasses					
$\bar{x}$	97.5	8.5	28.9	23.3	0.110
SD	1.5	0.3	1.0	1.0	0.009
Beet pulp					
$\bar{x}$	92.1	8.5	41.4	25.2	0.083
SD	0.4	0.1	0.4	1.5	0.004
Blood meal					
$\bar{x}$	92.1	102.0	. . .	. . .	0.207
SD	1.1	3.5	. . .	. . .	0.059
Diet refusals					
0.31% P					
$\bar{x}$	43.1	16.7	39.0	29.6	0.331
SD	4.7	1.3	4.3	4.3	0.075
0.40% P					
$\bar{x}$	42.3	17.3	37.9	28.9	0.409
SD	4.4	1.3	3.8	3.7	0.033
0.49% P					
$\bar{x}$	42.0	16.6	38.7	29.6	0.473
SD	3.9	1.1	3.9	3.4	0.111

Table 4. Reproductive measures and health records of lactating cows fed diets differing in P content.

	Treatment				*P*	
Item	0.31% P	0.40% P	0.49% P	SEM	Linear	Quadratic
Number of cows	8	9	9	...	...	...
Days to first estrus	40.6	77.6	43.6	11.4	0.86	0.02
Days to first AI	69.5	91.7	66.8	7.7	0.81	0.02
Days open[1]	78	106	112	15	0.12	0.57
Cows conceived at first AI	7	4	3	...	...	...
Cows conceived						
Before 120 DIM	7	6	3	...	...	...
Before 206 DIM	8	8	8		...	...
Services per conception[1]	1.4	1.6	2.3	0.4	0.10	0.67
Abortion	1	0	0	...	...	...
Incidence of foot rot	4	0	1	...	...	...
Incidence of off feed	0	2	0	...	...	...
Mastitis incidence	8	4	4	...	...	...

[1]Includes only the cows that became pregnant before 206 DIM.

tion during approximately the first two-thirds of lactation, but resulted in decreased milk yield during the last one-third of lactation. Other studies have compared dietary P of 0.33 and 0.39% (3), 0.34, 0.51, and 0.69% (13), 0.37 and 0.55% (38), 0.35 and 0.44% (4), 0.39 and 0.65% (14), and 0.38 and 0.48% (42) and have shown no effect of dietary P on milk production. However, with cows milking 8700 kg per lactation, Kincaid et al. (23) reported a lower milk yield for cows fed 0.30% P than those fed 0.54% P. Call et al. (5) also reported a reduced milk yield when 0.24% P was fed, as did Valk and Ebek (40). It appears that dietary P should be above 0.30% for low to medium producing cows (7500 to 9000 kg per lactation), but 0.38 to 0.40% P is suggested for high producing cows (>10,000 kg per lactation).

In view of the notion that P content of the diet should be especially high to compensate for low feed intake in early lactation [0.48% dietary P during the first 3 wk as recommended by NRC (29)], it is interesting to note that cows fed the highest P diet appeared to lag behind

Table 5. Performance of cows fed diets differing in P content.

	Treatment				*P*		
Item	0.31% P	0.40% P	0.49% P	SEM	L[1]	Q[1]	T × M[1]
DMI, kg/d	23.0	22.4	23.4	0.2	0.19	0.01	0.01
Milk, kg/308-d	10,790	11,226	11,134	607	0.69	0.72	...
Milk, kg/d	35.0	36.5	36.2	0.7	0.27	0.32	0.01
3.5% FCM, kg/d	36.4	37.5	37.9	0.7	0.17	0.69	0.01
Milk fat							
%	3.66	3.69	3.71	0.05	0.51	0.94	0.99
kg/d	1.333	1.344	1.348	0.028	0.71	0.92	0.01
Milk protein							
%	3.14	3.07	3.11	0.03	0.57	0.16	0.01
kg	1.128	1.099	1.123	0.019	0.86	0.26	0.01
Milk lactose, %	4.89	4.92	4.82	0.03	0.11	0.04	0.20
Milk SNF, %	8.79	8.78	8.71	0.05	0.23	0.58	0.27
Milk SCC, 10^3/ml	320	235	222	64	0.30	0.64	0.21
BW during lactation							
Initial[2], kg	627	626	589	21	0.22	0.49	...
Ending, kg	694	731	681	26	0.73	0.18	...
Change, g/d	283	341	296	102	0.68	0.68	...
BCS[3]							
Initial[2]	3.31	3.50	3.47	0.15	0.46	0.56	...
Ending	3.53	3.94	3.75	0.18	0.42	0.19	...
Change	0.22	0.44	0.28	0.31	0.84	0.44	...

[1]Effect of linear, quadratic, and treatment by month interaction.

[2]Initial measures were taken on an average DIM of 17 (SD 23) for BW and 8 (SD 10) for body condition score.

[3]Body condition score (thin = 1 to fat = 5).

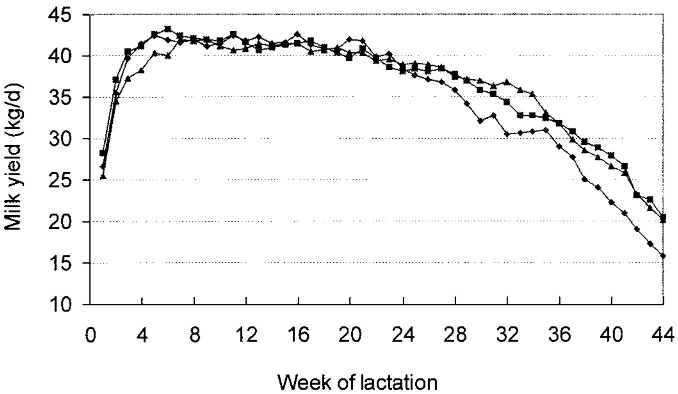

Figure 1. Lactation curves of cows fed diets containing 0.31 (◆), 0.40 (■), or 0.49% P (▲). Means for the respective treatments over the entire lactation were 35.0, 36.5, and 36.2 kg/d (SE 0.7, $P > 0.1$), with a treatment by sampling period interaction ($P < 0.01$).

the other two treatments in milk production during the first 7 wk of lactation (Figure 1). Although milk yield in the first few weeks postpartum is normally unstable, the data at least suggest that feeding an especially high P diet during these weeks is of little or no value. Carstairs et al. (7) also reported lack of response to high dietary P during early lactation. Mobilization of bone P can readily provide 500 to 600 g of P in early lactation and must be credited as an important source of P for milk production during this period. It is likely that a significant portion of the mobilized P is an inevitable consequence of Ca mobilization from bone in early lactation.

The concentration of inorganic P in blood serum was lower ($P < 0.01$) for the 0.31% P group than for the other two groups, particularly during the first 14 d postpartum (Figure 2a). During the sampling periods after d 14, little or no difference in serum P concentration between treatment groups was evident. Other studies (4, 5, 16, 38) have suggested that serum P concentration can reflect P intake. The lowest concentration measured in the present study was slightly below 5 mg/dl, marginally above the level (4 mg/dl) that is considered normal for lactating cows (16). Serum Ca concentrations differed ($P < 0.05$) among treatments during the entire lactation (Figure 2b), but the differences were very small. Serum concentrations of both P and Ca decreased around parturition, reaching their lowest concentrations 1 to 2 d after parturition. While the concentration of P for the two higher P treatments reached prepartum concentrations by d 3, the serum concentration of Ca was still lower than prepartum concentrations by d 5 postpartum, but the concentration reached prepartum concentrations on d 14. This slight difference in the pattern of recovery between the two elements, however, was not observed in the study of Goff and Horst (17).

Blood serum concentrations are not always good indicators of P status (33), and this may be the reason why serum P concentrations appeared similar between treatments during mid to late lactation, even when milk production was less with the 0.31% P treatment.

The concentration of P in urine varied widely among cows, with a few individual animals having concentrations as high as 20 to 50 mg/dl in wk 23 and 40 of lactation. The concentration in other weeks was negligible for all cows. All the high concentrations were from cows in the 0.40 and 0.49% P treatments and that had serum P concentrations above 7 mg/dl (Figure 3a). Challa and Braithwaite (8) suggested that urinary P excretion is not significant until serum P concentration exceeds 6 to 9 mg/dl. The amount of P excreted through urine can be significant when P concentrations in urine are elevated. For example, a concentration of 20 mg/dl would result in 8 g/d of P excretion, assuming a urine volume of 40 L/d. While many sheep (2) and calves (9) will have very complete recovery of P from the distal tubule of the kidney, some individuals will use urinary

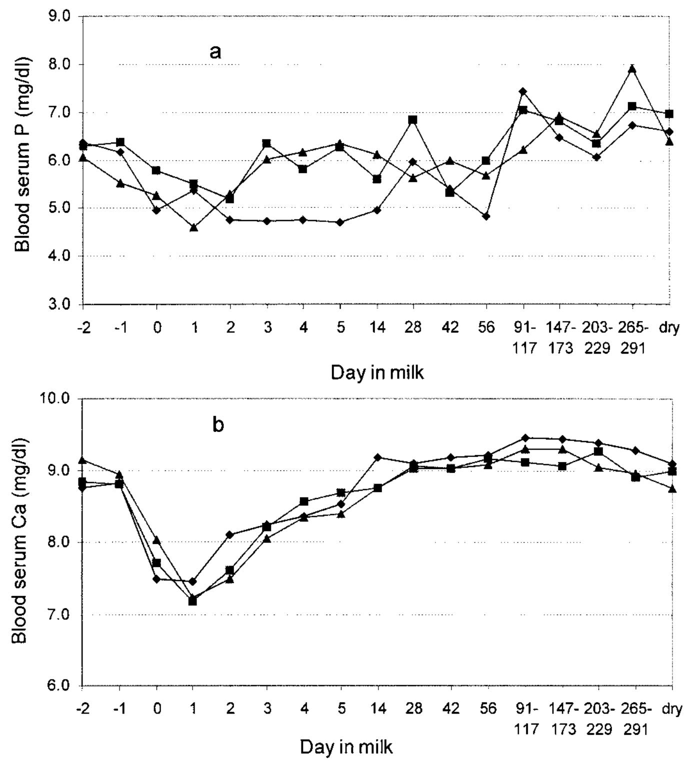

Figure 2. The concentration of inorganic P (a) and Ca (b) in blood serum of cows fed diets containing 0.31 (◆), 0.40 (■), or 0.49% P (▲) for complete lactation. Means for P for the respective treatments during lactation were 5.5, 6.2, and 6.1 mg/dl (SE 0.11, $P < 0.01$) with an effect of treatment by sampling period interaction ($P < 0.01$). Means for Ca for the respective treatments during lactation were 8.8, 8.7, and 8.6 mg/dl (SE 0.06, $P < 0.5$) with an effect of treatment by sampling period interaction ($P < 0.01$).

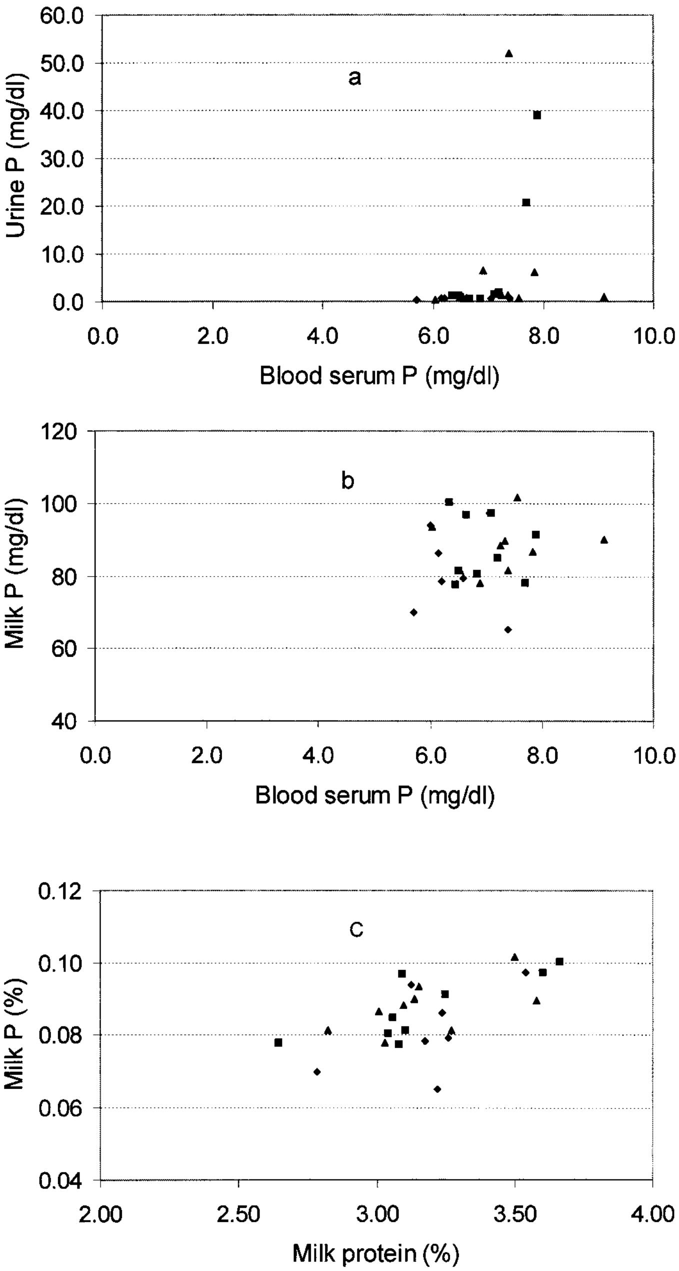

Figure 3. Relationship between the concentration of total P in urine and inorganic P in blood serum (a; Y = 5.91X – 35.4; $r^2 = 0.12$, $P < 0.1$), the concentration of total P in milk and inorganic P in blood serum (b; Y = 1.60X + 74.8; $r^2 = 0.02$, $P > 0.1$), and the concentration of total P in milk and the concentration of protein in milk (c; Y = 0.02X + 0.01; $r^2 = 0.37$, $P < 0.01$) of cows fed diets containing 0.31 (◆), 0.40 (■), or 0.49% P (▲). Values are averages of measurements taken at wk 23 and 40 of lactation.

excretion as a significant route for disposing of surplus P.

The concentration of total P in milk and the concentration of inorganic P in blood serum had no relationship ($r^2 = 0.02$, Figure 3b). Rather, milk P concentration appeared to be related to milk protein concentration ($r^2 = 0.37$, Figure 3c). This is not surprising, because about half of the total P in milk is complexed with casein and the other half exists as diffusible ions (21). It follows that cows with high milk protein content will have a higher dietary requirement for P than cows with lower milk protein content.

The P content of feces increased as dietary P concentration was increased, with the average concentrations from all weeks being 0.508, 0.728, and 0.898% on a DM basis for the 0.31, 0.40, and 0.49% P treatments, respectively (Table 6). In calculating apparent digestibility of P, we used an average value for DM digestibility (66.1, SD 7.5) from all treatments measured during wk 2, 4, 6, and 8 for these weeks, and another average (69.2, SD 5.5) was used for wk 23 and 40 for all treatments. Dietary P content would not be expected to affect DM digestibility in this study; therefore, an average DM digestibility across treatments was used for all calculations of apparent P digestibility. We did this to avoid introduction of variance (experimental error) from apparent differences in DM digestibility across treatments. Assuming that the fecal output was the same for all treatments, the fecal P concentration averages suggest that decreasing dietary P from 0.49 to 0.40% reduced fecal P excretion by 23%. Apparent digestibility of P was similar for wk 2 to 40 for the 0.31% P treatment, and wk 2 to 8 for the 0.40% and 0.49% P treatments. The overall average for apparent digestibility of P during these weeks for the three treatments was 47%. With the exception of wk 4 for the 0.49% P treatment, where apparent digestibility of P was 56.3%, it appeared that 47% apparent digestibility represented an upper limit. Interestingly, based on a large number of digestion trials from several studies, Conrad (11) calculated the following regression equation between apparent digestibility of P and P intake:

$$\text{Apparently digested P (g/d)} = -3.9 + 0.47 \times \text{P intake (g/d)}$$

It appears that most measures of apparent digestibility of P in ruminants will be in the range of 45 to 50% when P is fed close to the requirements and will seldom exceed this range (3, 27, 37). Lower values for apparent digestibility of P occur when P is fed in excess of requirements, because the gut attempts to regulate P uptake according to body needs, and if P is not required, P uptake is reduced. Feeding diets of extremely low P content will result in low apparent digestibilities as well.

A plot (Figure 4) using averages from all the collection weeks for individual cows illustrates a linear relationship between the amount of P consumed and excreted

Table 6. Phosphorus content of feces and apparent digestibility of P during different weeks of lactation in cows fed diets differing in phosphorus content.

	Treatment				*P*	
Item	0.31% P	0.40% P	0.49% P	SEM	Linear	Quadratic
Fecal P content (% of DM)						
wk 2	0.497	0.631	0.773	0.052	0.01	0.96
wk 4	0.537	0.685	0.643	0.051	0.16	0.13
wk 6	0.476	0.613	0.879	0.071	0.01	0.46
wk 8	0.464	0.629	0.761	0.049	0.01	0.78
wk 23	0.550	0.864	0.973	0.042	0.01	0.06
wk 40	0.525	0.945	1.361	0.037	0.01	0.97
Average	0.508	0.728	0.898	. . .	. . .	. . .
Apparent digestibility of P (% of intake)						
wk 2	45.6	47.0	47.4	3.8	0.75	0.92
wk 4	41.2	42.5	56.3	4.4	0.03	0.25
wk 6	48.0	48.5	40.2	5.3	0.32	0.50
wk 8	49.3	47.3	48.2	3.7	0.84	0.75
wk 23	45.5	34.2	40.0	2.7	0.19	0.02
wk 40	47.9	28.1	16.0	2.9	0.01	0.31

in feces. The slope of the regression indicates that for each gram of increased P intake, 0.64 g would be excreted in feces, higher than values of 0.53 and 0.55 obtained by Conrad (11; see above equation) and Morse et al. (27), respectively. The apparent digestibility of P, based on all sampling times in the present experiment, would therefore be 36%. This lower overall value for apparent digestibility reflects inclusion of sampling times when P was clearly in excess of the cow's requirements.

Table 7 contains P intake, fecal excretion, milk secretion, and balance of P for the six sampling weeks. Phosphorus intake was proportional to dietary content of P, because feed consumption did not differ among treatments. Fecal excretion of P increased as P content of the diet was increased. Secretion of milk P was similar across treatments, except for wk 40, where milk production was reduced for the 0.31% P treatment.

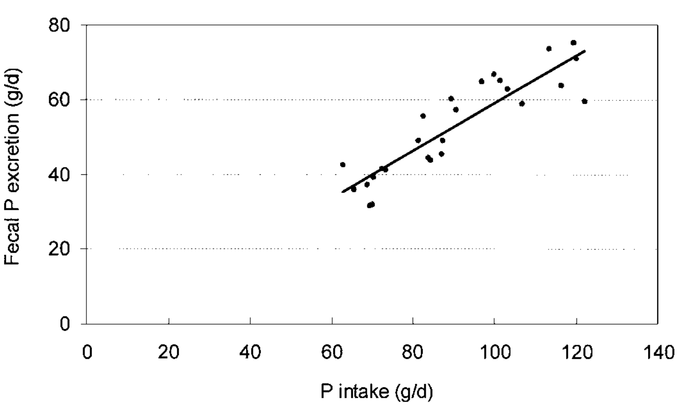

Figure 4. Relationship between intake (X) and fecal excretion (Y) of P: Y = 0.643X − 5.2; ($P < 0.01$) $r^2 = 0.81$, $P < 0.01$.

Calculated P balance was associated with considerable cow to cow variation. Removal of four cows by wk 40 (Table 2) left 22 cows for collection of data for that week. The values for the 0.49% P treatment seemed unrealistically high for many of the sampling periods, and this prompted an examination of how fecal P concentrations varied through the 24 h day. In a companion study, cows (N = 38) fed a TMR containing approximately 0.32, 0.40, or 0.48% P were sampled for feces at 0900, 1300, 1700, 2000, 0100, and 0500 h. A plot of fecal P concentration is shown in Figure 5. A diurnal pattern of fecal P concentration is apparent, particularly with the high P treatment. With that treatment, time of fecal sampling would have an important impact on calculated P balance. Fecal samples in this study were typically obtained between 0930 and 1100 h, and again between 1400 to 1530 h on each of the 4 d during the sampling week. Based on Figure 5, samples at these times would have underestimated the mean 24 h fecal P concentration, leading to an inflated estimate of P retention. This would be particularly so for the 0.49% P treatment and less evident for the 0.31% and 0.40% P treatments. As shown in Table 7, fairly realistic estimates of P balance were obtained with these two treatments. Given the diurnal variation in fecal P content and difficulties in estimating digestibilities of DM and P using a marker, total collection of feces would enable more accurate estimates of P balance. However, large amounts of retained P have been reported, even with total collection of feces. Herbein et al. (18) reported values of up to 18 g/d, and Morse et al. (27) reported up to 26 g/d in lactating cows.

A possible cause for the diurnal variation in fecal P concentration might be related to saliva flow. Saliva contributes large amounts of P to the rumen, and diur-

Table 7. Estimated balance of P during different weeks of lactation in cows fed diets differing in P content.

	Treatment				*P*	
Item	0.31% P	0.40% P	0.49% P	SEM	Linear	Quadratic
	(g/d)					
Intake						
wk 2	58.7	68.0	83.9	4.8	0.01	0.57
wk 4	68.4	82.6	103.1	3.1	0.01	0.40
wk 6	72.8	90.4	111.8	3.0	0.01	0.62
wk 8	73.6	93.1	117.0	3.1	0.01	0.56
wk 23	81.6	104.4	134.4	3.0	0.01	0.34
wk 40	59.9	85.7	116.2	4.5	0.01	0.69
Estimated fecal excretion						
wk 2	31.8	36.4	44.6	4.1	0.04	0.72
wk 4	39.4	47.9	54.0	4.4	0.03	0.83
wk 6	39.9	51.3	68.9	5.7	0.01	0.66
wk 8	37.1	48.9	60.7	4.0	0.01	0.99
wk 23	44.5	68.8	80.0	3.1	0.01	0.10
wk 40	30.2	61.5	97.3	3.4	0.01	0.60
Milk secretion						
wk 2	26.4	33.9	28.4	2.4	0.56	0.03
wk 4	31.9	31.1	31.5	2.6	0.90	0.85
wk 6	34.7	37.7	32.5	2.4	0.52	0.16
wk 8	33.0	33.1	33.1	2.0	0.95	0.99
wk 23	34.6	32.7	33.6	1.0	0.67	0.47
wk 40	19.7	25.0	25.4	2.1	0.11	0.36
Estimated balance[1]						
wk 2	–0.4	–3.3	10.0	3.8	0.07	0.09
wk 4	–4.0	2.6	16.7	3.7	0.01	0.40
wk 6	–2.7	0.5	9.4	4.5	0.07	0.60
wk 8	2.5	10.1	22.2	4.5	0.01	0.69
wk 23	1.5	–0.5	17.2	3.2	0.01	0.02
wk 40	9.0	–4.3	–7.8	2.0	0.01	0.08

[1]Calculated as intake – fecal excretion – urinary excretion – milk secretion; urinary excretion was small and 1 g/d was used for most of the cows.

nal changes in saliva flow could conceivably alter P content of digesta leaving the reticulo-rumen. Some of the P of salivary origin would be expected to be excreted in the feces without being reabsorbed in the small intestine for cows fed excess P.

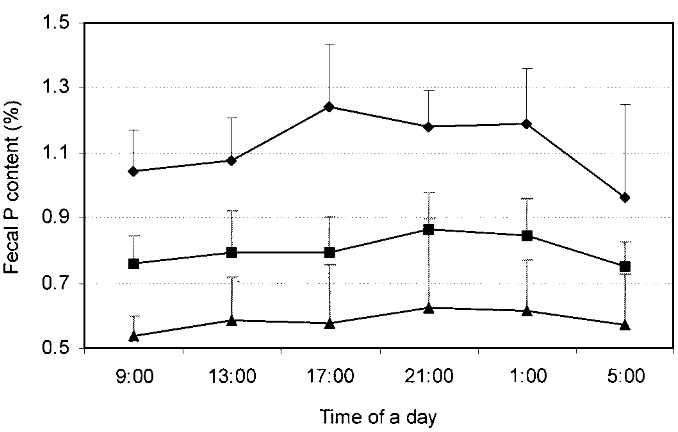

Figure 5. Diurnal variation in fecal P concentration (DM basis) of cows fed diets containing 0.48 (◆), 0.40 (■), or 0.32% P (▲). Bars represent the standard deviations of the means.

Cows in the 0.31% P treatment were in negative P balance during the first 6 to 7 wk of lactation, and then hovered at near balance until the last sampling week, when a positive balance was noted. This pattern would seem to conflict with the lactation data that suggested that cows in the 0.31% P treatment began to reduce their milk production around wk 25 because of inadequate P intake. The positive P balance at wk 40 is surprising, unless one reasons that the cow at this stage of lactation and pregnancy is giving priority to supplying the fetus with P and replenishing bone P in preparation for the next lactation. It is probable that cows can mobilize, and then restore, larger amounts of P than we realize. Pfeffer et al. (31) measured the amount of P mobilized by goats (~45 kg of BW) placed on a P depletion diet, and reported a loss of 67 g from body tissues, and 18 g that presumably came from contents of the digestive tract. Extrapolation of these results to a 600-kg cow would suggest that more than 1 kg of P could be mobilized when placed under P deficient conditions.

Fecal P can be broadly defined as being of exogenous (dietary) or endogenous origin. Feeding standards such as the NRC (29) use the endogenous fecal P plus urinary P as the maintenance requirement. This represents the loss of P from the body when a P-free diet is fed. This endogenous loss is assumed to be constant under P deficient conditions and is usually expressed on a live weight basis. Measurement of endogenous P loss through feces is difficult. Approaches used have included intravenous infusion of ^{32}P followed by measurement of ^{32}P transferred to feces (25). An alternate method is to estimate P excretion by regressing P absorbed on P intake (11). Extrapolating to zero P intake gives a negative intercept, which represents endogenous fecal P. Values thus obtained represent P passing from blood to the digestive tract and excreted as microbial P, salivary P, P in sloughed gut tissue, and P from digestive secretions. Martz et al. (25, 26) estimated endogenous P to be 0.9 to 1.5 g/100 kg of BW per day in lactating cows and 0.7 g/100 kg of BW per day in nonlactating cows using ^{32}P. Using extrapolation to zero P intake, Conrad (11) obtained 3.9 g/d, or 0.7 g/100 kg of BW (assuming 600 kg BW) in lactating cows. The values used by different feeding standards range from 1 to 3.5 g/100 kg of live weight (39).

Spiekers et al. (37) suggested that fecal P can be divided into the following three fractions: 1) the unavailable part of dietary P which cannot be absorbed under any condition, 2) the inevitable loss which has to be excreted under actual nutritional and physiological conditions, and 3) the regulated portion of fecal P which can range from 0 to some very large amounts, depending on P intake of the animal.

The unavailable P for ruminants is likely to be a small fraction of dietary P. Von Koddebusch and Pfeffer (41) estimated that dietary P was 90% available when goats were in a highly P deficient state. Martz et al. (25, 26) estimated true absorption of P from corn silage to be 80 to 94% in lactating and nonlactating cows fed very low P diets. As dietary P approaches the requirement, it is likely that true absorption decreases from the maximum amounts absorbed when animals are clearly P deficient.

The inevitable P losses in feces were reported to be approximately 1.2 g/kg of DMI, assuming availability (true digestibility) of 100% (37). If true digestibility was in fact 85% under conditions of the trial by Spiekers et al. (38), then inevitable P loss in feces would be about 0.9 g/kg of DMI. The inevitable fecal fraction consists of salivary P, P in sloughed gut tissue, and P from digestive secretions, all of which may be referred to as metabolic P, plus P in microbial residues excreted in feces. This total fraction, without counting the negligible urinary P under zero P intake, can be viewed as the maintenance requirement.

The regulated P fraction is that fecal P over which the animal has discretion. If the animal has sufficient P in the diet to meet needs, then much of the surplus P will be excreted in the manure in this fraction. If the animal is very deficient in P, no surplus is available for excretion, and this fraction will be zero. Small amounts of P will likely be in this fraction under marginally P deficient situations.

As pointed out earlier, the inevitable fecal P as described by Spiekers et al. (37) contains metabolic P and P of microbial origin. Conrad (11) has estimated the amount of microbial P in feces as follows:

$$\text{Bacterial P (g/d)} = 0.0037 \times \text{fecal DM (g/d)}$$

This equation is based on an average P content of rumen bacteria of 1.438% (15), and the assumption that microbial residues in the feces are 50% protein, and that 89.5% of the fecal CP is of microbial origin. In studies by Conrad et al. (12), mean fecal crude protein content was 14.4%. The assumption that 89.5% of fecal N is of microbial origin seems high to the authors. If true digestibility of dietary protein is 85 to 90%, then the undigested dietary protein alone could account for 40 to 45% of fecal N. Some amount of fecal N is from sloughed intestinal cells and secretions into the gut, so a value of about 50% or smaller would seem more likely. If 50% is used, then the coefficient in the equation above becomes 0.00207. This is a highly tentative approach for estimating fecal P derived from gut microbes, but it is a reasonable starting point.

Table 8 attempts to illustrate an overview of this discussion. The example is for a cow producing 45 kg/d of milk and consuming 24 kg/d of DM. The diet has a DM digestibility of 66.7%. Diets illustrated in the table contain from 0.25 to 0.55% P. The P content of milk is assumed to remain constant at 0.089% over the range of dietary P reported in the table. Phosphorus excretion in urine will be <1 g/d for cows fed less than about 0.35% dietary P. Some cows will start spilling P in urine as dietary P exceeds 0.35%, and as much as 6 to 8 g/d may be excreted via this route (27). The values in the table represent an estimate for the mean excretion.

As pointed out, the estimate for fecal P in microbial residues is very crude. Likewise, the estimate for metabolic P is tenuous, because it is very difficult to measure. The value of 5 g/d is from the lower end of the range of estimates. The sum of these two sources of P (inevitable fecal P) has been estimated from reliable measurements (37), but the estimate of inevitable P is based on the assumed amount of unavailable P. In their paper, Spiekers et al. (37) suggested that inevitable P equals 1.2 g/kg of DM consumed, but this assumption is that all dietary P is available, which is unlikely. If P avail-

Table 8. An example of P distribution for a cow milking 45 kg/d and consuming 24 kg/d of DM with 66.7% digestibility.

Dietary P		P secretion or excretion (g/d)								
				Feces						
				Inevitable		Undigested				
(%)	(g/d)	Milk[1]	Urine[2]	Microbial[3]	Metabolic[4]	Unavailable[5]	Regulated[6]	Total	Balance[7] (g/d)	Apparent digestibility (%)
0.25	60	40	1	16.5	5	9.0	. . .	30.5	–11.5	49
0.30	72	40	1	16.5	5	10.8	3.5	35.8	–6.8	50
0.35	84	40	1	16.5	5	12.6	8.9	43.0	0	49
0.40	96	40	2	16.5	5	14.4	18.6	54.0	0	44
0.45	108	40	2	16.5	5	16.2	28.3	66.0	0	39
0.50	120	40	3	16.5	5	18.0	37.4	77.0	0	36
0.55	132	40	5	16.5	5	19.8	45.6	87.0	0	34

[1]Milk P (g/d) = 45 kg/d of milk × 0.089% *P* content.

[2]Urinary P excretion is small (<1 g/d) in cows fed diets containing low P (<0.35%). Cows may spill P in urine when fed >0.35% P.

[3]Microbial P (g/d) = 0.00207 × fecal DM output (kg/d).

[4]Estimated based on values of 0.8 to 1.5 g/kg of BW (11, 25, 26).

[5]Unavailable P (g/d) = P intake (g/d) × 0.15 unavailability.

[6]Varies with P intake relative to requirement. In this example, regulated P is 0 or 3.5 g/d if the diet contains 0.25 or 0.30% P, respectively. At higher dietary P concentrations, regulated P is estimated as intake P – milk P – urinary P – inevitable P – unavailable P.

[7]This illustration is for a cow in P balance. A positive or negative balance in this column where zero balance is indicated will cause a corresponding reduction or increase in the value for regulated P.

ability is actually 85%, then Spiekers et al. (37) point out that the inevitable P would equal 0.9 g/kg of DM consumed, exactly what is shown for inevitable fecal P in Table 8.

Table 8 uses a value of 85% for available P, which represents the maximum amount available, and to achieve maximum availability the animal has to be very deficient in P. But by definition, if P is potentially available, it should be called such.

The regulated P represents an amount that would be appropriate if the cow is in a zero P balance (for diets containing at least 0.35% P). This would perhaps be 15 to 20 wk into lactation. In early lactation, feed intake would be less than the 24 kg/d used in this example, and the cow would most likely be in negative P balance. Once body P stores are restored, the cow can adjust this fraction of fecal P to maintain equilibrium in body P. Accordingly, during a time of P restoration of the body, the amount of regulated P in feces would be less. Therefore, the regulated P fraction in feces should be viewed as a maximum amount. Expected apparent digestibility is shown in the last column. These values are realistic, and fit those reported in the literature (11).

Table 9 contains comparisons between amounts of fecal P actually measured in feces in three experiments and the amounts predicted according to the scheme presented in Table 8 with the actual P intakes reported in the experiments. Considering that fecal P predictions in Table 8 are maximum values (see earlier discussion), one might conclude reasonable concurrence between predicted and measured values.

In the literature the terminology pertaining to P nutrition has been confused. The suggestion by Spiekers et al. (37) to use the term inevitable fecal P is an important step toward clarification. There has also been much confusion between apparent digestibility of P and available P. Available P is that dietary P that is potentially extractable from the gut under a state of P deficiency. Apparently digested P has frequently been taken to mean available P, creating confusion. While some of the numbers used in Table 8 are rather crude estimates, the division of fecal P into the fractions presented in Table 8 allows better understanding of P nutrition in ruminants.

Although Table 8 can help our understanding of P nutrition of the dairy cow, what really matters is knowing the minimum amount of dietary P required by the cow for normal function. The P feeding standards for dairy cows are under review in several countries. While the systems in Western Europe and North America do not differ greatly in terms of the amount of dietary P recommended for lactating cows, the assignment of P between maintenance and production functions is extremely variable. The German working group (24) has suggested a factorial approach that incorporates the concept of inevitable fecal loss from Spiekers et al. (37). The component parts of the total requirement are as follows:

P secreted in milk	1 g/kg of milk
P deposited in uterus during last 2 mo of gestation	2.0 to 2.5 g/d

Table 9. Predicted and measured P in feces for three experiments.

Experiment	Dietary P (%)	Measurements	Predicted (g/d)[1]	Measured (g/d)[2]
Herbein et al. (18)	0.34	36	42.6	40.8
	0.37	36	57.9	48.5
Morse et al. (27)	0.30	12	34.0	35.9
	0.41	24	60.2	46.8
	0.56	12	87.6	67.0
Present study	0.31	48	34.4	37.1
	0.40	54	50.3	52.4
	0.49	54	73.3	67.6

[1]Based on the illustration presented in Table 8.

[2]Averages from all the measurements made with total collection of feces (18, 28) or by estimating fecal dry matter using a digesta marker in the present experiment.

P accretion during growth	7.4 g/kg of gain
Inevitable loss (maintenance)	1.0 g/kg of DMI

These are summed and the amount is divided by 0.7 to give the recommended amount of dietary P. The 0.7 value reflects the availability of P for uptake from the gut when dietary P is fed at requirement.

Table 10 illustrates a comparison of current P recommendations based on Table 6.4 of the NRC publication (29), and the new recommendations developed in Germany. This example is for a 600-kg Holstein producing milk containing 3.75% fat. The DMI values are those suggested in Table 6.4 of the NRC publication. The DMI values used will, of course, have a direct effect on the P requirement when expressed as a percentage of diet DM.

The two systems project very similar P requirements. The NRC recommendation is based on what appears to be an unrealistically low maintenance requirement (1.43 g/100 kg of live weight), but this is offset by a very low value for P availability in the gut (50%). The final NRC recommendation comes out only slightly higher than what may be the more logically calculated German recommendation.

Table 10. Phosphorus feeding recommendations.

		Current NRC recommendations (29)		Recent German recommendations (24)	
Milk (kg/d)	Estimated DMI (kg/d)[1]	P (g/d)	Dietary P[2,3] (%)	P (g/d)	Dietary P[3] (%)
10	13.0	36.0	0.27	33.0	0.25
20	17.0	55.5	0.33	52.8	0.31
30	20.4	74.5	0.37	72.0	0.35
40	23.4	93.0	0.40	90.7	0.39
50	27.3	112.5	0.41	110.6	0.40

[1]From NRC (29).

[2]Recommends 0.48% dietary P during first 3 wk of lactation.

[3]Percent of diet DM.

One more comment is required regarding the NRC (29) P recommendation. Table 6.5 of the NRC publication suggests that the dairy diet contain 0.48% P during the first 3 wk of lactation. This concentration is intended to ensure adequate consumption of P during early lactation when feed consumption lags behind milk production. Significant bone P is mobilized during the first few weeks of lactation. Bone can provide a minimum of 500 to 600 g of P in early lactation, and this should be credited as a source of P. Feeding an additional large amount of dietary P in the first weeks of lactation is not necessary.

Although the NRC and European P standards differ greatly in their component parts, i.e., values assigned to maintenance, production, and P availability, the final feeding recommendations do not differ greatly. It may be a case of the standards being right for the wrong reason! The glaring discrepancies in the component parts of the feeding standards do little to build confidence that the final feeding recommendations may in fact be pretty reasonable. This may be one reason why our feeding practices call for much more P than our feeding standards do. It could develop that we can safely feed less P than the standards currently recommend, and less than what was concluded in this study. However, more long-term lactation studies with high producing cows are needed before taking that step.

CONCLUSIONS

Results of this study and several other studies indicate that dietary P at 0.38 to 0.40% is sufficient for high producing cows. This concentration of P can be obtained with no supplementation or minimum supplementation of P, depending on feed ingredients. Dietary P at 0.31% can support high milk production, but can not sustain comparable milk yield when cows proceed into late lactation. Feeding 0.48% P as suggested by the NRC (29) during early lactation, or even higher as practiced by some producers, is unnecessary. Aside from the high dietary P concentrations suggested for early lactation, the NRC (29) recommendations appear reasonable. Cows conserve P when fed diets low in P by reducing P excretion in feces and urine. They may experience some negative balance in the first few weeks of lactation due to mobilization of P from bone, but this mobilized P can be restored in later lactation. Excess dietary P will be excreted in feces and might be termed regulated P. An apparent digestibility of P of 40% or less may be an indication of excessive intake of P.

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REFERENCES

1 Association of Official Agricultural Chemists. 1980. Official Method of Analysis. 13 ed. AOAC, Washington, D. C.
2 Braithwaite, G. D. 1985. Endogenous faecal loss of phosphorus in growing lambs and the calculation of phosphorus requirements. J. Agric. Sci. (Camb.) 105:67–72.
3 Brintrup, R., T. Mooren, U. Meyer, H. Spiekers, and E. Pfeffer. 1993. Effects of two levels of phosphorus intake on performance and faecal phosphorus excretion of dairy cows. J. Anim. Physiol. Anim. Nutr. 69:29–36.
4 Brodison, J. A., E. A. Goodall, J. D. Armstrong, D. I. Givens, F. J. Gordon, W. J. McCaughey, and J. R. Todd. 1989. Influence of dietary phosphorus on the performance of lactating dairy cattle. J. Agric. Sci. (Camb.) 112:303–311.
5 Call, J. W., J. E. Butcher, J. L. Shupe, R. C. Lamb, R. L. Boman, and A. E. Olson. 1987. Clinical effects of low dietary phosphorous concentrations in feed given to lactating dairy cows. Am. J. Vet. Res. 48:133–136.
6 Carstairs, J. A., D. A. Morrow, and R. S. Emery. 1980. Postpartum reproductive function of dairy cows as influenced by energy and phosphorus status. J. Anim. Sci. 51:1122–1130.
7 Carstairs, J. A., R. R. Neitzel, and R. S. Emery. 1981. Energy and phosphorus status as factors affecting postpartum performance and health of dairy cows. J. Dairy Sci. 64:34–41.
8 Challa, J., and G. D. Braithwaite. 1989. Phosphorus and calcium metabolism in growing calves with special emphasis on phosphorus homoeostasis. 1. Studies of the effect of change in the dietary phosphorus intake on phosphorus and calcium metabolism. J. Agric. Sci. (Camb.) 110:573–581.
9 Challa, J., G. D. Braithwaite, and M. S. Dhanoa. 1989. Phosphorus homoeostasis in growing calves. J. Agric. Sci. (Camb.) 112:217–226.
10 Combs, D. K., and L. D. Satter. 1992. Determination of markers in digesta and feces by direct current plasma emission spectroscopy. J. Dairy Sci. 75:2176–2183.
11 Conrad, H. R. 1999. Dietary phosphorus, excretory phosphorus and environmental concerns. Pages 63–71 *in* Proc. 10th Annual Florida Ruminant Nutr. Symp. Gainesville, FL.
12 Conrad, H. R., J. W. Hibbs, and A. D. Pratt. 1960. Nitrogen metabolism in dairy cattle. Ohio Agricultural Experiment Station and Research Bulletin 861. Wooster, OH.
13 De Boer, G., J. G. Buchanan-Smith, J. K. Macleod, and J. S. Walton. 1981. Responses of dairy cows fed alfalfa silage supplemented with phosphorus, copper, zinc, and manganese. J. Dairy Sci. 64:2370–2377.
14 Dhiman, T. R., L. D. Satter, and R. D. Shaver. 1995. Milk production and blood phosphorus concentrations of cows fed low and high dietary phosphorus. Page 105 *in* Research Summaries, U. S. Dairy Forage Research Center, Madison, WI.
15 Durand, M., and R. Kawashima. 1980. Influence of minerals in rumen microbial digestion. Pages 375–408 *in* Digestive Physiology and Metabolism in Ruminants. Y. Ruckebusch and P. Thivend, ed. MTP Press Ltd., Lancaster, England.
16 Forar, F. L., R. L. Kincaid, R. L. Preston, and J. K. Hillers. 1982. Variation of inorganic phosphorus in blood plasma and milk of lactating cows. J. Dairy Sci. 65:760–763.
17 Goff, J. P., and R. L. Horst. 1997. Effects of the addition of potassium or sodium, but not calcium, to prepartum rations on milk fever in dairy cows. J. Dairy Sci. 80:176–186.
18 Herbein, J. H., J. D. Cox, M. M. Weisbarth, and W. A. Wark. 1996. Phosphorus retention in lactating Holstein cows fed inorganic or organic forms of supplemental dietary phosphorus. J. Dairy Sci. 79(Suppl. 1):229.(Abstr.)
19 Howard, W. T., and R. D. Shaver. 1992. Use of high producing herd diet evaluation in dairy extension programing. J. Dairy Sci. 75(Suppl. 1):186.(Abstr.)
20 Jacobson, N. L., K. D. Wiggers, M. H. Wiggers, and G. N. Jacobson. 1977. Phosphorus in dairy cattle and goat nutrition. Pages 1–43 *in* Phosphorus in Ruminant Nutrition. National Feed Ingredients Association, West Des Moines, IA.
21 Jenness, R. 1985. Biochemical and nutritional aspects of milk and colostrum. Pages 164–197 *in* Lactation. B. L. Larson, ed. The Iowa State University Press, Ames, IA.
22 Keuning, J. L., S. L. Gunderson, and R. D. Shaver. 1999. Survey of feeding and management practices on six high producing Wisconsin dairy herds. J. Dairy Sci. 82(Suppl. 1):844.(Abstr.)
23 Kincaid, R. L., J. K. Hillers, and J. D. Cronrath. 1981. Calcium and phosphorus supplementation of rations for lactating cows. J. Dairy Sci. 64:754–758.
24 Kirchgeßner, M. 1993. Mitteilungen des ausschusses für bedarfsnormen der gesselschaft für ernährungsphysiologie. Proc. Soc. Nutr. Physiol. 1:108–112.
25 Martz, F. A., A. T. Belo, M. F. Weiss, and R. L. Belyea. 1999. True absorption of calcium and phosphorus from corn silage fed to nonlactating, pregnant dairy cows. J. Dairy Sci. 82:618–622.
26 Martz, F. A., A. T. Belo, M. F. Weiss, R. L. Belyea, and J. P. Goff. 1990. True absorption of calcium and phosphorus from alfalfa and corn silage when fed to lactating cows. J. Dairy Sci. 73:1288–1295.
27 Morse, D., H. H. Head, C. J. Wilcox, H. H. Van Horn, C. D. Hissem, and B. Harris, Jr. 1992. Effects of concentration of dietary phosphorus on amount and route of excretion. J. Dairy Sci. 75:3039–3049.
28 National Research Council. 1978. Nutrient Requirements of Dairy Cattle. 5th rev. ed. Natl. Acad. Sci., Washington, D. C.
29 National Research Council. 1989. Nutrient Requirements of Dairy Cattle. 6th rev. ed. Natl. Acad. Sci., Washington, D. C.
30 Nelson, W. F., and L. D. Satter. 1992. Impact of stage of maturity and method of preservation of alfalfa on digestion in lactating dairy cows. J. Dairy Sci. 75:1571–1580.
31 Pfeffer, E., P. Windhausen, and M. Rodehutscord. 1994. Changes in body composition of dairy goats caused by phosphorus depletion. J. Anim. Physiol. Anim. Nutr. 72:65–70.
32 Robertson, J. B., and P. J. Van Soest. 1981. Page 123 *in* The Analysis of Dietary Fiber in Foods. W.P.T. Kames and O. Theander, ed. Marcel Dekker, Inc., New York, NY.
33 Rodehutscord, M., A. Pauen, P. Windhausen, R. Brintrup, and E. Pfeffer. 1994. Effects of drastic changes in P intake on P concentrations in blood and rumen fluid of lactating ruminants. J. Vet. Med. Ser. A 41:611–619.
34 Sansinena, M., L. D. Bunting, S. R. Stokes, and E. R. Jordan. 1999. A survey of trends and rationales for phosphorus recommendations among Mid-South nutritionists. Pages 51–54 *in* Proc. Mid-South Ruminant Nutr. Conf., Dallas, TX.

35 SAS Technical Report P-239, SAS/STAT Software: Changes and Enhancements, Release 6.07 Edition. 1992. SAS Inst., Inc., Cary, NC.
36 SAS User's Guide: Statistics, Version 6.08 Edition. 1985. SAS Inst., Inc., Cary, NC.
37 Spiekers, H. R. Brintrup, M. Balmelli, and E. Pfeffer. 1993. Influence of dry matter intake on faecal phosphorus losses in dairy cows fed rations low in phosphorus. J. Anim. Physiol. Anim. Nutr. 69:37–43.
38 Steevens, B. J., L. J. Bush, J. D. Stout, and E. I. Williams. 1971. Effects of varying amounts of calcium and phosphorus in rations for dairy cows. J. Dairy Sci. 54:655–661.
39 Tamminga, S. 1992. Feeding management for dairy cows as a means to contribute to environmental pollution control. J. Dairy Sci. 75:345–357.
40 Valk, H., and L.B.J. Ebek. 1999. Influence of prolonged feeding of limited amounts of phosphorus on dry matter intake, milk production, reproduction and body weight of dairy cows. J. Dairy Sci. 82:2157–2163.
41 Von Koddebusch, L., and E. Pfeffer. 1988. Untersuchungen zur Verwertbarkeit von phosphor verschiedener herkunfte an laktierenden Ziegen. J. Anim. Physiol. Anim. Nutr. 60:269–275.
42 Wu, Z., and L. D. Satter. 1999. Milk production and reproductive performance of dairy cows fed two levels of phosphorus for two years. J. Dairy Sci. (In press).