J Vet Intern Med 2005;19:894–898

Phosphorus Homeostasis in Dairy Cows with Abomasal Displacement or Abomasal Volvulus

Walter Grünberg, Peter Constable, Ulf Schröder, Rudolf Staufenbiel, Dawn Morin, and Marina Rohn

Abnormal phosphorus homeostasis occurs in dairy cows with an abomasal displacement or volvulus. The goal of this study was to identify potential mechanisms for hypophosphatemia and hyperphosphatemia in cows with a left displaced abomasum (LDA), right displaced abomasum (RDA), or abomasal volvulus (AV). Accordingly, the results of preoperative clinicopathologic analyses for 1,368 dairy cows with an LDA (n = 1,189), RDA, or AV (n = 179) (data set 1) and for 44 cows with an AV (data set 2) were retrieved. Laboratory values were compared by Student's *t*-tests, and correlation and regression analyses were performed. Thirty-four percent of the animals from data set 1 (463/1,368) were hypophosphatemic (serum phosphorus concentration ([Pi]) <1.4 mmol/L), and 9% (122/1,368) were hyperphosphatemic ([Pi] >2.3 mmol/L). Serum [Pi] was significantly lower ($P < .05$) in cows with an LDA (1.60 ± 0.53 mmol/L; mean ± SD) than in cows with an RDA or AV (1.85 ± 0.68 mmol/L). For cows with an LDA, [Pi] was correlated with serum urea nitrogen concentration ([SUN]) ($r = 0.34$) and serum concentration of magnesium ([Mg]) ($r = 0.20$). For cows with an RDA or AV, linear correlations existed between [Pi] and [SUN] ($r = 0.45$), [Mg] ($r = 0.43$), and serum chloride concentration ([Cl]) ($r = -0.27$). Stepwise logistic regression analysis indicated that low [SUN] and the diagnosis of an LDA had the strongest associations with hypophosphatemia. In cows with hyperphosphatemia, [Pi] was most strongly associated with azotemia. In cows with an AV, the strongest correlations with [Pi] were found for [SUN] and serum creatinine. We conclude that hypophosphatemia in cows with an LDA is primarily due to decreased feed intake. In contrast, hyperphosphatemia in cattle with an RDA or AV appears to result from dehydration and decreased renal blood flow.

Key words: Feed intake; Hemoconcentration; Hyperphosphatemia; Hypophosphatemia.

Phosphorus nutrition and homeostasis in dairy cattle has received increased attention during the past decade. Excessive dietary phosphorus intake leads to high fecal phosphorus concentration and surface runoff. This has raised environmental concerns and resulted in incentives to lower dietary phosphorus intake.[1–4] However, if phosphorus intake is limited, cows in early lactation might experience hypophosphatemia as the result of a sudden and increasing loss of phosphorus in milk.[1] Conditions such as Downer cow syndrome, postparturient hemoglobinuria, unthriftiness, inappetence, reduced milk production, and decreased fertility have been associated with hypophosphatemia.[1–5] Conditions that affect feed intake, milk production, or hydration status in early lactation could also alter phosphorus homeostasis.

Abnormal serum phosphorus concentration ([Pi]) has been reported in dairy cows with a left displaced abomasum (LDA), right displaced abomasum (RDA), or abomasal volvulus (AV), conditions frequently occurring in early lactation.[6–9] The mechanisms for these alterations in serum [Pi] are uncertain. The objective of our study was to determine the association between serum [Pi] and other clinicopathologic parameters in lactating dairy cows with a displaced abomasum (DA) or AV in order to identify potential mechanisms for the development of hypophosphatemia and hyperphosphatemia.

From the University of Illinois at Urbana-Champaign, Department of Veterinary Clinical Medicine, Champaign, IL (Grünberg, Constable, Morin); and the Freie Universität, Klinik für Klauentiere, Diagnostischer Dienst am Rind, Berlin, Germany (Schröder, Staufenbiel, Rohn). This work was performed at the University of Illinois at Urbana-Champaign. Data were provided in part by the Freie Universität, Berlin, Germany. Part of the data discussed in this paper was presented at the 23rd World Buiatrics Congress in Québec, Canada.

Reprint requests: Walter Grünberg, Dr Med Vet, Diplomate ECAR, Gobergasse 31, 1130 Vienna, Austria; e-mail: waltergruenberg@yahoo.com.

Submitted November 24, 2004; Revised May 9, 2005; Accepted May 9, 2005.

0891-6640/05/1906-0019/$3.00/0

Materials and Methods

The medical records of 1,368 dairy cows that presented for surgical correction of a DA or AV at the clinic for ruminants and swine of the Free University Berlin (data set 1) and of 44 dairy cows with an AV that underwent surgery at The Ohio State University Veterinary Teaching Hospital (data set 2) were retrieved, and data were extracted for analysis. Inclusion criteria were intraoperative confirmation of the diagnosis of a DA or AV according to established guidelines[10] and availability of results of a presurgical serum biochemistry panel.

For animals in data set 1, the following serum biochemical parameters were routinely assayed: phosphorus ([Pi]), magnesium ([Mg]), sodium ([Na]), calcium ([Ca]), potassium ([K]), chloride ([Cl]), total bilirubin ([TBil]), aspartate amino transferase (AST), and serum urea nitrogen ([SUN]). Hemoglobin concentration ([Hb]) and PCV were determined on blood collected into EDTA-containing tubes. The [Mg], [TBil], [SUN], and [Pi] as well as AST activity were determined on a Hitachi 704 chemistry analyzer.[a] The [Na], [Cl], and [K] were measured with ion selective electrodes,[b] and total [Ca] was assayed with a flame atomic absorption spectrophotometer.[c] PCV and [Hb] were obtained on an automatic cell counter.[d]

Serum samples from cows in data set 2 were analyzed for [Mg], [Na], [Ca], [K], [Pi], [TBil], total protein ([TP]), albumin, creatinine kinase (CK), [SUN], and [creatinine] with a Hitachi 704 autoanalyzer,[e] and the anion gap was calculated.[11] In addition, heparinized blood samples collected anaerobically were assayed immediately for pH, base excess, and P_{CO_2}.[f] Values were corrected for rectal temperature. Heparinized blood containing 8% perchloric acid was assayed spectrophotometrically for pyruvate ([Pyr]). Blood collected in a chilled Na-fluoride tube containing 8% perchloric acid was analyzed for L-lactate ([Lact]) by a spectrophotometric method as well.[12] Dehydration was subjectively estimated by means of the degree of eyeball recession and skin tent duration.[13]

Statistical Analysis

Hypophosphatemia was defined as serum [Pi] <1.4 mmol/L, and hyperphosphatemia was defined as serum [Pi] >2.3 mmol/L; the ref-

Table 1. Clinicopathologic variables that were significantly ($P < .05$) correlated with serum [Pi] in 1,189 lactating dairy cows with LDA and 179 lactating dairy cows with RDA/AV (data set 1).

	LDA		RDA/AV	
Variable	*r*	Probability	*r*	Probability
[SUN]	0.34	<.0001	0.45	<.0001
[Mg]	0.20	<.0001	0.43	<.0001
[Cl]	−0.19	<.0001	−0.27	.0004
Hb	0.14	<.0001	0.16	.033
PCV	0.12	<.0001	0.16	.035
LogAST	−0.12	<.0001		
LogTBil	−0.11	<.0001		
AST			0.15	.047
[Ca]			0.15	.046

[Pi], serum phosphorus concentration; [SUN], serum urea nitrogen concentration; [Mg], serum magnesium concentration; [Cl], serum chloride concentration; Hb, hemoglobin concentration; AST, aspartate amino transferase activity; TBil, total bilirubin; [Ca], calcium concentration; LDA, left displaced abomasum; RDA, right displaced abomasum; AV, abomasal volvulus.

erence range of 1.4–2.3 mmol/L was determined on the basis of current recommendations in the literature.[14]

Data are expressed as mean ± standard deviation. Clinicopathologic values for cows in different groups were compared by performing Student's *t*-tests and analysis of variance on raw, ranked, or log-transformed data. Effects of measured parameters on serum [Pi] were tested by multivariable linear and logistic regression analyses. Pearson correlation coefficients were calculated on raw or log-transformed values. The significance level was set at 5% ($P < .05$). The calculations were performed by SAS statistical software.[g]

Results

Data Set 1

Of the 1,368 animals, 1,189 presented with an LDA, and 179 presented with an RDA or AV.

Cows with an LDA had a mean [Pi] of 1.60 ± 0.53 mmol/L, which was lower ($P < .0001$) than for cows in the RDA/AV group (1.85 ± 0.68 mmol/L). Fifty-seven percent of cows with an LDA (n = 678) had normal serum [Pi] versus 52% (n = 93) of cows with an RDA or AV. Thirty-five percent (n = 416) of cows with an LDA were hypophosphatemic compared with 20% (n = 36) of cows with an RDA or AV. Hyperphosphatemia was diagnosed in 8% (n = 95) of cows with an LDA versus 28% (n = 50) of cows with an RDA or AV.

To assess a possible age-related influence on phosphorus homeostasis, animals with an exact age available were grouped. Cows up to 27 months of age were allocated to the heifer group, and cows that were at least 4 years of age formed a 2nd group. In the heifer group, serum [Pi] was 1.57 ± 0.49 mmol/L (n = 103), which did not differ from the mean value for the group of older cows (1.60 ± 0.58 mmol/L, n = 895). When grouping cows with exact calving dates available according to stage of lactation (group 1: cows from parturition to 10 days in milk [DIM]; group 2: cows between 11 and 30 DIM; and group 3: cows >30 DIM) group 1 showed a higher serum [Pi] (1.83 ± 0.60 mmol/L, n = 176) when compared with groups 2 (1.55 ± 0.54, n = 206) and 3 (1.63 ± 0.50, n = 136).

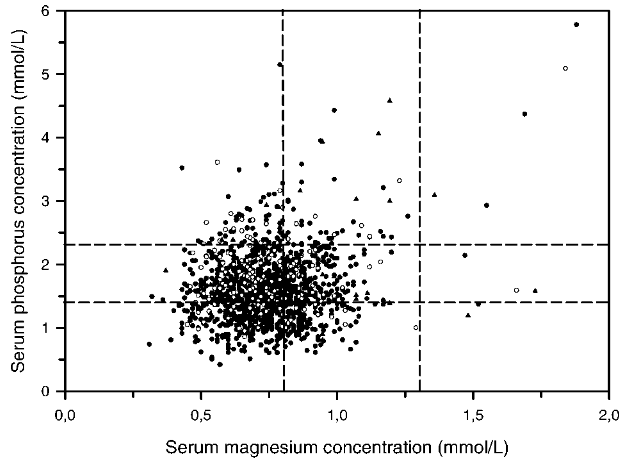

Fig 1. Relationship between serum phosphorus concentration and serum magnesium concentration in cows with a displaced abomasum or abomasal volvulus (AV). Open circles represent animals with a left displaced abomasum (LDA) (n = 1,189, data set 1), filled circles represent animals with a right displaced abomasum (RDA) or AV (n = 179, data set 1), and filled triangles represent animals with an AV (n = 44, data set 2). Dashed lines indicate lower and upper limits of the reference range.

In all cows, the strongest positive correlations with serum [Pi] were found for serum [Mg] (Table 1; Fig 1) and [SUN] (Fig 2), which were much stronger in the RDA/AV group than in the LDA group. In both groups, a negative correlation of serum [Pi] with serum [Cl] (Fig 3) and a positive correlation of serum [Pi] with PCV and [Hb] were found. Whereas a negative correlation was identified between serum [Pi] and serum [TBil], as well as serum [Pi] and AST activity, in cows with an LDA, a positive correlation be-

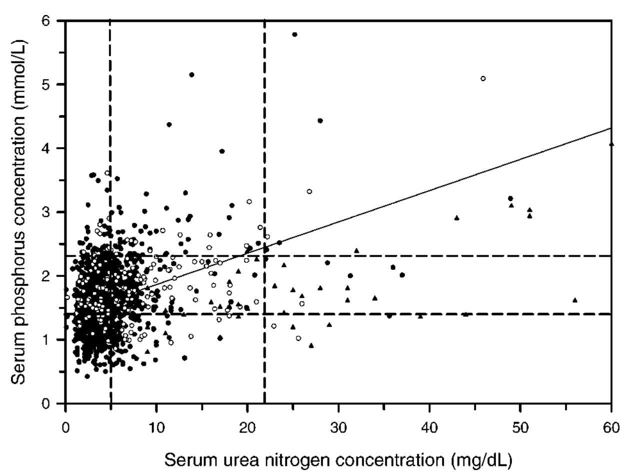

Fig 2. Relationship between serum phosphorus concentration and serum urea nitrogen concentration in cows with a displaced abomasum or abomasal volvulus (AV). Open circles represent animals with a left displaced abomasum (LDA) (n = 1,189, data set 1), filled circles represent animals with a right displaced abomasum (RDA) or AV (n = 179, data set 1), and filled triangles represent animals with an AV (n = 44, data set 2). Dashed lines indicate lower and upper limits of the reference range.

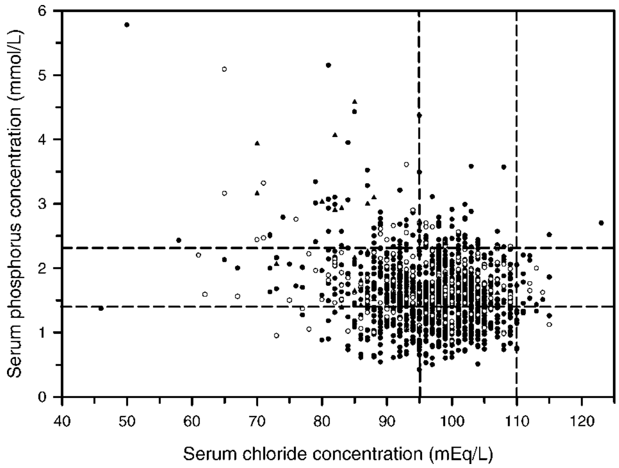

Fig 3. Relationship between serum phosphorus concentration and serum chloride concentration in cows with a displaced abomasum or abomasal volvulus (AV). Open circles represent animals with a left displaced abomasum (LDA) (n = 1,189, data set 1), filled circles represent animals with a right displaced abomasum (RDA) or AV (n = 179, data set 1), and filled triangles represent animals with an AV (n = 44, data set 2). Dashed lines indicate lower and upper limits of the reference range.

tween AST activity and serum [Pi] was found in cows with an RDA or AV.

The results of a backward logistic regression analyses for hypophosphatemic and hyperphosphatemic cows are presented in Table 2 (a forward logistic regression analyses produced the same result). The strongest associations with hypophosphatemia were a low [SUN] (<5 mg/dL), a diagnosis of LDA, and a high AST activity (>130 U/L). Hyperphosphatemia showed the strongest associations with azotemia ([SUN] >22 mg/dL) and hypochloremia ([Cl] <95 mmol/L).

Data Set 2

Cows with an AV in data set 2 had a mean serum [Pi] of 1.97 ± 0.86 mmol/L. The parameters that are correlated with serum [Pi] are summarized in Table 3. In cows in data set 2, the strongest positive correlations with serum [Pi] were found for serum [SUN], [creatinine], [Lact], [Pyr], [TP], anion gap, blood pH, and estimated percent dehydration. A negative correlation was found between serum [Pi] and [Cl]. Neither CK activity nor AST activity was correlated with serum [Pi] in this data set.

Table 3. Clinical and clinicopathologic variables that were significantly ($P < .05$) correlated with serum [Pi] in 44 lactating dairy cows with abomasal volvulus (data set 2).

	Abomasal Volvulus	
Variable	*r*	*P*
[Crea]	0.74	<.0001
[SUN]	0.72	<.0001
Anion gap	0.71	<.0001
[Pyr]	0.65	<.0001
Dehydration	0.63	<.0001
[Cl]	−0.61	<.0001
[Lact]	0.52	.0003
[TP]	0.51	.0004
pH	−0.42	.0049
P_{CO_2}	0.30	.049

[Pi], serum phosphorus concentration; [Crea], creatinine concentration; [SUN], serum urea nitrogen concentration; [Pyr], pyruvate concentration; [Cl], serum chloride concentration; [Lact], L-lactate concentration; [TP], total protein concentration.

The results of forward and backward stepwise linear regression analysis for serum [Pi] (dependent variable) and all measured parameters (independent variables) indicated that serum [Pi] was associated with [SUN] (0.086 ± 0.014; estimate of coefficient ± standard error; $P < .0001$) and [TP] (0.728 ± 0.235; $P = .0035$).

Discussion

We believe that this is the first study to deal specifically with phosphorus homeostasis in dairy cows with a DA or AV. An abnormal serum [Pi] was present in >40% of the lactating dairy cows with an LDA, RDA, or AV. Whereas hypophosphatemia was the most common abnormality of phosphorus homeostasis in cows with an LDA, cows with an RDA or AV had a higher mean serum [Pi] and were more frequently hyperphosphatemic.

The presence of an LDA increased the likelihood of hy-

Table 2. Results of backward stepwise logistic regression analysis for hypophosphatemia and hyperphosphatemia on all measured clinicopathologic variables and clinical examination findings (data set 1). The odds ratio, 95% confidence interval for the odds ratio, and *P* values are given.

	Hypophosphatemia			Hyperphosphatemia		
Variable	Odds Ratio	95% Confidence Interval	*P*	Odds Ratio	95% Confidence Interval	*P*
Low [SUN] (<5 mg/dL)	2.0	1.6–2.7	<.0001			
Diagnosis: LDA	1.9	1.3–2.8	.0021			
High AST (>130 U)	1.5	1.1–2.0	.0036			
High [SUN] (−22 mg/dL)				9.0	3.3–24.6	<.0001
Low [Cl] (<95 mmol/L)				1.7	1.1–2.6	.0091

[SUN], serum urea nitrogen concentration; LDA, left displaced abomasum; [AST], aspartate amino transferase activity; [Cl], serum chloride concentration.

pophosphatemia 1.9 times when compared to cattle without an LDA (Table 2), with age not influencing the likelihood of hypophosphatemia. A decrease in serum [Pi] with age has been previously reported in dairy cows[15,16]; however, serum [Pi] decreases in the early postparturient period due to the increased activity of the parathyroid hormone and the sudden loss of phosphorus into the milk.[17] Because the majority of cows in data set 1 were in early lactation, a possible effect of age on serum [Pi] may have been masked by the transient deregulation of phosphorus homeostasis in the postparturient period.

Cows that presented for surgical correction of a DA in the first 10 days after parturition had higher serum [Pi] values than did cows that presented at a later stage of lactation. It can be hypothesized that cows experiencing a DA shortly after calving have had substantially lower milk yield in the first days of lactation and a smaller loss of phosphorus into the milk compared with cows that developed DA later in lactation. Nonetheless, we believe that the timing of diagnosis and the duration of decreased feed intake are major factors influencing serum [Pi]. Cows that present at a later stage of DA are more likely to have been off feed for a longer time and therefore have a decreased serum [Pi].[18,19]

Serum [Pi] was most strongly associated with serum [Mg] and [SUN] on the basis of Pearson correlation coefficients. Like serum [Pi], serum [Mg] and [SUN] depend on a balance between feed intake and renal excretion.[20,21] The kidney is a more important route of excretion for urea nitrogen and magnesium than for phosphorus, because saliva is the major route of phosphorus excretion in ruminants.[21,22] The positive correlations between serum [Pi] and serum [Mg] and between serum [Pi] and [SUN], together with the association between low [SUN] and hypophosphatemia, imply that decreased feed intake is the major cause for hypophosphatemia in cows with a DA.[20]

The negative correlation between serum [Pi] and AST activity and between serum [Pi] and [TBil] in cows with an LDA, together with the association between hypophosphatemia and increased AST activity, suggest that disturbed liver function and hepatic injury also contribute to the development of hypophosphatemia. Hepatic lipidosis is considered a possible cause of hypophosphatemia in dairy cows,[h] and decreased serum [Pi] is frequently associated with liver failure in human beings.[23,24] However, it remains unclear whether patients with liver failure are inclined to develop hypophosphatemia or if hypophosphatemia is a predisposing factor for liver failure.[24,25] Similarly, in ruminants, it is not known whether the liver is directly involved in the regulation of phosphorus homeostasis or if serum [Pi] decreases solely as a result of reduced feed intake in animals with hepatic dysfunction.

The negative correlation between serum [Pi] and serum [Cl] found in patients with a DA or AV is consistent with the sequestration of chloride in the DA[26] and maintenance of electroneutrality, because chloride and inorganic phosphate are 2 of the 4 most important anions in plasma. Hypochloremia is a common finding in animals with decreased renal blood flow and azotemia.[22,27] Because dehydration and prerenal azotemia frequently develop in cows with an RDA or AV,[26] we would expect exacerbation of hypochloremia in cattle with an RDA or AV and deceased renal blood flow, potentially providing one explanation for the stronger negative correlation between serum [Pi] and serum [Cl] in cows with RDA/AV ($r = -0.61$) than in cows with an LDA ($r = -0.19$). The correlations of serum [Pi] with [SUN], [creatinine], [TP], [Mg], PCV, [Hb] and the degree of dehydration, as well as the strong association of hyperphosphatemia with azotemia and hypochloremia, indicate that dehydration and decreased renal blood flow are the main driving forces for the higher serum [Pi] in animals with an RDA or AV. The negative correlation of serum [Pi] with blood pH and the even stronger correlation of serum [Pi] with [Lact] and [Pyr] indicate the importance of decreased tissue perfusion, and the resulting lactic acidemia, as contributing to hyperphosphatemia in cows with an AV. Hypovolemia can be acute and severe enough to cause tissue hypoxia with a breakdown of high-energy organic phosphate compounds and can result in an increase in [Pi].[h] Moreover, lactic acidemia, resulting from increased anaerobic glycolysis, has been shown to be associated with hyperphosphatemia in other species.[28,29]

The weak correlation between serum [Pi] and AST activity in data set 1 could not be reproduced in data set 2, possibly because of the smaller number of animals. This weak correlation may be due to muscle weakness in dehydrated animals with an RDA or AV, which leads to a higher risk of muscle trauma and recumbency.

The data obtained in our study are in clear contrast to the results reported in another study. Robertson[9] found in a group of 46 cows with an LDA that 44% were hyperphosphatemic and that only 2% were hypophosphatemic. It must be mentioned that Robertson defined hypophosphatemia as serum [Pi] $<$0.65 mmol/L and hyperphosphatemia as serum [Pi] $>$1.6 mmol, ranges that nowadays must be considered inappropriate for dairy cattle.[14]

In conclusion, our findings indicate that hypophosphatemia occurs frequently in cows with an LDA, probably as a result of decreased feed intake and possibly due to decreased hepatic function or hepatic injury. In comparison, our findings indicate that hyperphosphatemia is the most common phosphorus derangement in cows with an RDA or AV and suggest that hyperphosphatemia is most likely the result of dehydration and decreased renal blood flow. Correction of hypophosphatemia in cows with an LDA should therefore focus on increasing feed intake, whereas correction of hyperphosphatemia in cows with an AV should focus on rehydration and increasing renal blood flow and the glomerular filtration rate.

Footnotes

[a] Hitachi 704 chemistry analyzer, Roche Diagnostics, Rotkreuz, Switzerland

[b] Ion selective electrodes, Beckman Synchron EL-ISE, Krefeld, Germany

[c] Flame atomic absorption spectrophotometer, Phillips Scientific PH9200, Cambridge, UK

[d] Automatic cell counter, Nihon Kohden MEK 6108, Rosbach, Germany

[e] Hitachi 704 autoanalyzer, Roche Diagnostics, Rotkreuz Switzerland

[f] IL system 1302 blood gas analyzer, Instrumentation Lab Inc, Lexington, MA
[g] SAS software, Statistical Analysis Systems Institute, Cary, NC
[h] Staufenbiel R, Gelfert CC. Clinical significance of hypophosphatemia in dairy cows. Proceedings XXII World Buiatrics Congress 2002, Hanover, Germany, 8 (abstract).

References

1. Satter L. What goes in must come out—Phosphorus balance on dairy farms. AABP Proc 2002;35:125–130.
2. Correa MT, Erb HN, Scarlett JM. Risk factors for Downer cow syndrome. J Dairy Sci 1993;76:3460–3463.
3. MacWilliams PS, Searcy GP, Bellamy JEC. Bovine postparturient hemoglobinuria: A review of the literature. Can Vet J 1982;23:309–312.
4. Call JW, Butcher JE, Shupe JL, et al. Clinical effects of low dietary phosphorus concentrations in feed given to lactating dairy cows. Am J Vet Res 1987;48:133–136.
5. Gerloff BJ, Morrow DA. Effect of nutrition on reproduction in dairy cattle. In: Morrow DA, ed. Current Therapy in Theriogenology, 2nd ed. Philadelphia, PA: WB Saunders; 1986:317–318.
6. Rohn M, Tenhagen BA, Hofman W. Survival of dairy cows after surgery to correct abomasal displacement: 1. Clinical and laboratory parameters and overall survival. J Vet Med Ser A 2004;51:294–299.
7. Roussel AJ, Cohen ND, Hooper RN. Abomasal displacement and volvulus in beef cattle: 19 cases (1988–1998). J Am Vet Med Assoc 2000;216:730–733.
8. Lattmann J. Untersuchung des Elektrolytgehaltes von Speichel, Serum and Pansensaft gesunder sowie an labmagenverlagerungsbedingter Störung der Ingestpassage leidender Rinder. Dtsch Tieraerztl Wochenschr 1984;91:146–149.
9. Robertson J McD. Left displacement of the bovine abomasum: Laboratory findings. J Am Vet Med Assoc 1966;149:1430–1434.
10. Geishauser T. Abomasal Displacement in the bovine: A review on character, occurrence, aetiology and pathogenesis. J Vet Med Ser A 1995;42:229–251.
11. Constable PD. Clinical assessment of acid-base status: Comparison of the Henderson-Hasselbalch and strong ion approaches. Vet Clin Pathol 2000;29:115–128.
12. Constable PD, Streeter RN, Koenig GJ, et al. Determinants and utility of the anion gap in predicting hyperlactatemia in cattle. J Vet Intern Med 1997;11:71–79.
13. Constable PD, Walker PG, Morin DE, et al. Clinical and laboratory assessment of hydration status of neonatal calves with diarrhea. J Am Vet Med Assoc 1998;212:991–996.
14. Goff JP. Treatment of calcium, phosphorus, and magnesium balance disorders. Vet Clin North Am Food Anim Pract 1999;15:619–639.
15. Tumbleson ME, Wingfield WE, Johnson HD, et al. Serum electrolyte concentrations, as a function of age in female dairy cattle. Cornell Vet 1972;63:58–64.
16. Roussel JD, Aranas TJ, Seybt SH. Metabolic profile testing in Holstein cattle in Louisiana: Reference values. J Am Vet Res 1982;43:1658–1660.
17. Goff JP. Pathophysiology of calcium and phosphorus disorders. Vet Clin North Am Food Anim Pract 2000;16:2:319–335.
18. Valk H, Sebek LBJ, Beynen AC. Influence of phosphorus intake on excretion and blood plasma concentration of phosphorus in dairy cows. J Dairy Sci 2002;85:2642–2649.
19. Rodehutscord M, Pauen A, Windhausen P, et al. Effects of drastic changes in P intake on P concentrations in blood and rumen fluid of lactating ruminants. J Vet Med Ser A 1994;41:611–619.
20. Ropstad E, Vik-Mo L, Refsdal AO. Levels of milk urea, plasma constituents and rumen liquid ammonia in relation to feeding of dairy cows during early lactation. Acta Vet Scand 1989;30:199–208.
21. Reinhardt TA, Horst RL, Goff JP. Calcium, phosphorus, and magnesium homeostasis in ruminants. Vet Clin North Am Food Anim Pract 1988;4:331–349.
22. Brobst DF, Parish SM, Torbeck RL, et al. Azotemia in cattle. J Am Vet Med Assoc 1978;173:481–485.
23. Pomposelli JJ, Pomfret EA, Burns DL, et al. Life-threatening hypophosphatemia after right hepatic lobectomy for live donor adult liver transplant. Liver Transplant 2001;7:637–642.
24. Knochel JP. The pathophysiology and clinical characteristics of severe hypophosphatemia. Arch Intern Med 1977;137:203–220.
25. Dawson DJ, Babbs C, Warnes TW, et al. Does hypophosphatemia play a role in acute liver failure? Br Med J 1987;295:1312–1313.
26. Taguchi K. Relationship between degree of dehydration and serum electrolytes and acid-base status in cows with various abomasal disorders. J Vet Med Sci 1995;57:257–260.
27. Watts C, Campbell JR. Further studies on the effect of total nephrectomy in the bovine. Res Vet Sci 1971;12:234–245.
28. O'Connor LR, Klein KL, Bethune JE. Hyperphosphatemia in lactic acidosis. N Engl J Med 1977;297:707–709.
29. Oster JR, Alpert HC, Vaamonde CA. Pathogenesis of hyperphosphatemia in lactic acidosis disparate effect of racemic (DL-) and levo (L-) lactic acid on plasma phosphorus concentration. Can J Physiol Pharmacol 1985;63:1599–1602.