Clinicopathologic variables associated with hypokalemia in lactating dairy cows with abomasal displacement or volvulus

Peter Constable, BVSc, PhD, DACVIM, DACVN; Walter Grünberg, Dr med vet, PhD; Rudolf Staufenbiel, Prof Dr med vet; Henry R. Stampfli, DVM, Dr Med Vet, DACVIM

Objective—To identify potential mechanisms for hypokalemia in dairy cows with left-displaced abomasum (LDA), right-displaced abomasum (RDA), or abomasal volvulus (AV).

Design—Retrospective analysis of clinicopathologic data from 2 convenience samples of cows.

Sample—112 lactating dairy cows with AV (group 1); 1,332 lactating dairy cows (group 2) with LDA (n = 1,160) or RDA or AV (172).

Procedures—Data were analyzed via Spearman ρ and multivariate stepwise regression.

Results—78 of 112 (70%) group 1 cows were hypokalemic (mean serum potassium concentration, 3.9 to 6.8 mEq/L). For group 1 cows, serum chloride concentration had the strongest positive association with serum potassium concentration, and serum potassium concentration was negatively associated with plasma bicarbonate and serum glucose, creatinine, and urea concentrations. Six hundred thirty-six of 1,160 (55%) of group 2 cows with LDA were hypokalemic (mean serum potassium concentration, 3.7 mEq/L). Ninety-two of 172 (53%) group 2 cows with RDA or AV were hypokalemic (mean serum potassium concentration, 3.8 mEq/L). For group 2 cows, serum chloride concentration had the strongest positive association with serum potassium concentration, and serum potassium concentration was negatively associated with indices of feed intake (serum bilirubin concentration) and hydration status.

Conclusions and Clinical Relevance—Results suggested hypokalemia was associated with hypochloremia, alkalemia, low feed intake with high amount of milk produced, hypovolemia, and hyperglycemia in lactating dairy cows. Treatment of hypokalemia should include surgical correction of abomasal displacement, increased dietary potassium intake via dietary dry matter intake or oral administration of KCl, and correction of hypochloremia, alkalemia, metabolic alkalosis, and dehydration. (J Am Vet Med Assoc 2013;242:826–835)

Hypokalemia commonly develops in dairy cows with LDA, RDA, AV, abomasal impaction,1–4 clinical mastitis,5,6 retained placenta,7 or hepatic lipidosis.8,9 Although reports10–12 of hypokalemia in recumbent cattle were published in the 1950s and 1960s, clinical signs of hypokalemia in lactating dairy cattle have been reported13–15 with increasing frequency during the past 15 years. Cows with severe hypokalemia have decreased gastrointestinal tract smooth muscle tone, signs of depression, and profound skeletal muscle weakness leading to recumbency.13–15 The reason for the apparent increase in the incidence of severe hypokalemia is unknown but may be related, in part, to increased milk yield16 and administration of multiple doses of isoflupredone acetate for treatment of ketosis in cows.10,13,15,17–19

Hypokalemia is more common in dairy cattle than it is in beef cattle.20 This finding is most likely attributable to the higher incidence of LDA, RDA, and AV in dairy cows versus beef cows21; such diseases cause alkalemia because of sequestration of chloride in the gastrointestinal tract and decreased dietary chloride intake.22,23 Loss of potassium in milk of lactating dairy cows (1.4 g of potassium/L of milk),24,25 lower muscle mass in dairy cows versus beef cows (which results in decreased total body potassium stores), and use of glucogenic and skeletal muscle protein for energy during early lactation. Dairy cows that produce large amounts of milk have a significantly lower mean serum potassium concentration than do dairy cows that produce small amounts of milk,16 and such cows are at an increased risk for hypokalemia during early lactation.

ABBREVIATIONS

AST  Aspartate aminotransferase
AV  Abomasal volvulus
LDA  Left-displaced abomasum
RDA  Right-displaced abomasum

From the Department of Veterinary Clinical Sciences, College of Veterinary Medicine, Purdue University, West Lafayette, IN 47907 (Constable); Inwendige Zieken, Faculteit der Diergeneeskunde, Universiteit Utrecht, 3584 CM Utrecht, The Netherlands (Grüngberg); and the Department of Clinical Studies, Ontario Veterinary College, University of Guelph, Guelph, ON N1H 2W1, Canada (Stampfli). Work for this study was performed at Purdue University, West Lafayette, IN 47907; The Ohio State University, Columbus, OH 43210; Freie Universität Berlin, D-14163 Berlin, Germany; and University of Guelph, Guelph, ON N1H 2W1, Canada.

Address correspondence to Dr. Constable (constabl@purdue.edu).

Unauthenticated | Downloaded 12/21/23 10:30 AM UTC
because of increased loss of potassium in milk and a marked negative energy balance. Catabolism of intracellular glycogen and protein leads to increased potassium excretion in urine (and therefore depletion of total body potassium) because some potassium in the body is bound to glycogen and protein. Hypokalemia also commonly develops in cattle with alkalosis because of metabolic alkalosis or hyperglycemia attributable to a shift of potassium from extracellular to intracellular spaces. Alkalosis causes a decrease in plasma potassium concentration, and acidemia causes an increase in plasma potassium concentration within 1 to 2 hours (mean ratio of change in potassium concentration to change in pH, –0.3 to –0.5 mEq/L:0.1). The effect of pH on plasma potassium concentration is independent of changes in the total amount of potassium in the body.

Development of optimal treatment protocols for hypokalemic lactating dairy cows requires a thorough understanding of the mechanisms of development of hypokalemia. Ruminants have evolutionarily adapted to high dietary intake of potassium and, as a result, have a greater capacity to excrete potassium versus other animals. Results of studies including small numbers of cattle with naturally acquired or experimentally induced hypokalemia indicate that serum potassium concentration is positively associated with serum chloride concentration and is negatively associated with plasma bicarbonate or total CO2 concentration. Similar, but stronger, relationships among those variables have been determined for potassium-depleted rats. These findings suggest that alkalosis secondary to sequestration of chloride in the gastrointestinal tract, as develops in cattle with abomasal displacement or gastrointestinal tract hypomotility, may have an important role in development of hypokalemia. Other potentially important factors that could contribute to development or persistence of hypokalemia are decreased appetite, hypovolemia with retention of sodium in the body, and hyperinsulinemia secondary to hyperglycemia. The primary objective of the study reported here was to analyze data for lactating dairy cows determined in vitro and in vivo to identify potential mechanisms for hypokalemia in such cows with abomasal displacement or volvulus.

Materials and Methods

Animals—Blood samples for in vitro performance of CO2 tonometry were obtained from 10 healthy Holstein-Friesian calves (5 female and 5 male; age range, 4 to 55 days). Medical records of 112 lactating dairy cows with AV that underwent surgery at The Ohio State University Veterinary Teaching Hospital from January 1987 to September 1988 and during 1990 were reviewed (group 1 cows). Medical records of 1,372 lactating dairy cows evaluated at the Freie Universität Berlin for surgical correction of LDA, RDA, or AV between January 2000 and September 2003 were reviewed (group 2 cows). The study was approved by the institutional animal care and use review board.

In vitro CO2 tonometry—Twenty milliliters of venous blood was collected from a jugular vein of each of 10 healthy Holstein-Friesian calves into partially evacuated tubes containing lithium-heparin. Plasma was harvested via centrifugation (1,300 × g for 5 minutes) within 30 minutes after collection and stored for up to 2 months at –70°C. Plasma was thawed at room temperature (approx 22°C) immediately before performance of CO2 tonometry for 20 minutes at 37°C as described elsewhere. The use of variable mixtures of humidified 20% CO2 and 100% O2 for tonometry produced varying values for PCO2 and pH over a PCO2 range of 15 to 159 mm Hg and a pH range of 7.79 to 6.93. A total of 157 plasma samples (14 to 16 plasma samples/calf) were analyzed via CO2 tonometry; therefore, 14 to 16 PCO2 and pH values were determined for each calf. Each plasma sample that was analyzed via tonometry was also analyzed in duplicate by use of ion-selective potentiometry for determination of plasma pH, PCO2, and concentrations of sodium, potassium, calcium, and chloride.

Data for group 1 cows—The medical records of 112 lactating dairy cows with AV that underwent surgery at The Ohio State University Veterinary Teaching Hospital from January 1987 to September 1988 and during 1990 were reviewed, and various data were obtained for analyses. Inclusion criteria were intraoperative confirmation of a diagnosis of AV in accordance with established guidelines and availability of the results of preoperative jugular venous blood gas analysis and serum biochemical analyses. The 112 lactating dairy cattle included in this study were a subset of 121 cattle with AV included in other studies.

For each cow, a blood sample had been collected from a jugular or the coccygeal vein with an 18-gauge, 1.5-inch needle attached to a 12-mL polypropylene syringe and transferred to a partially evacuated tube or collected directly into a partially evacuated tube. Blood samples were allowed to clot at room temperature, and serum was harvested and analyzed as previously described. For each cow, a blood sample had also been collected anaerobically into a polypropylene syringe containing heparin and analyzed immediately for determination of blood pH, PCO2, and PO2. The blood pH, PCO2, and PO2 values were corrected for the rectal temperatures of cows, and plasma bicarbonate concentration and base excess values were calculated by use of standard equations.

Data for group 2 cows—The medical records of 1,372 lactating dairy cows evaluated at the Freie Universität Berlin for surgical correction of LDA, RDA, or AV between January 2000 and September 2003 were reviewed, and various data were obtained for analysis. Inclusion criteria were intraoperative confirmation of a diagnosis of LDA, RDA, or AV in accordance with established guidelines and availability of results of preoperative serum biochemical analyses. Diagnoses of RDA and AV could not be differentiated on the basis of the medical records.

For each cow, blood samples had been collected via puncture of a jugular vein or the coccygeal vein or artery with an 18-gauge, 1.5-inch needle. Serum potassium, sodium, magnesium, calcium, chloride,
phosphorus, total bilirubin, and urea concentrations and AST activity were determined for blood samples collected in partially evacuated tubes without additives. Hemoglobin concentration and PCV were determined for blood samples collected in partially evacuated tubes containing EDTA. Serum magnesium, total bilirubin, urea, and phosphorus concentrations and AST activity were determined with an automated analyzer. Serum sodium, chloride, and potassium concentrations were measured with an ion-selective potentiometry analyzer. Packed cell volume and hemoglobin concentration were determined with an automated cell counter.

Statistical analysis—Hypokalemia was defined as a serum potassium concentration < 3.9 mEq/L, and hyperkalemia was defined as a serum potassium concentration > 5.8 mEq/L; the reference range (3.9 to 5.8 mEq/L) was determined on the basis of published recommendations. Data were expressed as mean ± SD values. Values of P < 0.01 were considered significant because of the large number of potentially related variables that were statistically compared. Various procedures of a statistical software program were used for analyses. Clinicopathologic values for cows in groups 1 and 2 were compared via ANOVA with raw, ranked, or log-transformed data so that the values approximated a normal distribution. The best transformation method was determined on the basis of the kurtosis and skewness values relative to a value of 0. Spearman correlation coefficients (ie, rs values) were calculated by use of raw values. Associations between measured clinicopathologic variables and serum or plasma potassium concentration were tested via stepwise regression. Raw or log-transformed values were used for regression analysis on the basis of the adequacy of model fit, as assessed via examination of plots of observed versus predicted concentrations and residual plots. Forward regression was used for determination of the model; variables with values of P < 0.01 were included in the model, and variables with values of P < 0.01 were retained in the model.

Multivariable regression analysis was used to determine the linear association between plasma potassium concentrations and measured variables determined via CO2 tonometry of plasma samples by use of dummy variables for each calf (C1 through Cn; C1 = 1 if calf i [i < n], –1 if calf = n, and 0 otherwise). This resulted in an ANCOVA that accounted for between-subject variability in data, thereby increasing the precision with which slope and intercept values were estimated. Dummy variables were entered into the model first to account for between-calf differences before analyzing the primary variables of interest. Regression coefficients associated with dummy variables for each calf indicated by how much the intercept value for each calf varied from the mean value; however, this information was of minimal interest in this study and only estimated values for slopes and intercepts were reported.

Results

In vitro CO2 tonometry—Plasma potassium concentration was negatively correlated with plasma pH (r = –0.23; P = 0.003; Figure 1) and positively correlated with plasma PCO2 (r = 0.22; P = 0.006). Results of regression for plasma potassium concentration (dependent variable) and plasma pH, PCO2, PO2, and sodium, chloride, and calcium concentrations (independent variables) indicated that variations in plasma pH and chloride and sodium concentrations significantly accounted for changes in plasma potassium concentration (Table 1). The mean value of the ratio of the change in plasma potassium concentration to the change in plasma pH was –0.039 mEq/L:0.1.

Group 1 cows—Group 1 cattle with AV had a mean ± SD serum potassium concentration of 3.48 ± 0.79 mEq/L. Thirty-four of the 112 (30%) cows with AV had a serum potassium concentration within the reference range, whereas 78 (70%) were hypokalemic. Hyperkalemia was diagnosed for 1 group 1 cow with AV.

Serum biochemical analysis variables associated with serum potassium concentrations for group 1 cows were summarized (Table 2). Serum chloride concentration was the only variable that had a significant positive correlation with serum potassium concentration for group 1 cows (Figure 2), whereas a significant negative correlation was identified between serum potassium concentration and blood pH, plasma bicarbonate concentration and base excess, and serum glucose and urea concentrations. The mean value of the ratio of the change in serum potassium concentration to the change in pH was –0.42 mEq/L:0.1.

Results of forward stepwise regression for serum potassium concentration (dependent variable) and blood pH, plasma bicarbonate concentration, and serum chloride, glucose, and urea concentrations (inde-

Figure 1—Relationship between plasma potassium concentration and plasma pH determined via in vitro CO2 tonometry of 157 plasma samples obtained from 10 healthy calves (r = –0.23; P = 0.003). Filled circles indicate data. Horizontal dashed lines indicate lower and upper limits of the reference range for plasma potassium concentration (3.9 to 5.8 mEq/L). The thick solid black line is the linear regression line, and the thin solid black lines are upper and lower limits of the 95% confidence interval for the linear regression line.
Different from the mean potassium concentration of 3.72 ± 0.72 mEq/L, which was not significantly (p < 0.001) correlated with indices of feed intake (serum bilirubin concentration) and hydration status. Serum potassium concentration was positively associated with serum cation and anion concentrations and hydration status (Figure 4). In general, serum potassium concentration had the strongest positive correlation with serum chloride concentration (Table 3; Figure 3) whereas log-transformed serum bilirubin concentration had the strongest negative correlation with serum potassium concentration (Table 3; Figure 3).

Table 1 — Results of forward stepwise regression for clinicopathologic variables associated with serum or plasma potassium concentrations for 157 plasma samples obtained from 10 healthy calves analyzed via in vitro CO2 tonometry, 112 group 1 lactating dairy cows with AV, 172 group 2 lactating dairy cows with AV or RDA, and 1,160 group 2 lactating dairy cows with LDA.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Partial $R^2$</th>
<th>Total $R^2$</th>
<th>Parameter estimate</th>
<th>SE</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma samples of calves</td>
<td>0.885</td>
<td>0.885</td>
<td>7.010</td>
<td>1.072</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Intercept and $C_1$ to $C_4$</td>
<td>0.885</td>
<td>0.885</td>
<td>7.010</td>
<td>1.072</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Plasma pH</td>
<td>0.060</td>
<td>0.885</td>
<td>-0.380</td>
<td>0.041</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Chloride (mEq/L)</td>
<td>0.014</td>
<td>0.890</td>
<td>0.039</td>
<td>0.007</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Sodium (mEq/L)</td>
<td>0.016</td>
<td>0.896</td>
<td>-0.203</td>
<td>0.007</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Group 1 cows with AV</td>
<td>NA</td>
<td>NA</td>
<td>5.566</td>
<td>0.349</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Bicarbonate (mmol/L)</td>
<td>0.357</td>
<td>0.357</td>
<td>-0.065</td>
<td>0.011</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Group 2 cows with AV or RDA</td>
<td>NA</td>
<td>NA</td>
<td>5.566</td>
<td>0.349</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Chloride (mEq/L)</td>
<td>0.289</td>
<td>0.289</td>
<td>0.025</td>
<td>0.006</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Phosphorus (mmol/L)</td>
<td>0.073</td>
<td>0.362</td>
<td>0.296</td>
<td>0.076</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>log$_e$ urea (µmol/L)</td>
<td>0.089</td>
<td>0.431</td>
<td>-1.010</td>
<td>0.218</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Magnesium (mmol/L)</td>
<td>0.052</td>
<td>0.483</td>
<td>0.737</td>
<td>0.212</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>log$_e$ bilirubin (µmol/L)</td>
<td>0.028</td>
<td>0.511</td>
<td>-0.436</td>
<td>0.157</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Calcium (mmol/L)</td>
<td>0.023</td>
<td>0.534</td>
<td>0.446</td>
<td>0.166</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Group 2 cows with LDA</td>
<td>NA</td>
<td>NA</td>
<td>-1.308</td>
<td>0.604</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Intercept and $C_1$ to $C_9$</td>
<td>NA</td>
<td>NA</td>
<td>-1.308</td>
<td>0.604</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Plasma bicarbonate (mmol/L)</td>
<td>0.299</td>
<td>0.299</td>
<td>0.036</td>
<td>0.003</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Chloride (mEq/L)</td>
<td>0.081</td>
<td>0.380</td>
<td>-0.399</td>
<td>0.067</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Calcium (mmol/L)</td>
<td>0.023</td>
<td>0.403</td>
<td>0.399</td>
<td>0.082</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>log$_e$ AST (U/L)</td>
<td>0.015</td>
<td>0.418</td>
<td>0.077</td>
<td>0.007</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Magnesium (mEq/L)</td>
<td>0.012</td>
<td>0.430</td>
<td>0.609</td>
<td>0.122</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Hemoglobin (g/dL)</td>
<td>0.012</td>
<td>0.442</td>
<td>-0.010</td>
<td>0.002</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>log$_e$ urea (µmol/L)</td>
<td>0.008</td>
<td>0.449</td>
<td>-0.343</td>
<td>0.102</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Sodium (mEq/L)</td>
<td>0.006</td>
<td>0.455</td>
<td>0.015</td>
<td>0.004</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RBCs ($\times 10^6$ cells/µL)</td>
<td>0.004</td>
<td>0.460</td>
<td>0.091</td>
<td>0.032</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Variables are listed in order of entry into the forward stepwise regression model. *Values indicate results for dummy variables for calves 1 to 9. NA = Not applicable.

For group 2 cows with LDA, serum chloride concentration had the strongest positive correlation with serum potassium concentration (Table 3; Figure 3), whereas log-transformed serum bilirubin concentration values had the strongest negative correlation with serum potassium concentration (Figure 4). In general, serum potassium concentration was positively associated with serum cation and anion concentrations and hydration status whereas negative correlations with indices of feed intake (serum bilirubin concentration) were observed.

Table 2 — Clinicopathologic variables that were significantly correlated with serum potassium concentrations for 112 group 1 lactating dairy cows with AV.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$r_s$</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma bicarbonate (mmol/L)</td>
<td>-0.59</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Base excess (mmol/L)</td>
<td>-0.58</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Chloride (mEq/L)</td>
<td>-0.56</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Glucose (mg/dL)</td>
<td>-0.55</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Creatinine (mg/dL)</td>
<td>-0.42</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Blood pH</td>
<td>-0.37</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Urea (µmol/L)</td>
<td>-0.38</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Hemoglobin (g/dL)</td>
<td>-0.32</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Values of $P < 0.01$ were considered significant. $r_s$ = Spearman correlation coefficient.

To identify potential influences of age on potassium homeostasis, analyses were performed for group 2 cows with LDA categorized on the basis of age. For the analysis, animals ≤ 27 months old were classified as heifers, and animals ≥ 4 years old were classified as cows. Mean ± SD serum potassium concentration for heifers (n = 81) was 3.76 ± 0.64 mEq/L; this value did not significantly (P = 0.51) differ from the mean ± SD serum potassium concentration for cows (3.70 ± 0.72 mEq/L; n = 768).

For group 2 cows with LDA, serum chloride concentration had the strongest positive correlation with serum potassium concentration (Table 3; Figure 3), whereas log-transformed serum bilirubin concentration values had the strongest negative correlation with serum potassium concentration (Figure 4). In general, serum potassium concentration was positively associated with serum cation and anion concentrations and hydration status whereas negative correlations with indices of feed intake (serum bilirubin concentration) were observed.

Group 2 cows — Of 1,332 group 2 cows, 1,160 (87%) had LDA and 172 (13%) had RDA or AV. Group 2 cows with LDA had a mean potassium concentration of 3.72 ± 0.74 mEq/L, which was not significantly (P = 0.52) different from the mean potassium concentration of the reference range; of the 172 group 2 cows with RDA or AV, 80 (47%) had a serum potassium concentration within the reference range. Of the 1,160 cows with LDA, 636 (55%) were hypokalemic. Of the 172 cows with RDA or AV, 92 (53%) were hypokalemic. Hyperkalemia was diagnosed for 1 group 2 cow with RDA or AV and 1 group 2 cow with LDA.

To identify potential influences of age on potassium homeostasis, analyses were performed for group 2 cows with LDA categorized on the basis of age. For the analysis, animals ≤ 27 months old were classified as heifers, and animals ≥ 4 years old were classified as cows. Mean ± SD serum potassium concentration for heifers (n = 81) was 3.76 ± 0.64 mEq/L; this value did not significantly (P = 0.51) differ from the mean ± SD serum potassium concentration for cows (3.70 ± 0.72 mEq/L; n = 768).

For group 2 cows with LDA, serum chloride concentration had the strongest positive correlation with serum potassium concentration (Table 3; Figure 3), whereas log-transformed serum bilirubin concentration values had the strongest negative correlation with serum potassium concentration (Figure 4). In general, serum potassium concentration was positively associated with serum cation and anion concentrations and hydration status whereas negative correlations with indices of feed intake (serum bilirubin concentration) were observed.
Results of forward stepwise regression for group 2 cows with RDA or AV were summarized (Table 1). Serum chloride concentration accounted for 29% of the variation in serum potassium concentration. Serum phosphorus concentration, log10-transformed urea concentration values, and magnesium concentration accounted for 7%, 7%, and 5% of the variation in serum potassium concentration, respectively. The log10-transformed values of serum bilirubin and calcium concentrations were also significantly associated with serum potassium concentration.

Results of forward stepwise regression for group 2 cows with LDA were summarized (Table 1). Variation in serum chloride concentration accounted for 30% of the variation in serum potassium concentration, and variation in log10-transformed values of serum bilirubin concentration accounted for 8% of the variation in serum potassium concentration. Seven other variables were significantly associated with serum potassium concentration, but the contribution of those variables to the total $R^2$ value was < 8%.

In group 2 cows with RDA or AV, serum chloride concentration had the strongest positive correlation with serum potassium concentration (Table 3; Figure 3), whereas log10-transformed serum urea and bilirubin concentration values had the strongest negative correlation with serum potassium concentration (Figures 4 and 5). In general, serum potassium concentration was positively associated with serum cation and anion concentrations and was negatively correlated with indices of feed intake (serum bilirubin concentration) and hydration status (serum urea concentration [Figure 5] and blood hemoglobin concentration and RBC count).

In group 2 cows with RDA or AV, serum chloride concentration had the strongest positive correlation with serum potassium concentration (Table 3; Figure 3), whereas log10-transformed serum urea and bilirubin concentration values had the strongest negative correlation with serum potassium concentration (Figures 4 and 5). In general, serum potassium concentration was positively associated with serum cation and anion concentrations and was negatively correlated with indices of feed intake (serum bilirubin concentration) and hydration status (serum urea concentration [Figure 5] and blood hemoglobin concentration and RBC count).

Results of forward stepwise regression for group 2 cows with LDA were summarized (Table 1). Variation in serum chloride concentration accounted for 30% of the variation in serum potassium concentration, and variation in log10-transformed values of serum bilirubin concentration accounted for 8% of the variation in serum potassium concentration. Seven other variables were significantly associated with serum potassium concentration, but the contribution of those variables to the total $R^2$ value was < 8%.

Results of forward stepwise regression for group 2 cows with RDA or AV, serum chloride concentration had the strongest positive correlation with serum potassium concentration (Table 3; Figure 3), whereas log10-transformed serum urea and bilirubin concentration values had the strongest negative correlation with serum potassium concentration (Figures 4 and 5). In general, serum potassium concentration was positively associated with serum cation and anion concentrations and was negatively correlated with indices of feed intake (serum bilirubin concentration) and hydration status (serum urea concentration [Figure 5] and blood hemoglobin concentration and RBC count).

Results of forward stepwise regression for group 2 cows with LDA were summarized (Table 1). Variation in serum chloride concentration accounted for 30% of the variation in serum potassium concentration, and variation in log10-transformed values of serum bilirubin concentration accounted for 8% of the variation in serum potassium concentration. Seven other variables were significantly associated with serum potassium concentration, but the contribution of those variables to the total $R^2$ value was < 8%.

Results of forward stepwise regression for group 2 cows with RDA or AV, serum chloride concentration had the strongest positive correlation with serum potassium concentration (Table 3; Figure 3), whereas log10-transformed serum urea and bilirubin concentration values had the strongest negative correlation with serum potassium concentration (Figures 4 and 5). In general, serum potassium concentration was positively associated with serum cation and anion concentrations and was negatively correlated with indices of feed intake (serum bilirubin concentration) and hydration status (serum urea concentration [Figure 5] and blood hemoglobin concentration and RBC count).
Hypokalemia is common in lactating dairy cattle with abomasal displacement; 636 of 1,160 (55%) group 2 cows with LDA, 92 of 172 (53%) group 2 cows with RDA or AV, and 78 of 112 (70%) group 1 cows with AV in the present study were hypokalemic. Results of the present study suggested that hypokalemia in lactating dairy cattle with displaced abomasum developed in response to alkalemia secondary to sequestration of chloride in the gastrointestinal tract, low feed intake with high milk production, hyperglycemia (presumably with hyperinsulinemia), and hypovolemia.

Results of the present study indicated that low serum potassium concentrations were significantly associated with low serum chloride concentrations in group 2 cattle with LDA, RDA, and AV and high blood pH (indicating alkalemia), plasma base excess and bicarbonate, and total CO2 concentrations in group 1 cattle with AV; these findings suggested a negative relationship between serum potassium concentrations and strong ion (metabolic) alkalosis of cows. Alkalemia and metabolic alkalosis are frequently detected in dairy cattle with clinical signs of severe hypokalemia. Alkalalemia causes a decrease in serum potassium concentration and acidemia causes an increase in serum potassium concentration because of transfer of potassium between intracellular and extracellular spaces. The decrease in extracellular H+ concentration that develops during alkalemia presumably increases the transport of H+ out of cells in exchange for Na+ via Na+-H+ exchangers, thereby increasing the amount of intracellular sodium that can be exchanged for potassium via Na+,K+-ATPase pumps. Serum potassium concentration is widely accepted as an accurate indication of the amount of intracellular potassium in euglycemic or hypoglycemic animals with a blood pH within the reference range; however, during severe alkalemia, it is likely that only serum potassium concentrations < 2.5 mEq/L accurately indicate depletion of total intracellular potassium stores. Results of several other studies indicate that experimentally induced hypochloremia or alkalemia causes hypokalemia in cows. Feeding of a diet with low chloride content for 10 weeks induces severe metabolic alkalosis (mean circulating total CO2 concentration, 44 mmol/L) and marked hypokalemia (mean circulating potassium concentration, 2.2 mEq/L) in lactating dairy cattle. In another study, experimental induction of metabolic alkalosis in 3 Jersey cows via oral administration of sodium bicarbonate (1.5 g/kg [0.68 g/lb]) once, followed by 0.5 g/kg [0.23 g/lb], q 6 h for 36 hours) caused marked strong ion (metabolic) alkalosis (plasma base excess range, 14 to 19 mEq/L), hypokalemia (plasma potassium concentration range, 2.6 to 3.1 mEq/L), and a 6% to 10% increase in muscle potassium concentration; these findings indicated a shift of potassium from extracellular spaces to intracellular spaces in cows. Alkalemia and hypokalemia were experimentally induced in 5 Holstein-Friesian bulls following oral administration of sodium bicarbonate (2.5 g/kg [1.1 g/lb]).

Because cattle in the present study with hypokalemia typically had metabolic alkalosis, future studies may be warranted to determine whether hypokalemic cattle have total body potassium depletion. Successful treatment of hypokalemia in lactating dairy cattle requires correction of concurrent metabolic alkalosis and alkalemia. Oral administration of KCl seems to be the best route of administration and type of salt for treatment of cattle with hypokalemia, considering that potassium is needed in cattle with total body depletion of potassium and chloride is needed in cattle with alkalemia and a shift of potassium from extracellular to intracellular spaces. Because hypokalemia is frequently associated with hypophosphatemia, administration of K2HPO4 or KH2PO4 may also be indicated for treatment of hypokalemic cattle.

When plasma pH is within the reference range, approximately 1% and 2.5% of total potassium in plasma is bound to plasma proteins and bicarbonate, respectively.
Results of in vitro plasma CO₂ tonometry in the present study suggested that hypokalemia in cattle with plasma pH and bicarbonate concentrations higher than the reference range was partly attributable to increased binding of potassium to albumin or bicarbonate in plasma, which decreased the concentration of ionized potassium in plasma. This conclusion was made because the mean value of the ratio of the change in plasma potassium concentration to the change in plasma pH determined via in vitro plasma CO₂ tonometry was ~0.039 mEq/L:0.1, which was approximately one-tenth the values determined for cows with AV in the present study (~0.42 mEq/L:0.1) and estimates determined by other authors (~0.3 to ~0.5 mEq/L:0.1).32,42

Decreased dietary dry matter intake has an important role in development of hypokalemia in ruminants because decreased potassium intake decreases the rumen potassium concentration and therefore decreases the amount of potassium absorbed.24,33–41 In nonlactating dairy cattle, food withholding for 48 hours decreases the mean serum potassium concentration from 4.9 to 4.3 mEq/L.46 In beef steers, food withholding for 4 days decreases the mean plasma potassium concentration from 4.1 to 3.7 mEq/L.47 In adult steers, food withholding for 18 hours significantly decreases mean plasma potassium concentration from 4.2 to 3.6 mEq/L.48 Food withholding for 12 hours followed by transportation for 48 hours significantly decreases plasma potassium concentration in 2-year-old steers.49 In sheep, food withholding for 26 hours decreases mean rumen potassium concentration from 50 to 24 mEq/L and decreases mean plasma potassium concentration from 4.2 to 3.7 mEq/L.50 The positive associations between serum potassium concentration and serum calcium and phosphorus concentrations detected in group 2 dairy cattle with LDA, RDA, or AV in the present study were most likely attributable to a balance between dry matter intake and loss of electrolytes in milk. Similar associations between serum potassium concentration and serum calcium and phosphorus concentrations were detected for dairy cows from Denmark within 12 hours after calving.51 These findings regarding the effect of dry matter intake on serum potassium concentration are supported by results of another study52 that included cattle with abomasal displacement; results of that study indicated cattle are clinically normal within 3 days after surgical treatment of abomasal displacement, whereas serum potassium concentration of cattle does not increase to within the reference range until day 4 after surgery.

The efficiency of the gastrointestinal tract for absorption of potassium in lactating dairy cows is approximately 74% to 88%; potassium is absorbed in the forestomach and small intestine, and absorption in the forestomach predominates.53,54 Rumen fluid in cattle typically has a potassium concentration of 24 to 85 mEq/L.55 Because rumen fluid is typically isotonic, the potassium concentration in rumen fluid is dependent on the total dietary intake of potassium and sodium; the sum of the concentrations of potassium and sodium in rumen fluid of sheep is approximately 130 to 160 mEq/L.56 Rumen fluid potassium concentration and potassium absorption are both strongly dependent on dietary intake, indicating an increase in rumen potassium concentration via an increase in dietary intake of potassium directly increases potassium absorption from the gastrointestinal tract, even in cattle with decreased abomasal emptying rates attributable to displaced abomasum or gastrointestinal hypomotility. Results of another study56 indicate a strong linear relationship between the amount of potassium absorbed from the rumen and the rumen potassium concentration of sheep (amount of potassium absorbed from the rumen of sheep during 24 hours = 3.1 × rumen potassium concentration [in mEq/L] – 54). Cattle with LDA have a mean rumen potassium concentration of approximately 25 mEq/L, whereas the mean rumen potassium concentration in cattle with RDA or AV is approximately 35 to 40 mEq/L.57 Therefore, increasing dry matter intake or oral administration of KCl should increase the rumen potassium concentration and the amount of potassium absorbed from the forestomach in cattle with LDA, RDA, or AV.

Serum potassium concentration was negatively associated with serum glucose concentration in group 1 cattle with AV in the present study. Parenteral administration of insulin or release of endogenous insulin secondary to hyperglycemia induced via IV administration of dextrose or administration of corticosteroids can lead to hypokalemia because of movement of potassium with glucose into cells; such decreases in circulating concentrations of potassium are caused by transfer of potassium from extracellular to intracellular compartments and are not necessarily indicative of depletion of total body potassium stores.30,31 Insulin-dependent cellular uptake of potassium is thought to occur via translocation of isoform-specific Na⁺,K⁺-ATPase subunits from various intracellular sources to the plasma membrane,32 thereby increasing activity of Na⁺,K⁺-ATPases.

The findings of the present study that serum potassium concentrations of cows were negatively correlated with serum total bilirubin concentrations and AST activities suggested that liver function abnormalities and damage may also have contributed to development of hypokalemia. Alternatively, the negative association between serum potassium and total bilirubin concentrations may have been attributable to the duration of decreased feed intake and abomasal displacement because hyperbilirubinemia may result from stretching of the bile duct caused by changes in the position of the duodenum in cows with abomasal displacement.4 A distended gallbladder is frequently detected in cattle with LDA during surgery.4,22 This finding supports the theory that partial bile duct obstruction develops in cattle with LDA. Although hepatic lipidosis does not seem to cause an alteration in hepatic potassium concentrations in lactating dairy cattle,58 serum potassium concentration is negatively associated with percentage of fat in the liver of dairy cows that have LDA and hepatic lipidosis.59 Moreover, cows with hepatic lipidosis that die have a significantly lower serum potassium concentration versus cows with hepatic lipidosis that survive.9 Results of the present study indicated hypokalemia and hypovolemia (as indicated by high PCV and serum urea concentration) were associated with hypokalemia in cows, suggesting that hypovolemia-
hypokalemic-induced secretion of aldosterone had a role in development of hypokalemia. The effect of increased aldosterone secretion is increased renal excretion of potassium (so that sodium and a physiologically normal extracellular fluid volume are retained). Additional studies to determine the effects of hyperaldosteronemia in hypokalemic lactating dairy cows may be warranted.

For most cattle, LDA, RDA, or AV typically develops during the early period of lactation, and hypokalemia in cattle with displaced abomasum may be caused partly by factors other than that disease. Results of longitudinal studies indicate serum potassium concentrations in dairy cows slightly decrease during the first 2 to 4 weeks after calving. The amount of potassium in skeletal muscle is decreased at the time of calving. Urine potassium concentration is decreased immediately after calving, and erythrocyte potassium concentration increases after calving in cows (particularly in old cows). These results suggest dairy cattle have depletion of total body potassium stores immediately after calving. Moreover, mean plasma potassium concentration is 0.2 mEq/L lower in mature dairy cows than in heifers, and potassium concentrations in erythrocytes of dairy cows have a significant negative association with milk production and milk production rank. These findings support the theory that the amount of milk produced has an effect on potassium homeostasis in lactating dairy cows. A reduction in dry matter intake during the late period of gestation concurrent with increased loss of potassium after parturition (because of the onset of lactation) contributes to decreased total amount of potassium in the body and decreased plasma potassium concentration during the early period of lactation. To the authors’ knowledge, it is unknown whether the increase in milk production of dairy cows since the time that data were obtained for the present study (1987 to 1990 for group 1 cows and 2000 to 2003 for group 2 cows) has resulted in an increased prevalence of hypokalemia in cattle with abomasal displacement. Results of a study published in 1997 indicated hypokalemia preceded development of LDA in 3 cows in that study and results of an in vitro study published in 2010 indicated a decrease in potassium concentration causes a decrease in abomasal smooth muscle tone; therefore, hypokalemia may contribute to development of abomasal hypomotility and displacement in cows. Hypokalemia may also be associated with postpartum reproductive abnormalities, given that there is a negative correlation between serum potassium concentration and the frequency of development of retained placenta in cows and high serum sodium or potassium concentrations in cows during the postpartum period are associated with an increased time to uterine involution.

The serum potassium concentration reference range used to identify cows with hypokalemia in the present study was 3.9 to 5.8 mEq/L. This reference range was similar to a serum potassium concentration reference range (3.9 to 5.3 mEq/L) for adult cattle determined in another study but was higher than reference ranges reported in other studies (3.1 to 5.1 mEq/L in one study and 2.1 to 4.7 mEq/L in another study that included 14 dairy and 26 beef cattle > 1 month old). Age-specific reference ranges may be useful because serum potassium concentration is higher in calves < 6 months old than it is in cattle ≥ 6 month old. Measured values for serum or plasma potassium concentration can be affected by various factors. Lysis of RBCs during blood sample collection, storage, or centrifugation can increase the plasma sample potassium concentration because the potassium concentration in RBCs is approximately 10-fold higher than the potassium concentration in plasma. Results of another study indicate hemolysis frequently develops in blood samples during collection from the coccygeal vein or artery by use of an 18-gauge, 1.5-inch needle attached to a 5-mL partially evacuated tube; serum potassium concentration is 0.29 mEq/L higher in samples collected via that method versus samples collected from a jugular vein by use of a 14-gauge, 2-inch needle attached to a syringe. Blood samples collected for determination of plasma or serum potassium concentration should not be stored in iced water because cold temperatures decrease the activity of Na+-K+ pumps, which causes leakage of potassium from erythrocytes and leukocytes, thereby increasing the concentration of potassium in plasma or serum samples prepared from such blood samples. Results of other studies suggest blood samples should be centrifuged before transportation and plasma or serum should be harvested by use of a swinging bucket centrifuge within 2 hours after blood sample collection. Plasma samples are preferred (vs serum samples) for measurement of potassium concentrations because potassium is released from platelets during clotting; variability in platelet counts can therefore cause variability in differences between plasma and serum sample potassium concentrations. Even for blood samples collected via optimal methods, measured potassium concentrations can diurnally vary because circulating potassium concentrations in lactating dairy cows vary in response to feeding and milking; plasma potassium concentration varies from 3.8 to 4.3 mEq/L during a 24-hour period 2 weeks after calving and varies from 3.3 to 4.3 mEq/L during a 24-hour period 7 weeks after calving in cows fed a diet with high potassium content. Such diurnal effects on plasma potassium concentration are not as important in cattle with disease as they are in healthy cattle because dry matter intake and milk production are low in cows with disease.

Hypokalemia commonly developed in dairy cows with LDA, RDA, or AV in the present study; hypokalemia most likely resulted from alkalemia and metabolic alkalosis attributable to sequestration of chloride within the gastrointestinal tract, decreased feed intake relative to the amount of milk produced, and hypovolemia. Because most cattle with abomasal displacement have hypokalemic, hypochloremic metabolic alkalosis, and because serum potassium concentration is closely associated with serum chloride concentration, KCl should be routinely administered orally to dairy cows in which hypokalemia is suspected. For treatment of hypokalemia, dairy cattle with LDA, RDA, or AV should also undergo surgical correction of abomasal displacement, increase dietary dry matter intake, and receive treatments for dehydration.
The relationship between hypokalemia and depletion of total body potassium stores in cattle with displaced abomasum is not known, to the authors’ knowledge.

c. Stal Profile 91, NOVA Biomedical, Canada Ltd, Mississauga, ON, Canada.
d. IL system 1302 blood gas analyzer, Instrumentation Lab Inc, Lexington, Mass.
e. Hütcher 704 chemistry analyser, F Hoffmann-La Roche AG, Basel, Switzerland.
f. Beckman Synchrotron EL-ISE, Beckman Coulter GmbH, Krefeld, Germany.
g. Philips PK9200, Philips EWI Analysetechnik, Kassel, Germany.
h. Nilson Kohnen MEK 6108, Nilson Kohnen Europe GmbH, Rosbach vor der Höhe, Germany.
i. PROC ANOVA, SAS, version 9.2, SAS Institute Inc, Cary, NC.