Evaluation of the reticulorumen pH throughout the feeding period for beef feedlot steers maintained in a commercial feedlot and its association with liver abscesses

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OBJECTIVE
To evaluate the reticulorumen pH of beef feedlot steers throughout the feeding period and to assess the association between the respective durations that the reticulorumen pH was ≤ 5.6 (subacute ruminal acidosis) and ≤ 5.2 (acute ruminal acidosis) and liver abscess severity.

ANIMALS
59 feedlot steers (mean body weight, 349.5 kg).

PROCEDURES
On day 0, each steer was orally administered an electronic bolus that monitored the reticulorumen pH every 10 minutes for 150 days. Steers were transitioned from a starter to intermediate ration on day 8 (transition 1) and from the intermediate to finish ration on day 19 (transition 2). The ration carbohydrate and megacalorie contents increased with each transition. During each transition, the lower megacalorie ration was fed at the 8:00 AM feeding and the higher megacalorie ration was fed at the 2:00 PM feeding for 3 days before the higher megacalorie ration was fed extensively. Steers were sent to slaughter after 182 days; each carcass was assessed for liver abscesses.

RESULTS
The diurnal reticulorumen pH pattern was characterized by a peak at 7:00 AM and nadir at 8:00 PM. The mean percentages of time that the reticulorumen pH was ≤ 5.6 and ≤ 5.2 were more than 10-fold greater during transition 1, compared with during transition 2, and were significantly greater for steers with extensive liver abscesses than for steers without extensive liver abscesses.

CONCLUSIONS AND CLINICAL RELEVANCE
Efforts to minimize the duration that the reticulorumen pH is ≤ 5.6 might mitigate liver abscess formation in feedlot cattle. (*J Am Vet Med Assoc* 2021;259:899–908)

The rumen is remarkable at processing and digesting roughage and concentrates. Acetate, propionate, and butyrate are the primary VFAs produced in the rumen during the fermentation process. These VFAs are absorbed through the rumen wall, enter the circulation, and are transported to the liver where they are used for energy. Acetate is the primary VFA produced from high-fiber rations, whereas propionate is the predominate VFA produced from high-starch (ie, high-concentrate or high-carbohydrate) rations. Butyrate is produced through anaerobic fermentation and provides an energy source for epithelial cells.[1,2] An increase in propionate production is associated with a decrease in methane production and rumen pH.[3] The ability to adapt to high-concentrate rations varies greatly among cattle.[4] This individual animal variation results in the development of subacute or acute ruminal acidosis in some feedlot cattle, as the carbohydrate concentration in the ration is increased throughout the feeding period. Thus, subacute and acute ruminal acidosis are important issues in beef feedlot production.[5,6] Management of ration ingredients and feed bunks and the use of monensin to decrease meal size are examples of different practices the feedlot industry has adopted to regulate rumen pH and maximize cattle health and performance outcomes.[7–9]

In cattle, highly fermentable carbohydrates are considered the primary cause for clinical and subclinical ruminal acidosis, which contribute to the subsequent development of liver abscesses.[10,11] Severe liver abscesses are associated with a significant reduction in hot carcass weight (weight of the carcass immediately after the animal is slaughtered), carcass quality grade, and ADG.[12,13] The primary objective of the study reported here was to evaluate the reticulorumen pH of beef feedlot steers throughout the feeding

ABBREVIATIONS
ADG	Average daily gain
CFU	Colony-forming unit
DMI	Dry matter intake
DOF	Days on feed
VFA	Volatile fatty acid
VFD	Veterinary feed directive

period as they were transitioned onto rations with ever-increasing concentrations of highly fermentable carbohydrates. The secondary objective was to evaluate the association of the duration that steers had a reticulorumen pH ≤ 5.6 (subacute ruminal acidosis) and ≤ 5.2 (acute ruminal acidosis) during the entire feeding period with the incidence and severity of liver abscesses observed in those animals at slaughter.

Materials and Methods

Animals

All procedures were approved by the Veterinary Research and Consulting Services LLC Institutional Animal Care and Use Committee (IACUC No. 1005). The study was conducted at a commercial and research feedlot located near Montezuma, Kan, with the owners' consent. Sixty black beef steers from a single origin with a mean ± SD body weight of 349.5 ± 27.8 kg were enrolled in the study. All steers had been weaned for at least 60 days and were between 8 and 10 months old at the time of study enrollment. The steers were provided ad libitum access to grass hay and water at feedlot arrival. Approximately 12 hours later, the steers were processed (ie, day 0 or 0 DOF), during which each steer was individually weighed, had a uniquely numbered plastic ear tag and an electronic radio-frequency identification tag[a] applied to an ear, and was administered a trivalent modified-live virus vaccine[b] against bovine herpesvirus type 1 and bovine viral diarrhea virus types 1 and 2 (2 mL, SC), moxidectin[c] (0.2 mg/kg, SC), oxfendazole[d] (4.5 mg/kg, PO), a topical pyrethroid[e] (15 mL, topically along dorsal midline), and a growth-promoting implant[f] containing 80 mg of trenbolone acetate and 16 mg of estradiol (SC on the back of an ear). Seventy-three days later (ie, at 73 DOF), each steer received another growth-promoting implant[g] that contained 200 mg trenbolone acetate and 20 mg estradiol (SC on the back of an ear).

Reticulorumen pH bolus

The steers did not have any access to food other than grass hay until after processing in an effort to decrease rumen fill for placement of a reticulorumen pH monitoring bolus,[h] which was administered orally during processing. Prior to placement in each steer, the bolus was cross-referenced with the animal's identification number (plastic ear tag) and activated and calibrated with a buffer solution (pH, 7.00). The bolus was administered with a 35-mm-diameter balling gun. Following administration, the bolus settled on the floor of the reticulum, where it monitored the pH every 10 minutes for 150 days. The pH measurements were transmitted to an electronic data repeater that was mounted on a feeder where the steers were fed, which in turn transmitted the information to a base station. Data were continuously uploaded from the base station to a secure website via the internet. The accuracy of pH measurements obtained by the bolus is reported to be within ± 0.2 for up to 90 days after activation and placement and ± 0.4 between 90 and 150 days after placement.[14] The bolus could store data for up to 50 days if it could not communicate with the data repeater or base station.

Housing and feeding regimen

All steers were housed outside in 1 drylot (30.48 X 76.20 m). The steers had ad libitum access to water through an automatic float-activated water system. The pen was equipped with 8 data acquisition nodes[i] (nodes), through which all feed was delivered. The data acquisition system has been validated for use with feedlot cattle.[15,16] Each node could be accessed by only 1 steer at a time and was mounted on 2 load cells that continuously weighed the animal and available feed. The system recognized each steer by the radio-frequency identification tag in the animal's ear. It collected information regarding each individual animal's feed intake on a daily basis and stored it in a database for analysis.

The steers were fed 3 (starter, intermediate, and finish) rations throughout the feeding period **(Appendix)**.

Table 1—Summary of live animal and carcass performance variables for 59 black beef feedlot steers that were enrolled in a study to evaluate the reticulorumen pH during transitions from low- to intermediate- to high-carbohydrate rations throughout the feeding period.

Variable	Measure
ADG (kg/d)	1.78
F:G	6.01
Carcass weight (kg)	437.1
Dressing percentage (%)*	64.02
Quality grade†	
Prime	36 (61.02)
Choice	23 (38.98)
Yield grade‡	
1	0 (0.0)
2	3 (5.08)
3	22 (37.29)
4	26 (44.07)
5	8 (13.56)
Liver classification§	
Normal	23 (38.98)
A+	25 (42.37)
A−, A, and A+ combined	36 (61.02)

Values represent the mean for the pen or number (percentage) of steers.

*Dressing percentage represents the proportion of the carcass weight relative to the animal's live weight (ie, [carcass weight/live animal weight] X 100). †Quality grade is an assessment of tenderness, juiciness, and flavor of meat. The USDA defines 4 quality grades ([in descending order] prime, choice, select, and standard) on the basis of carcass maturity and marbling (ie, amount of fat within the muscle). ‡Yield grade is an estimate of the difference in the amount of lean red meat to waste fat. The USDA scores yield on a scale of 1 to 5, where 1 is most desirable (ie, a carcass with little waste fat), 3 is the industry standard, and 5 is the least desirable (ie, a carcass with excessive waste fat). §Livers with no abscesses were classified as normal. Livers with 1 or 2 small (≤ 2 cm in diameter) abscesses or inactive scars were classified as A–. Livers with 1 to 2 large (2 to 4 cm in diameter) abscesses or multiple small abscesses were classified as A, and livers with multiple large abscesses or a single abscess > 4 cm in diameter were classified as A+. Livers with ruptured abscesses and those with tissue adhesions were also classified as A+.

F:G = Feed-to-gain ratio.

Figure 1—Mean reticulorumen pH (A) and percentage of time that the reticulorumen pH was ≤ 5.6 (B) and ≤ 5.2 (C) during the 3 days before and 5 days after initiation of the transition from a starter ration to an intermediate ration (transition 1) for 59 black beef feedlot steers. All steers were instrumented with an electronic bolus that measured the reticulorumen pH every 10 minutes. The steers were fed twice daily at approximately 8:00 AM and 2:00 PM. The starter ration was fed during both feedings on transition days −3, −2, and −1. On transition days 0, 1, and 2 (ie, at 8, 9, and 10 DOF), the starter ration was fed during the morning feeding and the intermediate ration was fed during the afternoon feeding. The intermediate ration was fed during both feedings on transition days 3, 4, and 5. The red shading around the mean line represents the SE.
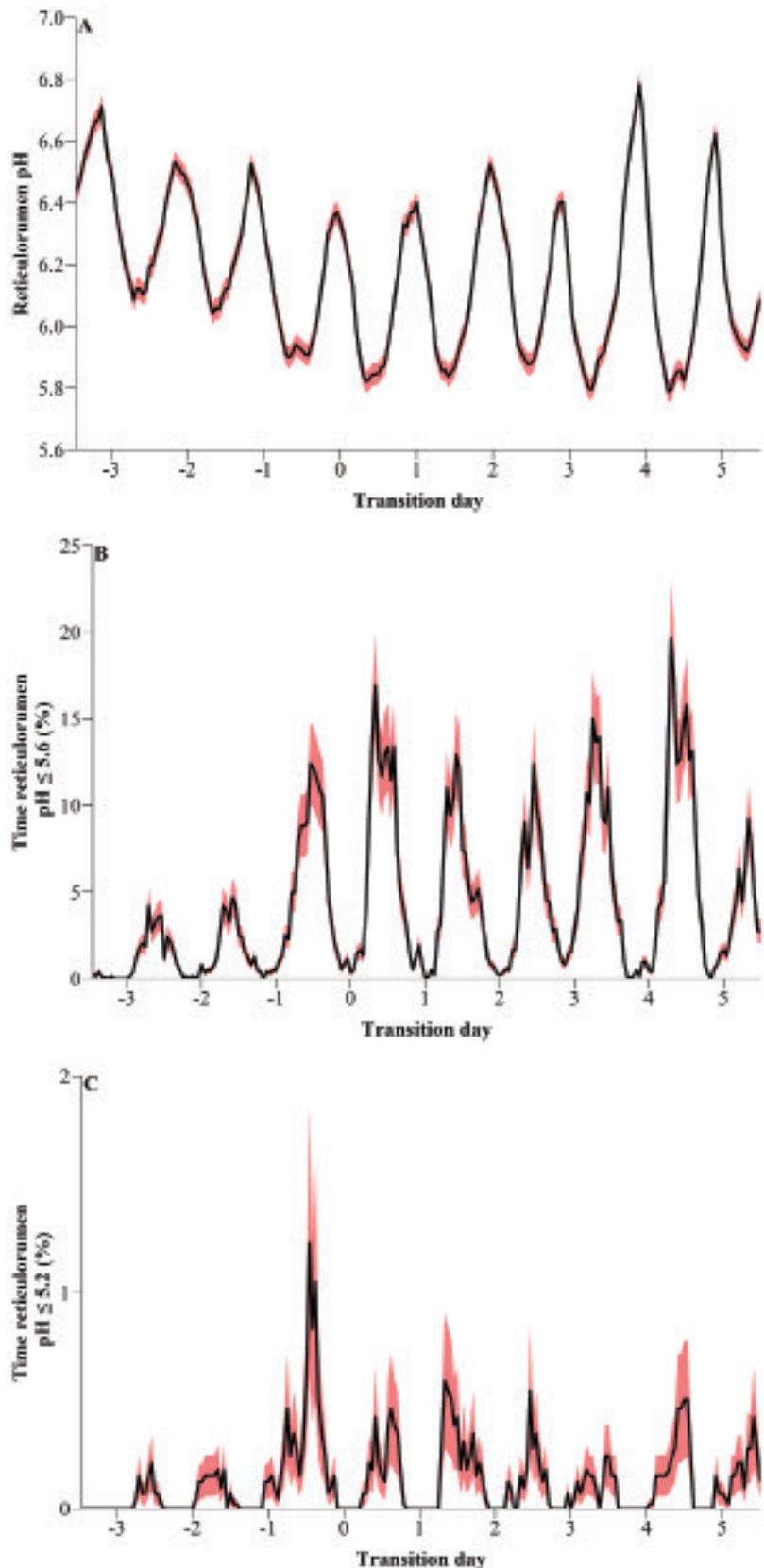
The carbohydrate content (and thus energy and megacalorie contents) progressively increased from the starter to intermediate to finish rations. Each ration was formulated to provide each steer with 60 to 90 mg of tylosin phosphate[j]/d (assuming 90% dry-matter basis), monensin[k] (37 g/ton), *Propionibacterium freudenreichii* (1 X 10^9 CFUs/steer/d)[l], and *Lactobacillus animalis* (1 X 10^9 CFUs/steer/d)[l] to enhance rumen fermentation and feed efficiency.

Steers were fed twice daily throughout the trial at approximately 8:00 AM and 2:00 PM. For the first 5 DOF, prairie hay was provided in bunks next to the nodes to facilitate adaptation of the steers to the starter ration. Steers were transitioned from the starter ration to the intermediate ration on day 8 and from the intermediate ration to finish ration on day 19. During each ration transition, the lower megacalorie ration was fed during the morning feeding and the higher megacalorie ration was fed during the afternoon feeding for 3 days before the higher megacalorie ration was fed during both daily feedings.

After 182 DOF, steers were shipped to a commercial packinghouse in Dodge City, Kan, on July 14, 2020. Steers were not fed on the day they were transported to the packinghouse. They were weighed in groups (23 and 36 steers/group) on a certified scale. A 4% pencil shrink (the percentage subtracted from the final live weight to adjust for expected variation in intra-animal weight [owing to normal daily homeostasis and effects of transport] and standardize weighing conditions across all cattle) was applied to the final live weight of each steer, and the shrink-adjusted weight was used to calculate ADG and feed-to-gain ratio.

Figure 2—Mean reticulorumen pH (A) and percentage of time that the reticulorumen pH was ≤ 5.6 (B) and ≤ 5.2 (C) during the 3 days before and 5 days after initiation of the transition from an intermediate ration to a finish ration (transition 2) for the steers of Figure 1. The intermediate ration was fed during both feedings on transition days –3, –2, and –1. On transition days 0, 1, and 2 (ie, at 19, 20, and 21 DOF), the intermediate ration was fed during the morning feeding and the finish ration was fed during the evening feeding. The finish ration was fed during both feedings on transition days 3, 4, and 5. *See* Figure 1 for remainder of key.

Liver classification

At the packinghouse, trained personnel cross-referenced the individual animal identification tags with the packing plant carcass identification. Quality grade and yield grade were provided for each carcass by a visual camera grading system. Trained personnel[m] classified the liver of each steer on the basis of the Elanco Liver Check System[n] as described.[13,17] Briefly, livers that were free of abnormalities were considered normal and acceptable for human consumption. Livers with 1 or 2 small (≤ 2 cm in diameter) abscesses or inactive scars were classified as A–. Livers with 1 to 2 large (2 to 4 cm in diameter) abscesses or multiple small abscesses were classified as A, and livers with multiple large abscesses or a single abscess > 4 cm in diameter were classified as A+. Livers with ruptured abscesses and those with tissue adhesions were also classified as A+. Liver specimens were not collected for culture or histologic evaluation.

Data analysis

Data were imported into a commercial software package.[o] The day of processing, during which the reticulorumen pH bolus was administered, was designated as 0 DOF, and all data from that day were excluded from analysis. Descriptive data were generated to describe the live (ADG and feed-to-gain ratio) and carcass (carcass weight, dressing percentage, quality grade, yield grade, and liver score) performance of the steers. For each steer, the reticulorumen pH was measured every 10 minutes for 150 days, and it was assumed that the pH remained the same for the duration of each 10-minute interval. The reticulorumen pH data were then aggregated into 3 subsets of
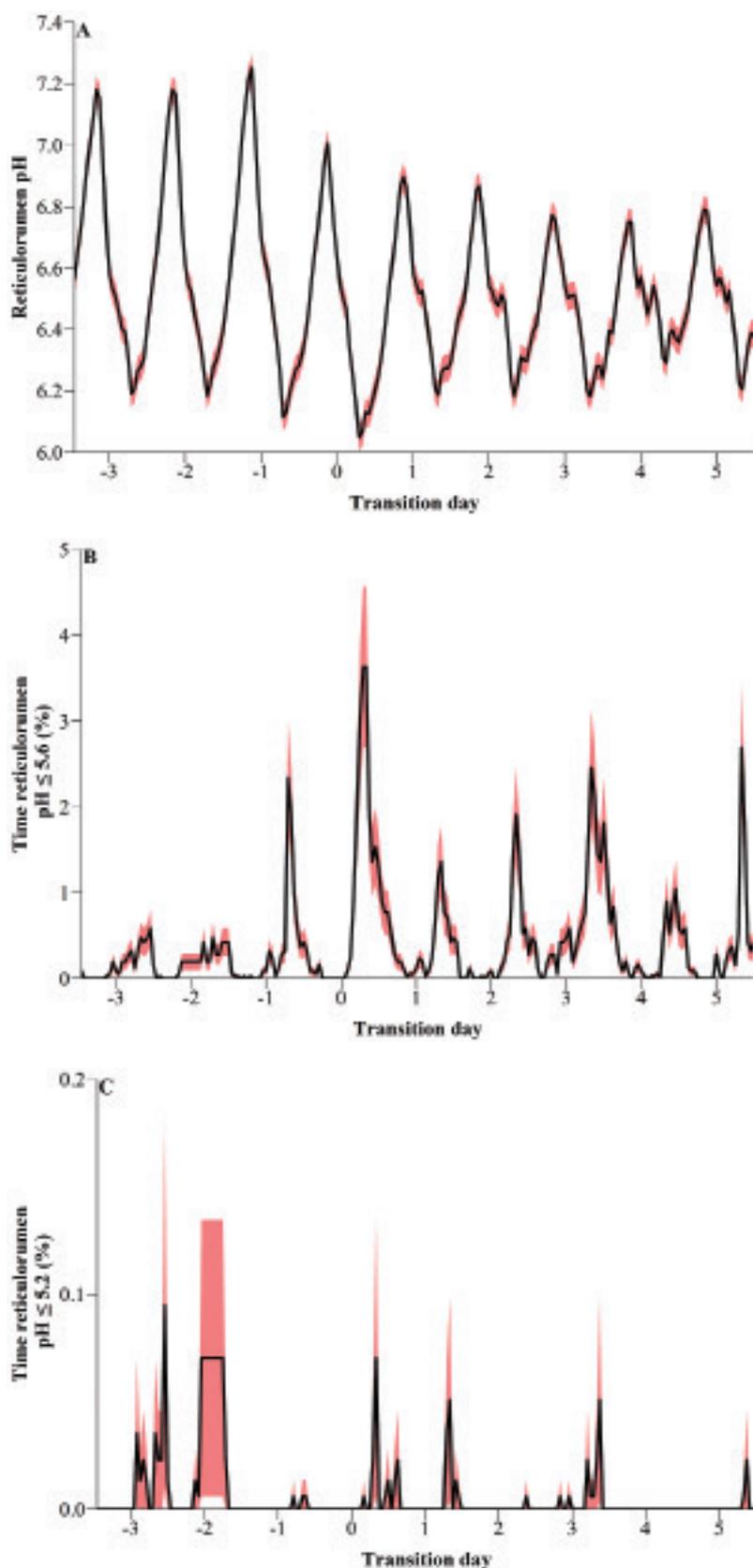
data (5 to 13 DOF [3 days before to 5 days after initiation of transition from starter to intermediate ration; transition 1], 16 to 24 DOF [3 days before to 5 days af-

ter initiation of transition from intermediate to finish ration; transition 2], and 22 to 150 DOF [time during which only the finish ration was fed; finish period]). Within each subset, data were dichotomized and tabulated to determine the frequency that each steer had a reticulorumen pH ≤ 5.6 (subacute ruminal acidosis) and ≤ 5.2 (acute ruminal acidosis).

For the transition 1 and 2 pH data subsets, generalized linear mixed models were used to assess factors associated with the mean reticulorumen pH and percentage of time that the reticulorumen pH was ≤ 5.6 and 5.2. For those models, the pH data for each steer were aggregated into (ie, the mean was calculated for) 1-hour intervals. Multivariable models were created in a stepwise manner by means of including all potential effects and removing nonsignificant ($P > 0.05$) effects 1 at a time in a stepwise manner. Each model included a random effect to account for repeated measures within steers. Only variables with $P < 0.05$ were retained in the final model.

For the finish period pH data subset, a generalized linear mixed model was used to assess the diurnal variation in reticulorumen pH. The model included random effects to account for repeated measures within steers and DOF and a fixed effect for initial body weight. A linear model was used to assess the effect of mean DMI on mean reticulorumen pH.

Generalized linear models were used to evaluate the respective relationships between the percentage of time that steers had a reticulorumen pH ≤ 5.6 and 5.2 throughout the entire feeding period and the prevalence of A+ liver abscesses and all liver abscesses (grades A–, A, and A+ combined). Each model included fixed effects for initial body weight and mean DMI. Linear models were used to assess the association between the minimum reticulorumen pH and the presence of A+ liver abscesses and all liver abscesses.

Results

One of the 60 steers was alternatively marketed because of musculoskeletal issues unrelated to the study, and all data for that animal were excluded from the analysis. All boluses were retained in the steers. Live animal and carcass performance data were summarized for the remaining 59 steers **(Table 1)**. The mean reticulorumen pH and respective percentages of time that the reticulorumen pH was ≤ 5.6 and ≤ 5.2 during transitions 1 **(Figure 1)** and 2 **(Figure 2)** were

plotted. The frequency distribution and diurnal pattern for the reticulorumen pH during the finish period were also plotted **(Figure 3)**. During the finish period, the mean ± SD reticulorumen pH was 6.48 ± 0.32 (median, 6.44). Evaluation of the diurnal pattern indicated that the reticulorumen pH peaked at 7:00 AM and achieved its nadir at 8:00 PM. The mean DMI was not significantly ($P = 0.73$) associated with the mean reticulorumen pH during the finish period.

The percentage of time that the reticulorumen pH was ≤ 5.6 during the entire feeding period for steers with an A+ liver abscess was significantly ($P < 0.01$) greater than that for steers without an A+ liver abscess. Conversely, the percentage of time that the reticulorumen pH was ≤ 5.6 during the entire feeding period for steers with any grade of liver abscess was significantly ($P = 0.03$) less than that for steers with normal livers **(Figure 4)**. The percentage of time that
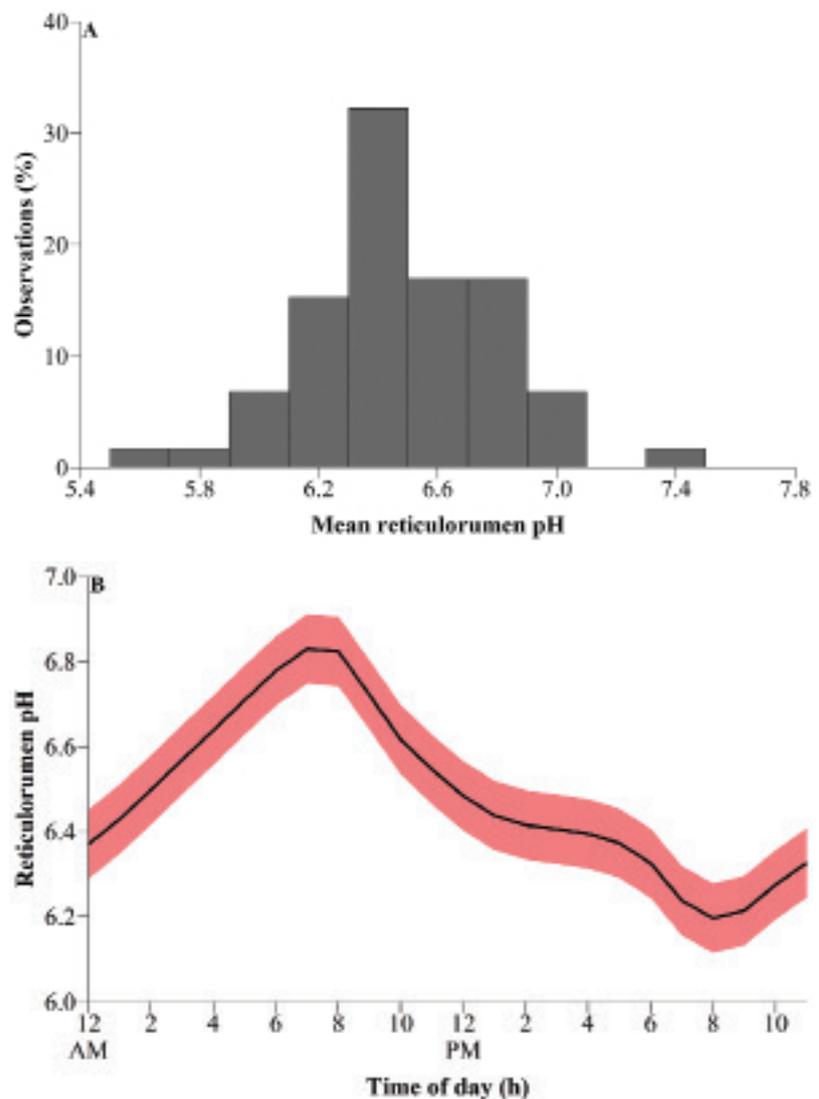
Figure 3—Histogram of the frequency distribution for the mean reticulorumen pH (A) and plot of the diurnal variation in mean reticulorumen pH (B) during the finish period (22 to 150 DOF) for the steers of Figure 1. *See* Figure 1 for remainder of key.
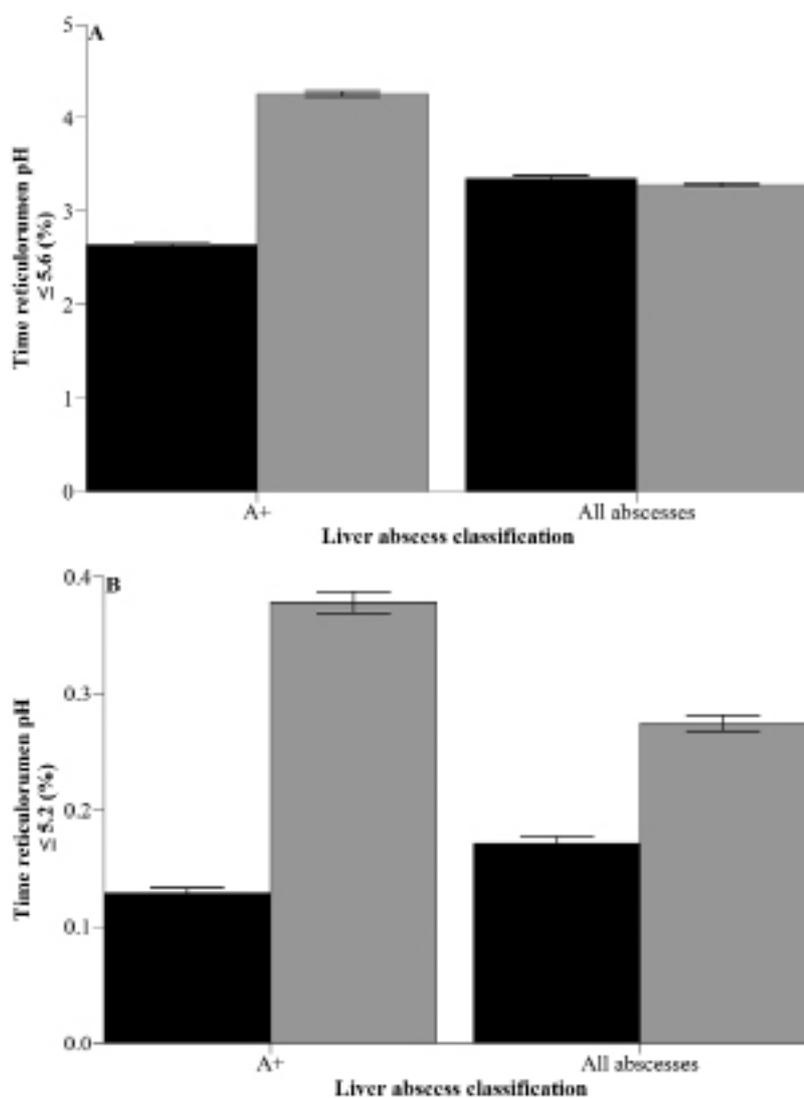
Figure 4—Mean ± SE percentage of time that the reticulorumen pH was ≤ 5.6 (A) and 5.2 (B) for the steers of Figure 1 that did (gray bars) and did not (black bars) have severe (grade A+) liver abscesses and all liver abscesses (grades A–, A, and A+ combined; all abscesses) identified at slaughter. *Within a liver abscess classification, the mean differs significantly ($P < 0.01$) between animals that did and did not have liver abscesses. **See** Figure 1 for remainder of key.

lorumen pH and the prevalence of liver abscesses in a fairly large number (n = 59) of feedlot steers maintained in a commercial feedlot setting. The steers of the present study were fed approximately 30 days past the planned or optimal endpoint owing to packinghouse disruptions caused by the COVID-19 pandemic. This was evidenced by the fact that the majority (34/59 [57.6%]) of the steers had a yield grade of 4 or 5 (ie, the carcasses had an excessive amount of waste fat [a yield grade of 3 is the industry standard]).

In the present study, the mean percentages of time that the steers had a reticulorumen pH ≤ 5.6 and ≤ 5.2 during transition 1 (ie, 3 days before to 5 days after initiation of the transition from the starter ration to the intermediate ration) were more than 10-fold greater than those during transition 2 (ie, 3 days before to 5 days after initiation of the transition from the intermediate to the finish ration). Reticulorumen pH values ≤ 5.6 and ≤ 5.2 were selected as cutoffs to represent subacute and acute ruminal acidosis.[5] A decrease in reticulorumen pH as the amount of highly fermentable carbohydrates in the ration increases is consistent with results of other studies.[19,21] Adaptation of cattle to a ration with a high concentration of carbohydrates as soon as possible after feedlot entry allows for efficient use of resources and improves animal performance.[4,5] However, nutritionists recommend that cattle be slowly introduced to high-concentrate diets to allow the reticulorumen microbes, which are necessary for digestion, to likewise adjust to the ration.[22,23] Transitioning cattle to a high-concentrate ration too rapidly can result in ruminal acidosis, poor performance, and health issues.[4,7,24] The development of ration transition protocols for feedlot cattle that avoid or minimize large fluctuations in the reticulorumen pH is necessary for optimal animal health and performance.

In feedlot cattle, variation in the reticulorumen pH is associated with fermentable carbohydrate intake and the ability of individual animals to buffer and absorb VFAs.[25] The rumen has physiologic feedback loops to regulate its pH. When the rumen pH is < 5.6, primary VFAs are undissociated (approx pKa, 4.9), increasing their absorption across the rumen wall in an effort to prevent a further decrease in rumen pH.[26,27] Continued accumulation of lactic acid within the rumen allows the rumen pH to decrease below 5.0.[28,29] For the steers of the present

the reticulorumen pH was ≤ 5.2 during the finish period for steers with an A+ liver abscess was significantly ($P < 0.01$) greater than that for steers without an A+ liver abscess. Likewise, the percentage of time that the reticulorumen pH was ≤ 5.2 for steers with any grade of liver abscess was significantly ($P < 0.01$) greater than that for steers with normal livers. There was no association between the minimum reticulorumen pH and the presence of an A+ liver abscess ($P = 0.16$) or liver abscesses of any grade ($P = 0.72$).

Discussion

The reticulorumen pH has been measured and reported for small numbers of beef cattle[18–20]; however, to our knowledge, the present study was the first to assess the relationship between variations in the reticu-

study, the small percentages of time that the mean reticulorumen pH was ≤ 5.6 and ≤ 5.2 suggested that the physiologic feedback mechanisms were effective in regulating rumen pH. Feedlot cattle that die because of digestive issues typically have a rumen pH ≤ 5.2 and gross signs of congestion in the anterior portion of the carcass, edema between the hindquarters, and compressed lung and liver tissues owing to compression and displacement by a gas-filled rumen; generally, no other gross lesions are identified during necropsy.[30,31] Rumen pH remains fairly consistent for up to 24 hours after death.[32] Most cattle can effectively regulate rumen pH until continued lactic acid production causes it to fall below 5.2, leading to acute ruminal acidosis.[29] Lactic acid stimulates growth of bacterial species that are resistant to low pHs, including *Lactobaccilli* spp, which exacerbate the decrease of rumen pH.[25,33] Continued production of lactic acid in the rumen following death may explain, in part, the low rumen pH typically observed in cattle that die from digestive issues. None of the steers of the present study died because of digestive abnormalities; therefore, we were unable to evaluate reticulorumen pH and feed intake patterns prior to death.

In the present study, the reticulorumen pH was monitored only during the first 150 DOF because the boluses were inactivated after 150 DOF owing to the decrease in the accuracy of pH measurements. Thus, we did not have any reticulorumen pH data for the last month that the steers were fed the finish ration. The available data indicated that the reticulorumen pH varied greatly within individual steers while they were fed the finish ration, and some steers met the criterion for diagnosis of subacute or acute ruminal acidosis. This suggested that, when a subset of animals is used to estimate the reticulorumen pH for a pen of feedlot cattle, a fairly large number of animals needs to be monitored to appropriately account for individual animal variation. On the basis of the findings of the present study, we recommend that reticulorumen pH boluses be placed in a minimum of 6% of the animals (up to 30 animals) in a pen or 10 animals/pen to accurately estimate the reticulorumen pH at the pen level. These recommendations are consistent with the recommended number of cattle that need to be individually monitored to accurately assess the reticulorumen pH in groups of lactating dairy cattle.[34]

For the steers of the present study, the reticulorumen pH peaked at approximately 7:00 AM and reached its nadir at approximately 8:00 PM, which was consistent with the diurnal pattern for reticulorumen pH described for cattle in other studies.[18,35] The steers of the present study were fed at approximately 8:00 AM and 2:00 PM on a daily basis. Thus, the second daily feeding appeared to be additive to the first feeding in terms of its effect on the reticulorumen pH (ie, the reticulorumen pH declined from the first daily feeding until approx 6 hours after the second daily feeding). Additional research is needed to evaluate feeding frequency and bunk management (ie, amount of time feed is and is not present in the bunk on a daily basis)

to further evaluate the relationship of feeding on reticulorumen pH. In cattle, the amount of VFAs in the rumen generally increases following a meal, leading to a decrease in the rumen pH[36]; however, the correlation between rumen VFA content and pH is weak.[36,37] Production of saliva, which contains bicarbonate, helps regulate the rumen pH.[38,39] Saliva production increases when cattle are ruminating, which occurs primarily after a meal is eaten; thus, saliva production may help neutralize some of the VFAs and increase rumen pH.[40] The diurnal pattern for reticulorumen pH can be altered by means of changing the times cattle are fed throughout the day.[4] Rumenocentesis is an effective technique for measuring rumen pH in field settings and is less expensive than a reticulorumen pH bolus, but investigators need to consider the diurnal pattern for reticulorumen pH and the time the rumenocentesis was performed relative to feed consumption when making comparisons among different groups.[41]

A novel finding of the present study was the positive association between the percentages of time that the reticulorumen pH was 5.6 and ≤ 5.2 during the entire feeding period and the prevalence of liver abscesses. In feedlot cattle, the formation of liver abscesses is generally considered a sequela of ruminal acidosis.[11,42] In the present study, the prevalence of steers with A+ liver abscesses and liver abscesses of any size were greater than expected and may have been a consequence of the extended feeding period caused by the COVID-19 pandemic.[12,43] However, we believe the findings would have been similar had the steers of this study been slaughtered at their optimal body weight. Additional research is necessary to elucidate the relationship between liver abscesses and the duration that the reticulorumen pH is ≤ 5.6 and ≤ 5.2 during the feeding period for feedlot cattle that are fed to the optimal endpoint. It is possible that minimizing the amount of time that the reticulorumen pH is < 5.2 during the feeding period might decrease the incidence and severity of liver abscesses in feedlot cattle. Although the percentage of time that the reticulorumen pH was ≤ 5.6 during the entire feeding period for steers with any grade of liver abscess was significantly ($P = 0.03$) less than that for steers with normal livers, we do not believe the magnitude of that difference (0.07%) was biologically relevant.[44] Because the reticulorumen pH nadir for the steers of the present study occurred in the evening (8:00 PM) approximately 6 hours after the afternoon feeding, research may be warranted to focus on liver abscess mitigation strategies that target the afternoon feeding.

The steers of the present study were fed tylosin phosphate (60 to 90 mg/steer/d) throughout the feeding period. Results of a meta-analysis[45] indicate that feeding tylosin phosphate continuously to feedlot cattle throughout the feeding period decreases the prevalence of liver abscesses identified at slaughter. In the United States, the FDA has approved tylosin phosphate for the reduction of liver abscesses in

cattle when fed continuously throughout the feeding period at a dosage of 60 to 90 mg/animal/d. Tylosin phosphate is a type A VFD drug and can be administered in accordance with the product label only. Extralabel use of any VFD drug is prohibited in the United States.

Multiple studies[46,47,p] that investigated the effect of tylosin phosphate on liver abscess prevalence in feedlot cattle were conducted before the VFD was enacted in 2017. In 1 study,[46] the liver abscess prevalence and animal performance did not differ significantly between feedlot steers that were fed tylosin phosphate at the labeled dose continuously and steers fed the drug at the labeled dose intermittently (1 week on and 2 weeks off) after the first 21 DOF. In another study,[n] the prevalence of A+ liver abscesses was greatest in steers that were not fed tylosin phosphate and steers fed the labeled dose of tylosin phosphate for the last 84 DOF and lowest in steers fed the labeled dose of tylosin phosphate for the first 42 DOF, first 126 DOF, and continuously throughout the feeding period (approx 162 days). Those findings suggest that, in feedlot cattle, the greatest risk for liver abscess formation is during the early part of the feeding period.[n] In another study,[47] feedlot cattle that were fed tylosin phosphate for the first 125 DOF (first 78% of the feeding period) and between 41 and 161 DOF (last 75% of the feeding period) had more severe (A+) liver abscesses than did cattle that were fed tylosin phosphate continuously during the feeding period. Results of yet another study[48] indicate that the prevalence of A+ liver abscesses was 45.9% less for feedlot cattle fed a live yeast product (20 X 10^9 CFUs of *Saccharomyces cerevisiae boulardii* CNCM I-1079/animal/d) in addition to the labeled dose of tylosin phosphate for the first 45 DOF relative to cattle that did not receive the yeast product.

Liver abscesses have been identified by use of transabdominal ultrasonography in feedlot cattle during the ration transition period early in the feeding period (ie, transition 1), albeit in a low percentage ($\leq 5\%$) of animals.[42] Most liver abscesses develop after transition 1 during the later stages of the feeding period.[42] Additional research is necessary to identify optimal management and control strategies for liver abscesses in feedlot cattle. Methods that reduce the incidence of A+ liver abscesses will improve animal welfare and carcass quality and thereby improve profitability.[12,13,42]

The present study was not without limitations. One limitation was that the steers were fed through 8 data acquisition nodes so that individual animal feed intake could be monitored. This meant that all steers could not eat at the same time, which is typical cattle behavior when feed is provided in traditional bunks on commercial feedlots. However, feed was available ad libitum to ensure that timid or less aggressive steers had access to adequate feed. Additional research is necessary to quantify reticulorumen pH when cattle are fed in a traditional feedlot environment.[49,50] Another study limitation was that VFA concentrations were not monitored throughout the feeding period.

However, use of the reticulorumen pH boluses provided us a noninvasive method to accurately monitor pH data at 10-minute intervals for the first 150 DOF.

Results of the present study provided some information on reticulorumen pH variation in feedlot steers, particularly during ration transition periods, and a potential association between reticulorumen pH and the development of liver abscesses. When assessing feedlot rations, veterinarians need to consider normal variation within and between animals as well as clinical signs (eg, number of animals chewing their cud, fecal composition, and consistency) observed for the group. Small changes in the processing (eg, flake density) of corn can result in rapid changes to starch digestibility and animal performance outcomes.[51] Further research on the effects of reticulorumen pH regulation (by use of various management strategies, feed additives, or vaccines) in regard to the development of liver abscesses in feedlot cattle is necessary.

Acknowledgments

Footnotes

a. Half Duplex Technology (HDX) Ultra EID Tag, Allflex, Dallas, Tex.
b. Pyramid 3, Boehringer Ingelheim Vetmedica Inc, Duluth, Ga.
c. Cydectin, Bayer Animal Health, Shawnee Mission, Kan.
d. Synanthic, Boehringer Ingelheim Vetmedica Inc, Duluth, Ga.
e. Exile Pour-On, Aspen Veterinary Resources Ltd, Greeley, Colo.
f. Revalor-IS, Merck Animal Health, Whitehouse Station, NJ.
g. Revalor-200, Merck Animal Health, Whitehouse Station, NJ.
h. pH Premium Bolus, smaXtec, Graz, Austria.
i. GrowSafe Systems, Calgary, AB, Canada.
j. Tylan, Elanco Animal Health, Greenfield, Ind.
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Appendix

Macro ingredient composition and calculated nutrients for each of 3 rations fed to 59 black beef feedlot steers enrolled in a study to evaluate the reticulorumen pH during transitions from low- to intermediate- to high-carbohydrate rations throughout the feeding period.

Ingredient*	Ration†		
	Starter	**Intermediate**	**Finish**
Steam flaked corn	29.66	52.08	73.21
Wet distiller's grain	13.38	10.66	8.78
Ground alfalfa hay	46.75	25.68	9.36
Fat	0.00	1.45	3.60
Corn steep	6.39	5.66	0.00
Liquid finisher‡	3.81	4.46	5.04
Micro ingredients	0.01	0.01	0.01
Calculated nutrients			
Dry matter (%)	66.17	65.08	71.41
Net energy maintenance (Mcal/kg)	177.96	201.83	212.39
Net energy gain (Mcal/kg)	115.19	137.81	155.16
Crude protein (%)	18.10	17.50	16.00
Nonprotein nitrogen (%)	2.05	2.20	2.28
Crude fat (%)	3.53	5.60	6.59
Crude fiber (%)	17.00	11.11	6.89
Calcium (%)	1.11	0.92	0.82
Phosphorus (%)	0.39	0.41	0.43
Potassium (%)	1.44	1.03	0.74
Magnesium (%)	0.30	0.32	0.27
Sulfur (%)	0.36	0.35	0.33

*Each ingredient is reported on a percentage of dry-matter basis. †Each ration was formulated to provide each steer with 60 to 90 mg of tylosin phosphate/d (assuming 90% dry-matter basis), monensin (37 g/ton), *Propionibacterium freudenreichii* (1×10^9 CFUs/steer/d), and *Lactobacillus animalis* (1×10^9 CFUs /steer/d). ‡Provided macro (calcium, phosphorus, potassium, sodium, magnesium, and sulfur) and micro trace minerals (zinc, iron, copper, selenium, cobalt, and iodine).