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Technical note: The use of a telemetric system to continuously monitor ruminal temperature and to predict ruminal pH in cattle

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ABSTRACT

The objective of this study was to compare a telemetric monitoring system to an existing in situ methodology (conventional system) of monitoring ruminal temperature and to validate its use to detect changes in ruminal pH (RpH). Four nonlactating, ruminally cannulated Holstein dairy cows (760 ± 30 kg of body weight, mean ± standard deviation) housed in a tie-stall facility were used in the study. The experiment was conducted during the month of May and the recorded ambient temperature was 8.0 ± 2.0°C (mean ± SD). The cows were fed a diet consisting of chopped mixed hay (MH; 11.3% crude protein, 59.7% neutral detergent fiber, 17.3% nonfiber carbohydrate, 3.1% ether extract, and 11.3% ash; dry matter basis) during wk 1 and were gradually switched to a high-grain (HG) diet (11.6% crude protein, 30.2% neutral detergent fiber, 50.7% nonfiber carbohydrate, 3.0% ether extract, and 6.0% ash; dry matter basis) during wk 2. A conventional system that utilized an indwelling electrode was used to monitor RpH and ruminal temperature (RT_C) during d 6 and 7 of each week. The indwelling electrode was attached to a telemetric bolus and ruminal temperature (RT_T) was logged into a personal computer. The daily mean, minimum, and maximum RpH and duration (min/d) RpH <6.2 were 6.39 ± 0.04, 6.10 ± 0.05, 6.66 ± 0.03, and 107 ± 50 during MH feeding (wk 1) and 5.84 ± 0.03, 5.35 ± 0.05, 6.35 ± 0.03, and 1,257 ± 40 during HG feeding (wk 2), respectively, and were different across diets (week effect). Ruminal pH did not decrease below 5.6, 5.8, and 6.0 during MH feeding; mean duration of RpH <5.6, <5.8, and <6.0 during HG feeding was 279 ± 149, 611 ± 139, and 894 ± 101, respectively. Mean daily RT_C increased from 37.5°C ± 0.1 in wk 1 to 38.6°C ± 0.1 in wk 2; there was also an increase from wk 1 to wk 2 in minimum and maximum daily RT_C and durations (min/d) of RT_C >38.0, >38.2, >38.4, and >38.6°C. These increases were not detectable with the telemetric system. Ruminal temperature obtained by the conventional system was 0.68°C ± 0.005 lower than RT_T during MH feeding (wk 1), whereas RT_C was 0.04°C ± 0.004 higher than RT_T during HG feeding (wk 2). Daily minimum RpH was associated with maximum daily RT_C and RT_T during MH and HG feeding (R^2 = 0.88 and 0.43, respectively). There was a high association between low RpH and high ruminal temperature, with the highest associations being between duration (min/d) of RpH <6.0 and duration of RT_C >39.0°C ($R^2 = 0.68$) and RT_T >39.2°C ($R^2 = 0.72$). Unlike the telemetric system, the conventional system requires cow cannulation; therefore, the current study provided a noninvasive alternative for measuring ruminal temperature and the prediction of RpH. Additional studies are needed to develop an algorithm that accounts for diet type, seasonal variation in temperature, and core body temperature to predict subacute ruminal acidosis effectively on farm.
Key words: telemetry, ruminal temperature, ruminal pH

The ability to monitor physiological responses (e.g., temperature, fluid pH, heart rate), which can indicate diseases in livestock, via telemetric technology has great potential to increase timely disease detection, thus improving animals' health, productivity, and welfare. The first use of telemetric technology reported in the literature was by Jacobson and MacKay (1957) to study gastrointestinal physiology. However, early systems had some disadvantages such as the short life of transmitter batteries, drifting sensors, and high cost. Advancement in sensor and battery technologies facilitated the development of more stable sensors, particularly those used for measuring body temperature (Brown-Brandl et al., 2003). The implementation of telemetric systems to monitor core body temperature in cattle has recently attracted industry attention. Research shows that ruminal temperature (**RT**), measured via an intraruminal telemetric sensing device (bolus), can potentially be used to monitor the health of growing cattle (Sims et al., 2008; Small et al., 2008) and for the early diagnosis of bovine respiratory disease and bovine viral diarrhea

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in cattle (Dye et al., 2007). It also has the potential to predict parturition and estrus in cattle (Prado-Cooper et al., 2008).

Additionally, our research has shown that there is a close relationship between RT and ruminal pH (**RpH**), as RT is inversely related to RpH (AlZahal et al., 2008). It is not surprising that RT and RpH are so closely associated; ruminal fermentation produces end products such as VFA, methane, and heat (Hungate 1966). Therefore, cows receiving grain-rich diets are expected to have lower RpH and an elevated RT. The previous study (AlZahal et al., 2008) utilized an indwelling electrode to measure RT but which required cow cannulation. Alternatively, RT can be recorded in a noninvasive manner via a telemetric ruminal bolus administered orally and linked to an acquisition system. The objective of this study was to compare such a telemetric monitoring system to an existing in situ methodology (conventional system) of monitoring RT and validate its use to predict RpH.

Four nonlactating, ruminally cannulated Holstein dairy cows (760 ± 30 kg, mean ± SD) housed in a tie-stall facility at the University of Guelph, Ontario, Canada, were utilized for this study. Cows were cared for and handled in accordance with the Canadian Council on Animal Care regulations (CCAC, 1993). The University of Guelph Animal Care Committee approved the use of the cows for this experiment. Cows' rectal temperature was 38.3 ± 0.4°C (mean ± SD) at 0700 h at the beginning of the study, which is considered within the normal physiological range (Rebhun, 1995). The study was conducted from May 15 through May 30, 2008.

During d 1 to 7, cows were fed a diet consisting of chopped mixed hay (**MH**; 11.3% CP, 59.7% NDF, 17.3% NFC, 3.1% ether extract, and 11.3% ash; DM basis). During d 8 to 12, the amount of hay was gradually reduced and substituted with mixed-grain pellets (40% barley, 40% wheat, and 20% corn). During d 13 and 14, cows received a high-grain (**HG**) diet consisting of 65% mixed-grain pellets and 35% mixed hay (11.6% CP, 30.2% NDF, 50.7% NFC, 3.0% ether extract, and 6.0% ash; DM basis). The mixed hay was divided into 2 equal allotments (0800 and 1600 h) throughout the experiment and the amount of pellets was divided into 3 equal allotments (0800, 1200, and 1600 h) during wk 2. The amount of feed offered was 1.4% of BW during wk 1 and 1.7% of BW during wk 2. The amount of feed offered was approximately similar to the expected DM intake for this group of cows; however, this approach facilitated the calculation of feed allotments and the reduction of orts. Water was offered at all times and supplemental vitamins and minerals were offered at 0.02% of BW per d.

The conventional in situ method used to continuously monitor RpH and RT was described by AlZahal et al. (2007). Briefly, the system was composed of an indwelling electrode equipped with pH and temperature sensors and attached to a 1.0-kg weight to ensure that the electrode resided in the ventral sac. The electrode was connected to a data logger that was enclosed in a box mounted on the animal's back. The system was set to record both pH and temperature every minute during MH feeding (d 6 and 7) and during HG feeding (d 13 and 14). Ruminal temperature was also recorded using a telemetric acquisition system (SmartStock LLC, Pawnee, OK), which was composed of the following: a telemetric ruminal bolus (3 cm in diameter and 8.5 cm in height, 120 g in weight), an antenna, a barn receiver unit, a base receiver unit, and a personal computer equipped with a software program for data logging. Ruminal temperature measurements were broadcasted through a radio frequency (0.3–3.0 GHz) from the bolus to the barn receiver unit through the antenna that was within 100 m of the cows. The signal was then transmitted (0.9 GHz) from the barn receiver unit to the base receiver unit (located within a 2.5-km range), which was connected via a cable to the personal computer. The bolus was designed for oral administration using a bolus gun. However, for the purpose of this experiment, the bolus was placed in a mesh bag (20 × 15 cm, pore size = 2 mm) and attached to the conventional electrode. This was done in order to localize the position of the bolus in the ventral rumen. The bolus was originally designed to transmit once per hour. Each transmission contained 12 to 48 readings (i.e., the current and previous 11 to 47 recordings) in order to minimize the loss of data resulting from lost transmissions. The battery life expectancy of the bolus is approximately 4 to 5 yr. For the purpose of validating the telemetric system and to be consistent with previous work, the bolus was customized to transmit every minute and each transmission included 12 recordings.

Ruminal temperature recordings obtained by the conventional system (**RT_C**) were synchronized by the minute with ruminal temperature recordings obtained by the telemetric bolus (**RT_T**) using the merge function of SAS (SAS Institute, 2004). A paired *t*-test was conducted using SAS on the difference between each pair of observations ($RT_T - RT_C$) for each minute.

Mean, minimum, and maximum daily RpH, RT_C, and RT_T were calculated from all available observations using PROC MEANS of SAS (SAS Institute, 2004). Although the use of data minima and maxima is beneficial in describing the range of data change, it does not indicate the magnitude of this change. Therefore, the duration (min/d) that ruminal fluid pH was below a given threshold (i.e., 5.6, 5.8, 6.0, and so on) was computed to describe the magnitude of ruminal pH depression. AlZahal et al. (2008) utilized the same approach to describe the magnitude of RT elevation (i.e., time above a specific RT threshold) in the rumen. The durations that RpH measurements were below a given pH threshold and RT_C and RT_T recordings were above a given temperature threshold were calculated for each day of recording using PROC MEANS of SAS (SAS Institute, 2004). To determine which pH and temperature thresholds were suitable for performing statistical analysis across treatment groups, normality statistics was performed on the duration data as described by AlZahal et al. (2009). For example, RpH data showed positive skewness at pH 5.6, 5.8, and 6.0 during MH feeding; therefore, 6.2 proved the most appropriate threshold at which an ANOVA test could be reliably conducted across treatments. The difference in overall performance between the conventional and telemetric systems was calculated from the daily values using PROC MIXED of SAS (SAS Institute, 2004). The model included the fixed effects of method, week, and their interaction and accounted for repeated measures. Multiple comparisons of treatments' least squares means were conducted using the Tukey test (Tukey, 1991). Ruminal pH parameters were analyzed similarly to the previous model using PROC MIXED of SAS (SAS Institute, 2004); the model included the fixed effect of week. Analysis of the association between RpH and temperature (RT_C or RT_T) was conducted using PROC GLM of SAS (SAS Institute, 2004).

The daily mean, minimum, and maximum RpH, and duration (min/d) of RpH <6.2 were 6.39 ± 0.04, 6.10 ± 0.05, 6.66 ± 0.03, and 107 ± 50, respectively, during MH feeding (wk 1) and 5.84 ± 0.03, 5.35 ± 0.05, 6.35 ± 0.03, and 1,257 ± 40, respectively, during HG feeding (wk 2) and were different across diets (week effect; $P < 0.05$). Ruminal pH did not decrease below 5.6, 5.8, or 6.0 during MH feeding, and duration of RpH <5.6, <5.8, and <6.0 was 279 ± 149, 611 ± 139, and 894 ± 101 (min/d), respectively, during HG feeding.

The average daily number of RpH and RT_C recordings obtained by the conventional system was 1,418 ± 43 (mean ± SD; 98% of expected) whereas the average daily number of RT_T was 1,154 ± 137 (80% of expected). The lower number of observations acquired by the telemetric system was likely a result of the high frequency of recording (1 per min) or the blockage of transmissions by barn structures.

The difference between pairs of readings ($RT_T - RT_C$) was +0.68 ± 0.005 ($P < 0.05$; n = 8,760 pairs) during MH feeding and −0.04 ± 0.004 ($P < 0.05$; n = 9,562 pairs) during HG feeding. The daily means of the RT parameters are presented in Table 1. There was a significant interaction between week and method; therefore, results interpretation was conducted by week. During wk 1, most temperature variables measured by the telemetric system were greater than those measured by the conventional system. During wk 2, there was no difference across the RT variables between methods of measurement ($P > 0.05$; Table 1). Daily mean, minimum, and maximum RT_C and durations (min/d) of RT_C >38.0, >38.2, >38.4, and >38.6°C increased from wk 1 to wk 2 (Table 1; $P < 0.05$). There were no changes in any RT_T parameter from wk 1 to wk 2 ($P > 0.05$; Table 1). The reason for the higher values of RT_T compared with RT_C, and thus the failure to detect an increase in RT_T with HG feeding, is not clearly understood. During high-forage feeding, stratification of digesta is distinct and becomes less notable with increasing concentrate:forage ratio (Tafaj et al., 2004). The materials in the top stratum of the digesta are freshly ingested and are more actively fermenting than those in the middle and bottom strata of the rumen (Tafaj et al., 2004). Therefore, ruminal temperature may vary from 40°C at the top of the rumen to 38.5°C at the bottom of the rumen (Dale et al., 1954). Additionally, Beatty et al. (2008) reported a ruminal temperature of approximately 40°C in the dorsal sac of the rumen for heifers fed pelleted feed. They suggested that rumen temperature under this feeding condition was homogeneous as a result of a lack of clear stratification of digesta within the rumen. In the current experiment, the conventional electrode was placed in the ventral sac of the rumen and anchored with a 1-kg weight whereas the telemetric bolus relied on its own weight (120 g) and was attached to the conventional electrode via a mesh bag in order to maintain its position within the rumen. Therefore, a spatial separation between the 2 measurement devices during high-roughage feeding could not be ruled out.

High daily maximum RT_C and RT_T were associated with low daily minimum RpH during both wk 1 and 2 (minimum RpH = 27.3 − 0.56 × maximum RT_C, R^2 = 0.87, $P < 0.05$; minimum RpH = 40.86 − 0.90 × maximum RT_T, $R^2 = 0.43$, $P < 0.05$). Low RpH during HG feeding, described by longer durations (min/d) of RpH <5.6, <5.8, and <6.0, was associated with an elevated RT obtained via both the telemetric and conventional systems. Low RpH was associated with durations (min/d) of RT_C >38.6, >38.8, >39.0, and >39.2°C ($P < 0.05$), with the highest association being between the duration of RpH <6.0 and the duration of RT_C >39.0°C [RpH <6.0 (min/d) = 802 + 0.63 × RT_C >39.0°C, R^2 = 0.68, $P < 0.05$]. Low RpH was associated with the duration (min/d) of RT_T >39.2°C only ($P < 0.05$), with the highest association being between the duration of RpH <6.0 and the duration of RT_T >39.2°C [RpH <6.0 (min/d) = 769 + 1.46 × RT_T >39.2°C, $R^2 = 0.72$, $P <$

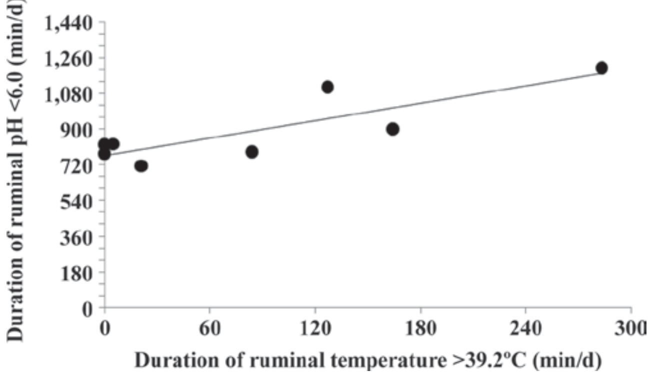

Figure 1. The association between daily means of durations (min/d) of ruminal pH <6.0 using an established in situ method and duration (min/d) of ruminal temperature >39.2°C using a telemetric bolus system during feeding of the high-grain diet (wk 2) [Ruminal pH <6.0 (min/d) = 769 + 1.46 × ruminal temperature >39.2°C, $R^2 = 0.72$, $P < 0.05$].

0.05; Figure 1]. The data demonstrated, in agreement with our previous study (AlZahal et al., 2008), that accelerated ruminal fermentation during grain feeding was associated with a reduction in ruminal pH and an elevation in ruminal temperature. This is understandable because VFA, lactate, and temperature are by-products of bacterial ruminal fermentation (Hungate, 1966). Variations in RpH were explained mostly by variations in RT; for example, Figure 1 shows that the duration (min/d) of RpH <6.0 can be computed using the duration of RT >39.2°C. This concept has the potential to be further developed into an on-farm method for predicting ruminal pH in lactating cows during subacute ruminal acidosis (**SARA**).

The differences between RT_C and RT_T in their relation to RpH during HG feeding could be partially explained by the lower sensitivity of the telemetric bolus to small changes in ruminal temperature. The reading resolution for the telemetric bolus was 0.28°C compared with only 0.01°C for the conventional system. Although the telemetric bolus was not able to detect a significant increase in RT between wk 1 and wk 2 (MH and HG feeding) compared with the conventional system, results showed an improved performance during wk 2 (HG feeding). Furthermore, the magnitude of RpH depression during wk 2 was explained by the extent of the elevation in both RT_C and RT_T.

The association between RpH and RT was in agreement with a previous study (AlZahal et al., 2008). Nonetheless, RT values reported during wk 2 (HG feeding) in the current experiment were lower than RT values reported in the previous study (AlZahal et al. 2008). The cows in AlZahal et al. (2008) were lactating and their DMI was 2-fold the DMI of the nonlactating cows in the current experiment. This suggests that the amount of heat produced in the rumen is related not only to the type of feed but also to the amount of feed fermented within the rumen.

It is important to note that normal core body temperature has been reported to range from 38.0 to 39.1°C; thus, cows with core body temperature exceeding 39.1°C were defined as febrile or abnormal (Rebhun, 1995). The cows used in this study were nonfebrile at the initiation of the study and no health issues were diagnosed during the experiment. However, both RT_C and RT_T were >39.2°C for 75 ± 35 and 90 ± 35 min/d, respectively, with maximum RT ranging from 39.0 to 40.0°C. Therefore, the use of RT as a measure of core

Table 1. Least squares means for ruminal temperature characteristics obtained by either a conventional method or a telemetric monitoring system[1]

	Conventional[2]		Telemetric[3]			*P*-value		
Item	Wk 1	Wk 2	Wk 1	Wk 2	SE	Method	Week	Method × week
Mean (°C)	37.5[a]	38.6[b]	38.2[b]	38.5[b]	0.1	0.02	<0.01	0.02
Maximum (°C)	38.3[a]	39.4[b]	39.0[b]	39.3[b]	0.1	0.05	<0.01	0.01
Minimum (°C)	35.4[a]	37.1[b]	36.5[b]	37.5[b]	0.2	0.01	<0.01	0.19
Duration[4] (min/d)								
>38.0°C	265[a]	1,289[b]	901[b]	1,144[b]	96	0.02	<0.01	<0.01
>38.2°C	223[a]	1,228[b]	678[ac]	1,029[bc]	118	0.29	<0.01	0.01
>38.4°C	95[a]	1,005[b]	535[ab]	811[b]	147	0.42	<0.01	0.05
>38.6°C	20[a]	677[b]	223[ab]	575[ab]	141	0.73	<0.01	0.30

[a–c]Means within a row with the same superscript letter are not significantly different.

[1]Ruminal temperature was recorded on d 6 and 7 (wk 1) and d 13 and 14 (wk 2) every minute. During wk 1, cows were fed 100% chopped mixed hay, then gradually acclimated during wk 2 to a 35% hay and 65% grain diet.

[2]As described by AlZahal et al. (2007).

[3]Manufactured by SmartStock LLC (Pawnee, OK).

[4]Duration = length of time ruminal temperature was above a given temperature threshold.

body temperature, hence as an indication of fever, without taking into account type of diet or the possibility of SARA may be misleading. Heat stress has been shown to increase core body temperature in dairy cows exceeding 39.0 to 40.0°C (Rhoads et al., 2009); nonetheless, the current study was conducted under thermoneutral conditions and the increase in RT was believed to be a result of SARA only. The effect of seasonal variation in ambient temperature on the relationship between RT and RpH is not yet investigated. The mean daily air temperature (8°C ± 2, mean ± SD) was consistent throughout the current study.

In conclusion, the current study provides a noninvasive telemetric alternative that does not require cow cannulations in order to measure ruminal temperature and thus predict ruminal pH. Further improvement in the response of the current telemetric bolus to subtle changes in temperature, such as those encountered during pH depression, is needed. Further investigations, such as using roaming boluses within the rumen, are needed in order to determine the effect of diet type on rumen temperature. Also, studies are needed to develop an algorithm that accounts for diet type, seasonal variation in temperature, and core body temperature to predict SARA effectively on farm.

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