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Evaluation of sensors for monitoring rumen pH, temperature and pressure

X. LIN¹, D. PACHECO², P.D. KEMP¹, G.C. WAGHORN³ and G.P. COSGROVE^{2*}

¹Institute of Natural Resources, Massey University, Private Bag 11-222, Palmerston North 4442, New Zealand

²AgResearch Grasslands, Private Bag 11-008, Palmerston North 4442, New Zealand

³DairyNZ, Private Bag 3221, Hamilton 3240, New Zealand

*Corresponding author: gerald.cosgrove@agresearch.co.nz

ABSTRACT

Electronic intra-ruminal sensors and telemetry offer new opportunities for remote monitoring of the rumen environment. Sensors capable of measuring pH, temperature and pressure were subjected to laboratory and intra-ruminal evaluation in rumen-fistulated cows offered baleage indoors or hay with pasture outdoors. Each bolus underwent a testing sequence consisting of i) bench-top calibration against certified devices, ii) testing in the rumen to validate sensor measurement against actual measurement, and iii) monitoring the rumen environment of cows under contrasting feeding conditions for periods up to 72 hours. Bolus efficacy was evaluated from the accuracy of temperature and pressure measurements, stability of pH measurements over several days and the data capture rate being the actual number of data transmissions received as a proportion of the number expected based on transmission frequency setting. Intra-ruminal records show clear relationships of pH with diet and feeding bouts, whilst temperature records indicated drinking. Pressure changes were more difficult to interpret but may indicate satiety. These devices provide non-disruptive monitoring of rumen parameters and would be useful for studies of nutritional manipulation and rumen digestion efficiency, and for monitoring aspects of animal health.

Key words: intra-ruminal bolus; rumen sensor; pH; temperature; pressure.

INTRODUCTION

Monitoring the rumen environment provides valuable information for interpreting animal responses in nutrition studies. Furthermore, if rumen parameters can be measured in real time and without disturbance to the animal, this offers a means of monitoring aspects of animal health. Most techniques for monitoring the rumen environment, such as stomach tube, rumenocentesis and rumen fistulae, involve manipulation of the animal. The process of sample collection can affect the data being collected. In addition, there are animal welfare and ethical considerations associated with these methods, particularly where frequent measurement might be required.

Telemetry offers the advantage of real time measurement and recording of rumen parameters in non-restrained animals, and with no restrictions on the frequency of measurement. Potentially useful measurements in commercial environments include ruminal pH and temperature. Monitoring pH becomes critical in cases where there is a likelihood of acidosis as grain is introduced to roughage fed animals, or when it comprises a significant portion of the diet, as in feedlot beef fattening systems. High ruminal pH will also indicate a lack of feeding when volatile fatty acid production declines and saliva increases pH to 7.0, or higher (Church, 1976). Ruminal temperature is highly correlated with core body temperature (Beatty *et al.*, 2008) and could be

used to monitor health, for example incidence of sub acute ruminal acidosis (Al Zahal *et al.*, 2008) or presence of fungal endophyte (*Neotyphodium lolii*) in pastures which can reduce water intake (Thom *et al.*, 2007), or simply an unavailability of water. Changes in intra-ruminal pressure would serve as a valuable indicator of bloat if a device was installed in an “indicator” cow. Additional benefits of remote sensing would include extending the measurements to grazing situations.

Many indwelling devices have been developed for continuously measuring ruminal pH in fistulated animals (Johnson & Sutton, 1968; McArthur & Miltimore, 1968; Dado & Allen, 1993; Enemark *et al.*, 2003; Duffield *et al.*, 2004; Al Zahal *et al.*, 2007; Gasteiner, *et al.*, 2008; Zosel *et al.*, 2010). Early continuous recording systems required that the animal’s movement be restricted as the data logging device could not be moved with the animal and the pH electrode had to be protected by a rigid casing to prevent breakage in the rumen (Johnson & Sutton, 1968; McArthur & Miltimore, 1968). Others have developed devices for measuring temperature or motility and telemetering data to remote receivers (Dracy *et al.*, 1963; Dracy & Kurtenbach, 1965; Cook & Riley, 1970; Riley & Cook, 1974; Riley, 1986; Ipema *et al.*, 2008).

The purpose of this study was to evaluate the performance of a recently developed rumen sensor and telemetry system in terms of accuracy and the sensitivity to changes in the rumen environment

associated with feed intake and digestion of contrasting diets offered to cattle. Similar evaluation has recently been undertaken with sheep (Kaur et al., 2010).

MATERIALS AND METHODS

The rumen sensors, incorporated into a bolus, data transceivers and associated operating software were supplied by Kahne Technologies Ltd., Auckland, New Zealand. These were models commercially available at the time the study commenced in May 2008. The study used model KB1101 boluses which were capable of measuring pH, temperature and pressure, and three models of transceiver (KR 2001, KR 2002 and KR 2105). The Kahne Data Processing System software V1.1 was used for setting up and communicating with the boluses, and downloading data. The experimental evaluation was based on bench top calibration of boluses and *in vivo* comparisons between bolus pH and a reference probe pH, measurements of ruminal pH, temperature and pressure in cattle offered baleage indoors to determine variation among animals, and a comparison of those same rumen measurements between cattle offered baleage indoors or hay with pasture outdoors (Table 1). All aspects of the study were conducted under laboratory or field conditions at AgResearch Grasslands, Palmerston North, during May to December 2008. Advice on setting up and maintaining the operating system was provided by technical staff of Kahne Ltd. The number of boluses available varied during the study because on occasions units had to be returned to the manufacturer for servicing.

Calibration

Eight boluses and the KR 2001 transceiver were used in this laboratory calibration. To

determine the accuracy of the data provided by the bolus sensors, each was calibrated against a reference thermometer (Hanna Instruments Inc., Woonsrocket, Rhode Island, USA) using a variable temperature water bath over the temperature range 35 to 42°C, encompassing the range expected in the rumen. Pressure was calibrated against a reference digital barometer (Vaisala Pty. Ltd., Victoria, Australia) using natural variations in atmospheric pressure over the range 98.3 to 102.5 kPa. Subsequent measurements indicated ruminal pressures up to 106 kPa.

The pH probe of each bolus was calibrated to pH 4 and 7 prior to each use, using commercial buffer solution (Eutech Instruments Pte Ltd., Waltham, Massachusetts, USA). Boluses were also compared to a reference pH probe (Hanna Instruments Inc., Woonsrocket, Rhode Island, USA), enabling correction for drift in pH over seven days. pH was measured in the rumen adjacent to the bolus, twice daily using the reference probe, as part of the study comparing feeding regimes described below. The difference between reference and bolus pH was regressed on time. The four boluses were switched among six cows at the end of each 24 hour period, so the drift for each bolus reflected the individual characteristics of the bolus and the cow rumen environment.

Animals

For this evaluation fistulated cattle were used for all *in vivo* measurements, so the bolus could be placed in the rumen and located and retrieved when required. Boluses can be used in non-fistulated animals, by oral administration, but recovery is not possible until slaughter.

Determining variation among animals

To determine between-animal variation in rumen parameters, nine rumen-fistulated, non-

TABLE 1: A description of the different phases of evaluation and their location, the purpose of the recorded measurements, the number of boluses and cows used, the duration of measurements and the number of 24-hour recordings made.

Phase of evaluation	Location	Purpose	Number of boluses used	Number of cows	Duration (days)	Number of 24-hour recordings
Benchtop calibration	Indoors	Determine accuracy of boluses sensors	8	NA ¹	NA	NA
<i>In vivo</i> calibration	Indoors & outdoors	Stability of pH sensor over prolonged measurement	4	6	7	Morning and afternoon measurements daily for 7 days
Determining variation among animals	Indoors	Assess rumen environment of multiple cows treated similarly	5	9	3	15
Comparing feeding regimes	Indoors & outdoors	Assess rumen environment of multiple cows offered contrasting diets	4	6	6 (3 days baleage indoors and 3 days hay/grass outdoors)	24 (12 for each feed type)

¹NA Not applicable under those circumstances.

lactating Holstein-Friesian x Jersey cows (517 ± 23 kg live-weight and more than nine-years-old) were held for three days in a yard that was 19 m x 8.5 m, containing 12 feeding stalls and one water trough. The cows were secured in individual feeding stalls for 40 minutes twice daily at around 09:00 and 16:00 h. Each was offered 7.6 kg of baleage (Fibre-Pro, Fibre Fresh Feeds, New Zealand; 40% dry matter (DM), pH 4.5) at each meal or approximately 6.1 kg DM/d. Baleage was fully consumed within 40 minutes and the cows were released to roam in the holding yard. The five boluses were switched among cows every 24 hours in a pre-determined sequence, such that there were 2 x 24-hour recording for six cows and 1 x 24-hour recording for three cows. The transmission frequency was set at 12 measurements per hour at 5 minute intervals, and the maximum transmission distance was 22 m.

Comparing feeding regimes

Six of the above cows were used to evaluate the rumen environment under contrasting feed management regimes. These cows were held outdoors at pasture for three days and once daily at 10:00 h offered a maintenance ration consisting of 5.4 kg DM of hay and 600 g DM fresh grass, giving each cow a total allowance of about 6 kg DM/d, and then moved indoors and offered baleage twice daily, as described above, for three days. Only four boluses were available to undertake measurements in the six cows so the boluses were switched among cows for each successive 24-hour period of measurement during the experiment, according to a predetermined sequence. This ensured that over each three-day period there were 2 x 24-hour recordings for each cow.

Each 24-hour recording commenced at 09:00 h, at feeding. Direct measurements of rumen pH were

taken twice daily at 08:30 and 15:30 h, before each feed of baleage for cows indoors, and at 08:30 h and 15:30 h for cows at pasture offered hay and grass once daily at 10:00 h. For this phase of the study, each bolus was set at a different transmission frequency at between 65 and 90 measurements per hour equivalent to 55 to 40 second intervals, to avoid synchronous transmission and thereby improve the data capture. The maximum transmission distance was 21 m.

Data processing and analysis

All bolus-derived data were adjusted based on the calibration relationships, before being analysed to determine variation among animals and differences between diets. This adjustment standardized the data and removed the confounding effect of variation among boluses. The data capture rate (DCR), being the actual number of data transmissions received/number expected based on transmission frequency, was calculated as one indicator of system performance from data obtained under a range of operating conditions. The DCR was evaluated for each of two transceivers (KR2001, KR 2105) operating individually with a bolus in each of two cows grazing outdoors for 2 x 24-hour recordings, the KR2105 operating alone with five boluses switched among nine cows over three days for 15 x 24-hour recordings when determining variation among animals indoors, the KR2002+KR2105 operating together indoors with five boluses switched among eight cows over three days for 15 x 24-hour recordings, and then 12 x 24-hour recordings both indoors and outdoors when comparing feeding regimes.

To determine the drift in pH of each bolus, in relation to the calibrated reference probe, the difference between bolus pH and reference pH measured over seven days was regressed on time. For assessing variation among cows fed baleage indoors for three days, the data for each cow were smoothed by calculating the mean pH for successive intervals of one hour, resulting in 72 data points for each cow. For the comparison between feeding regimes of baleage offered indoors for three days followed by hay/pasture offered outdoors for three days, the data were smoothed over 15 minute intervals, resulting in 288 data points for each cow within diets comprised of 72 hours with four points per hour.

RESULTS

Although the data presented focuses on pH, an example of a 24 hour recording of ruminal temperature, pressure and pH (Figure 1) shows clear relationships between eating and ruminal pH, and

FIGURE 1: The profile of rumen temperature, pressure and pH over one 24-hour period for a single animal fed baleage twice daily at 09:45 and 15:45 h. Arrows indicate the times of feeding and the temperature drops associated with drinking are also indicated by arrows.

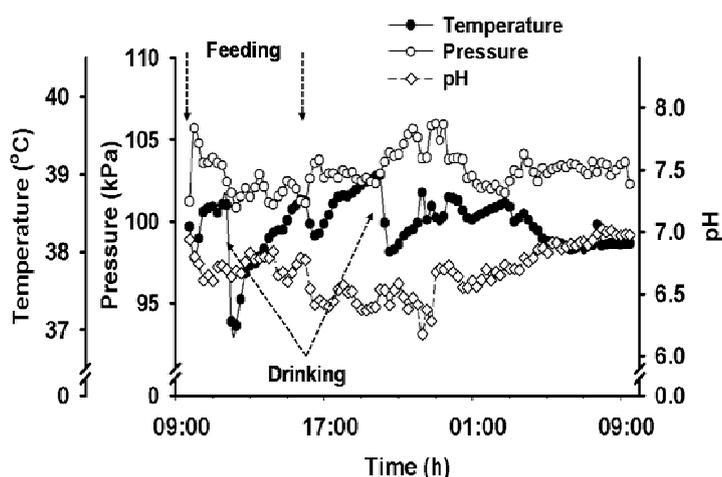


FIGURE 2: The profile of mean rumen pH plotted over 24 h, for 6 cows each recorded for 2 x 24 h periods, when offered baleage twice daily indoors or offered grass and hay once daily outdoors, at the times indicated by arrows (arrows from solid circles indicated the times of offering baleage and the arrow from the open circle indicates the time of offering grass and hay). Error bars indicate standard error of mean.

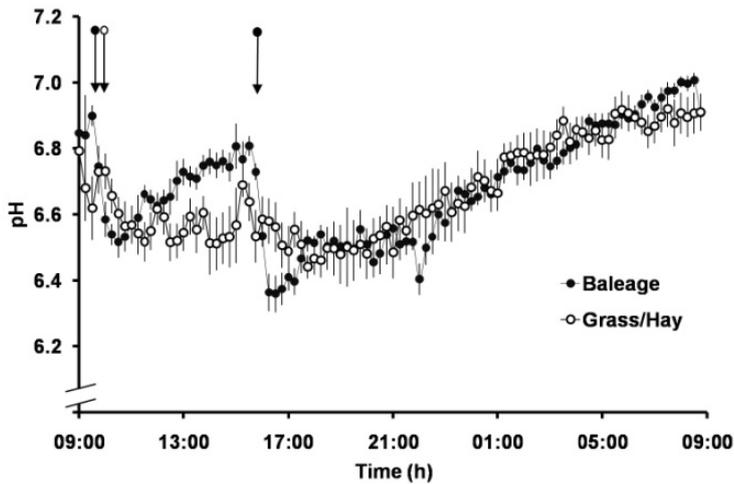
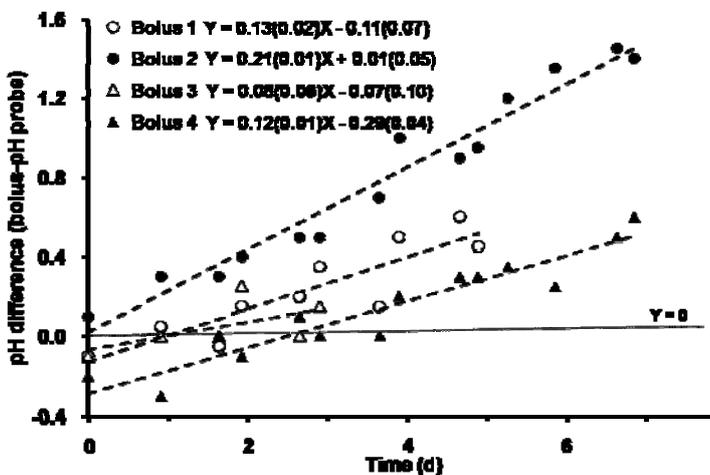


FIGURE 3: The difference between bolus pH and reference probe pH, measured twice daily for up to 7 days, regressed on time to determine the rates of pH drift for each of 4 different boluses (regression relationship and standard error of slope and intercept is shown for each bolus).



drinking events with temperature. The ruminal pressure recorded shows an overall increase during the night, but with smaller fluctuations in pressure over one to two hour intervals during the 24-hour period. The 24-hour profile for mean pH in Figure 2 derived from 12 x 24-hour recordings from six cows over three days on each feed, shows a similar pattern to that for a single animal over 24 hours, and also demonstrates clear differences between feeding regimes. However the mean for temperature, and especially pressure (X. Lin, Unpublished data), concealed much of the short-term fluctuation apparent for individual cows.

Calibration of temperature, pressure and pH drift

The laboratory calibration indicated that for temperature, the overall slope of 1.006 (Standard error \pm 0.004, $P < 0.001$) did not differ from 1.0, whereas individual boluses differed significantly from the overall intercept of $-0.298 (\pm 0.159, P = 0.11)$ by -0.44 to 0.78 . These differences translate to a relative prediction error of 2% in the temperature range of calibration. For pressure, the overall slope of 0.989 (\pm 0.008, $P < 0.001$) was not significantly different from 1.0, and the intercept of 1.2 (\pm 0.8, $P = 0.13$) was not significantly different from zero. The difference between bolus pH and reference probe pH, regressed on time, showed a significant overall upward drift (Figure 3). Slopes differed significantly ($P < 0.01$) among boluses (0.07 – 0.21 pH units/d), but only for Bolus #3 was the slope not significantly greater than zero. For Bolus #4 the intercept differed significantly from zero (-0.29), but for the others it did not.

Data capture rate

Data capture rate was highly variable, and influenced by the transceiver model, transceiver positioning and differed for indoor versus outdoor situations. For indoor measurements using a single transceiver the DCR was 1.7% (range 0.9 – 2.6%) and 20.8% (0.5 – 30.4%) for the KR2001 and KR2105 transceivers, respectively, but DCR outdoors was 8.3% (6.9 – 9.8%) and 46.4% (43.1 – 49.7%) for the KR 2001 and KR 2105 transceivers, respectively. The use of two transceivers operating simultaneously increased the DCR for cows indoors to 64.3% (58.7 – 69.9%) and outdoors to 53.6% (50.6 – 55.5%).

Variation among animals

The hourly-mean ruminal pH value measured from nine cows offered baleage indoors over three days was used to derive estimates of between animal variability. The 24-hour mean pH was 6.8 ± 0.17 . The hourly mean pH ranged from a low of 6.5 ± 0.19 to a high of 7.1 ± 0.21 . The highest hourly standard deviation was 0.33 (coefficient of variation 4.9%).

Contrasting feeding regimes

The overall daily mean rumen pH for cows offered baleage indoors did not differ from those offered grass and hay outdoors, and was pH 6.7 for each treatment, after adjusting for drift. However, the diurnal profile differed for each diet treatment (Figure 2), particularly in the periods immediately

following feeding. For cows offered baleage the ruminal pH decreased 0.35 units to a low-point 45 minutes following allocation of feed in the morning and then began increasing. Following feed allocation in the afternoon pH decreased 0.45 units to a low point, also 45 minutes following feed allocation. In comparison, for the cows offered their daily allocation of hay and grass once daily in the morning at 10:00 h, ruminal pH decreased 0.15 units to a low-point one hour following feeding.

DISCUSSION

The boluses used in this study were able to monitor rumen function in unrestrained animals. Although there were some weaknesses in performance of the boluses tested here, once the weakness in performance can be overcome, this technology offers excellent opportunities for improving management of animal health and welfare and for studies in ruminant nutrition. We are aware that the problems of poor data capture and pH drift have been overcome in the current design (Kahne Ltd., Personal communication) and the evaluation reported here should be considered in relation to future opportunities. Poor data capture from similar devices has been reported by Ipema *et al.* (2008), who suggested the rumen contents affected transmission. Other possible factors arising in this study included interference from other radio transmissions, and the improved capture outside suggests an effect of the steel building construction. The use of two transceivers mounted in different positions on the perimeter of the indoor pen or grazing area improved the data capture rate substantially, but did not exceed 70%. Given that the frequency of transmission can be set as high as 12 per minute or as low as one per 24 hours, data acquisition should be adequate for most purposes, provided the successful transmissions are uniformly distributed throughout the measurement period. However, where the primary interest is in changes at short time-scales, such as during and immediately following eating, missing or erratic data capture could compromise interpretation. Battery longevity is inversely related to transmission frequency, so minimising transmission frequency whilst ensuring there are sufficient data points during each time-interval of interest, will enable longer recording periods.

Continuous monitoring of ruminal pH enables both the effect of diet and feeding to be measured. The sensitivity of bolus measurements was indicated by the contrasting pH profiles (Figure 2) when cows were offered either baleage twice daily, or hay with pasture once daily. Although the daily mean ruminal pH was similar for the different feeding regimes, the profiles of ruminal pH following eating differed

substantially. This level of discrimination in rumen environment changes would, for example, make it feasible to determine if the magnitude or duration of low ruminal pH is a limiting factor for fibre digestion by high-intake animals grazing highly digestible pasture (de Veth & Kolver, 1999; Kolver & de Veth, 2002). In such applications, however, pH drift associated with the model of bolus evaluated here would severely limit their utility because once inserted into the rumen of intact animals, the bolus settings cannot be changed and the bolus cannot be recovered until slaughter.

Application of the temperature measuring capability, alone or in combination with pH or pressure, may include situations where animals are exposed to heat stress, through either high temperatures or radiant energy where shelter is unavailable (Bryant *et al.*, 2007), or as in northern hemisphere feedlots during winter to ensure cattle are not hypothermic. The decline in intra-ruminal temperature with drinking events (Figure 1) are of a similar magnitude to reports by Ipema *et al.* (2008) and Gasteiner *et al.* (2008). Records provide opportunities for monitoring access to water supply, and animal health, in both hot and cold environments (Dracy & Kurtenbach, 1968). Increased body temperature at pasture, in conjunction with lower intakes, changes in rumen volume (Aldrich *et al.*, 1993) and effects on intra-ruminal pressure (Attebery & Johnson, 1969) could also provide early indications of endophyte toxicity, especially when ergovaline is present in grasses (Bluett *et al.*, 2005; Thom *et al.*, 2007), and inform farmers of a need to move stock to safe grazing to maintain health and production (Al-Haidary *et al.*, 2001). The capacity to monitor rumen temperature could have widespread use for improving cattle welfare and productivity (Bewley *et al.*, 2008). In addition to the temperature, pressure and pH capability of the boluses evaluated here, other functions could be monitored if appropriate sensors were available.

The bases for variations in intra-ruminal pressure have not been interpreted. The changes in pressure associated with rumen contractions at 40 to 75 second intervals are well known, and the range is usually 1 to 3 kPa (Sellers & Stevens, 1966; Atterbury & Johnson, 1969). However, the pattern evident in Figure 1 suggests cyclical changes in pressure of similar magnitude at 60 to 120 minute intervals, and possibly also at 4 to 6 hourly intervals. These may be associated with changes in rumen fill and the ease with which digesta moves in response to contractions, but further interpretation is needed. A potential use for pressure recording is in a bloat "indicator" cow, as an early indication of the need for preventative treatment.

Despite the low data capture and pH drift associated with sensors evaluated here, improvements in both areas, as are evident in current models, will provide a useful aid to farmers to improve management and productivity, and for research in the rumen environment of undisturbed animals, particularly at pasture. The data measured may benefit from computer assisted interpretation and validation so that appropriate action can be provided in response to intra-ruminal signals. Accurate sensing and transmission of multiple measurements will enable feeding systems to be designed to optimise feed utilisation.

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