



Evaluation of ruminal motility in cattle by a bolus-type wireless sensor

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ABSTRACT. We evaluated the relationship between ruminal motility measured by a force transducer and acceleration measured by bolus sensor, and we assessed the detection of ruminal motility in cattle by a bolus-type wireless sensor. The bolus sensor can be orally administered to cattle and was placed in the reticulum for continuous measurements. The probe was almost horizontal to the longitudinal axis. The bolus sensor's basic y-axis acceleration movement appeared to have a very distinct vertical pattern, occurring roughly 1–1.5 times/min with a duration of approximately 8 sec, displaying at around 500 mG. A significant positive correlation was observed between the ruminal contraction revealed by the force transducer and the acceleration shown by the bolus sensor ($P<0.01$). The contraction of the dorsal sac of the rumen and the acceleration signals in the reticulum occurred at practically the same time. The frequency and amplitude of ruminal contraction demonstrated by the bolus sensor and the force transducer in feeding were significantly higher than those at rest ($P<0.01$). The bolus sensor could also detect ruminal atony in the cattle after the administration of xylazine. A bolus-type wireless sensor may thus be useful for the measurement of ruminal motility in cattle and for detecting rumen dysfunction (e.g., ruminal atony).

KEY WORDS: bolus sensor, cattle, force transducer, ruminal motility, wireless

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The frequency and amplitude of ruminal contractions in cattle are influenced by metabolic diseases such as ruminal acidosis and hypocalcaemia, as well as any of the many diseases that cause pain or fever [2, 10, 17]. In addition to anorexia, clinical signs of indigestion include reticuloruminal hypo-motility [11]. Reticuloruminal acidosis has shown to reduce the frequency of ruminal contraction, eventually resulting in ruminal stasis [2, 18]. Ruminal contractions decrease in number and strength and reticuloruminal stasis then develops, often within 15–30 min. Reticuloruminal stasis is of particular interest in relation to the pathogenesis of production diseases associated with gastrointestinal atony, such as displaced abomasum and ruminal tympany [2]. Therefore, the measurement of ruminal motility in its own right has value in the management of cattle to improve their health, welfare and production performance.

Radiotelemetry has been used in research for many decades to monitor numerous physiological parameters such as the respiratory rate, heart rate, and body temperature in animals [6]. Wireless sensors for intraruminal insertion through the esophagus (boluses) were recently developed as a noninvasive alternative to surgery. Various measurement systems have become available for the continuous monitoring of the ruminal and reticular pH or temperature values in cattle [1, 14, 19, 21, 23]. These bolus sensors are useful for detecting subacute ruminal acidosis or fever in cattle. However, it is unknown whether a bolus sensor can carry out continuous long-term measurements of reticuloruminal motility in cattle. Ruminal motility in cattle can be assessed physiologically using devices such as a strain gauge force transducer or by ultrasonography [4, 7]. A force transducer method requires surgery, and it is difficult to carry out continuous ultrasonography measurements over a long term. More recently, bolus wireless sensors with an accelerometer were developed, and several research groups have attempted to assess the function of reticulorumen such as rumination or the motion of reticulorumen in cattle [3, 15, 20]. It has been unclear whether a bolus wireless sensor with an accelerometer can assess the ruminal motility in cattle. If ruminal motility can be measured over a long term, the measurement could be useful for detecting dysfunctions of ruminal motility such as ruminal atony, ruminal tympany, and anorexia.

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We conducted the present study to examine the relationship between ruminal motility in cattle measured by a force transducer and acceleration measured by a bolus sensor, and we assessed the ability of a bolus-type wireless sensor to detect ruminal motility in cattle.

MATERIALS AND METHODS

Animals

Four healthy non-lactating Holstein cows weighing 420 to 595 kg were used in this study. All cattle were housed in individual stanchion stalls, and were given commercial cattle concentrate, hay and free access to water. Food was offered twice daily (9:00 and 16:00). The handling of the animals used in this study was approved by the Institutional Care and Use Committee for Laboratory Animals of the National Institute of Animal Health (Japan).

The bolus-type wireless sensor and system

The configuration of the wireless sensor and system were modified based on our methods [3, 20]. We designed a wireless sensor probe that can be administered to cattle orally. The probe is cylinder-shaped and consists of a three-axis accelerometer (ADXL362, Analog Devices, Chelmsford, MA, U.S.A.), a temperature sensor, a microcontroller unit (C8051F930, Silicon Labs, Austin, TX, U.S.A.), a transmitter (Si4461-B1, Silicon Labs), a radiofrequency (RF) antenna, and a battery. The probe housing was made from polytetrafluorethylene (PTFE) with glue and PTFE seal tape. The diameter of the probe is 22 mm, its length is 76 mm, and its weight is 55 g (its density is 1.9 g/cm³) (Fig. 1A).

The probe can be easily administered orally via a catheter into the rumen. Power is provided by a heavy-duty 3 V lithium battery. The acceleration is probed at 1 sec interval and in a ± 2 G range with 10-bit resolution. Transmissions are in the 429-MHz band. This frequency band does not require any license in Japan, but the maximum effective radiated power is restricted to 12.14 dBm. The battery has a mean life of 1 month when measurements of three-axis acceleration were transmitted continuously every 1 sec. This system uses a collar repeater to relay the transmissions to a receiver that stores the data on a cloud-connected server or a personal computer with special software (Monitoring data system ver.4, GSI Corp., Tokyo, Japan) (Fig. 1B). The communication distance from the collar repeater of the cattle to the receiver was about 60 m. The bolus sensor is a disposable device. The collar repeater can be reused by changing the battery.

Measurement of acceleration by the bolus sensor

The acceleration data from the bolus sensor are transmitted to the receiver in real time. Three-axis acceleration data were recorded to a personal computer with the GSI software cited above connected to the receiver. The sampling rates for acceleration was 1 Hz. In three-axis acceleration, the x- and z-axes indicate the radial acceleration of the probe, and the y-axis indicates vertical acceleration. The average values of the acceleration (mG) and the peak number of acceleration (times/min) using the bolus sensor were calculated each 10 min. The y-axis data were used as the measurement value of acceleration.

Measurement of ruminal motility by the force transducer

Ruminal motility in the cattle was measured by a strain gauge force transducers [4]. The size of the force transducer was 18 × 35 mm, and the force transducer contained the strain gauge (Foil Strain Gauge; NEC San-ei Instruments, Ltd., Tokyo, Japan). The force transducer was covered with silicone. Four cattle were sedated intramuscularly with xylazine hydrochloride (0.05 mg/kg; Bayer, Leverkusen, Germany). Ten min later, local anesthesia was applied to the left paralumbar fossa with an intramuscular infusion of procaine hydrochloride (8–100 ml/body, Kyoritsu Seiyaku Co., Tokyo, Japan). The force transducer was sutured onto the serosa of the dorsal sac of the rumen. The lead wires of the force transducer were exteriorized through the abdominal wall.

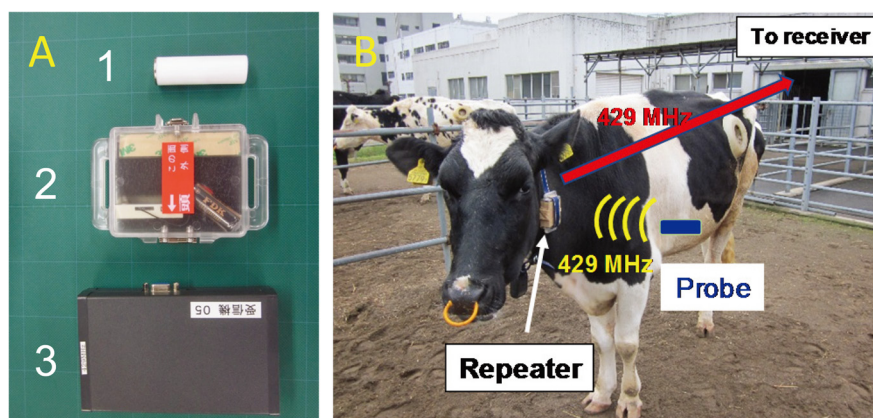


Fig. 1. A: Bolus sensor and radio-telemetry system. B: System operation. A1: Bolus sensor. A2: Collar repeater. A3: Receiver.

The wires from the force transducer were then subcutaneously tunneled and pulled out through the skin. The cattle were injected intramuscularly with antibiotics (10 mg/kg, ampicillin sodium; Meiji Seika Pharma Co., Ltd., Tokyo, Japan) after the surgery.

Ruminal motility was recorded on a polygraph (MP100A, BIOPAC Systems Inc., Santa Barbara, CA, U.S.A.) by connecting the lead wires of the transducers to the connecting cables from amplifiers (DA100, BIOPAC Systems Inc.), was digitized by an analog-to-digital converter, and continuously recorded on a computer for analysis. The amplitude of ruminal contraction was calculated as the average value of the measurements of the area ($\text{g} \times \text{sec}$) surrounded by the contraction wave at the base-line for 10 min. The frequency of ruminal contraction (contractions/min) was calculated as the average value for 10 min.

Experimental procedure

We first examined the correlation between ruminal motility shown by the force transducer and the acceleration shown by the bolus sensor. The bolus sensor was orally administered by using a custom-made gastric tube, without surgery, and the bolus sensor was confirmed to be located in the reticulum by the movement pattern of acceleration [3]. The force transducer was sutured onto the dorsal sac of the rumen, with surgery. The Measurements by the force transducer and bolus sensor were carried out starting at 7 days after the surgery. The ruminal motility measured by the force transducer and the acceleration measured by the bolus sensor were recorded continuously and simultaneously throughout the trial. The measurement data of ruminal motility and acceleration were collected for 30-min periods during feeding and resting for each cattle. We also repeated the same trial on another day. The y-axis data were used as the measurement values of acceleration. We were able to confirm the cattle's behavior as feeding or resting by video observations through a camera connected to a notebook computer; these videos were recorded.

We next examined the effects of the administration of xylazine hydrochloride on the ruminal motility and acceleration. The cattle were intramuscularly administered xylazine hydrochloride (0.05 mg/kg; Bayer) once at 12:00. The measurement data of ruminal motility and acceleration were collected for 120-min periods before and after xylazine hydrochloride administration. The y-axis data were used as the measurement values of acceleration.

Statistical analysis

Data are expressed as the mean \pm standard deviation (SD). The relationship between acceleration shown by the bolus sensor and the ruminal motility shown by the force transducer was examined by obtaining Pearson's correlation coefficient and by performing an analysis of regression. Student's *t*-test was used to evaluate differences in acceleration, the amplitude of concentration, the peak number of acceleration, and the frequency of contraction between feeding and resting. Student's *t*-test was also used to evaluate differences in acceleration shown by the bolus sensor and the ruminal motility shown by the force transducer between before (-10 min) and after the administration of xylazine. A value of $P < 0.05$ was considered as statistically significant.

RESULTS

Acceleration data revealed by the bolus sensor

Figure 2 illustrates the three-axis acceleration data from the reticulum for a 30-min period when the cattle was resting. The baseline y-axis data stayed level, but baseline data of the x- and z-axes followed a large curve over the day. The probe was in an almost horizontal position with respect to the longitudinal axis. The basic movement of acceleration of the y-axis appeared to have a very distinct vertical pattern (Figs. 2 and 3), occurring roughly 1 time/min, with a duration of approximately 8 sec, and displaying two local maximums at around 500 mG (Fig. 3). The acceleration of the x- and z-axes showed an indistinct vertical pattern (Fig. 2).

Relationship between ruminal motility and acceleration data

Figure 3 shows the measurement results of ruminal motility obtained with the force transducer and the acceleration data (y-axis) obtained with the bolus sensor. The waveforms of ruminal motility and that of acceleration revealed by the bolus sensor occurred

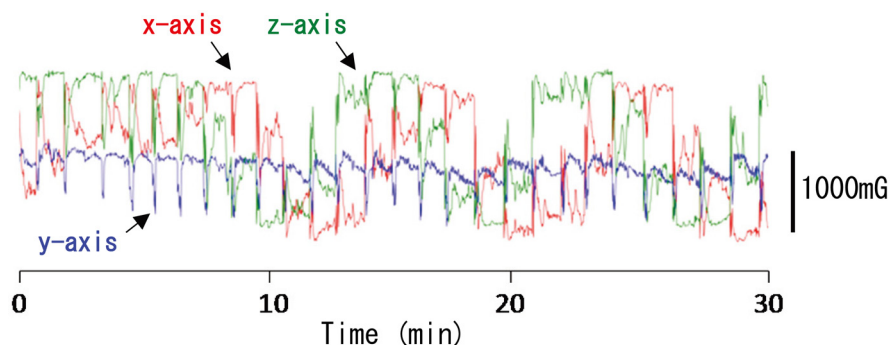


Fig. 2. Changes in the acceleration data of the x-, y-, and z-axes for a 30-min period when the cattle was at rest. The x- and z-axes indicate the acceleration in the radial direction. The y-axis indicates the acceleration in the vertical direction.

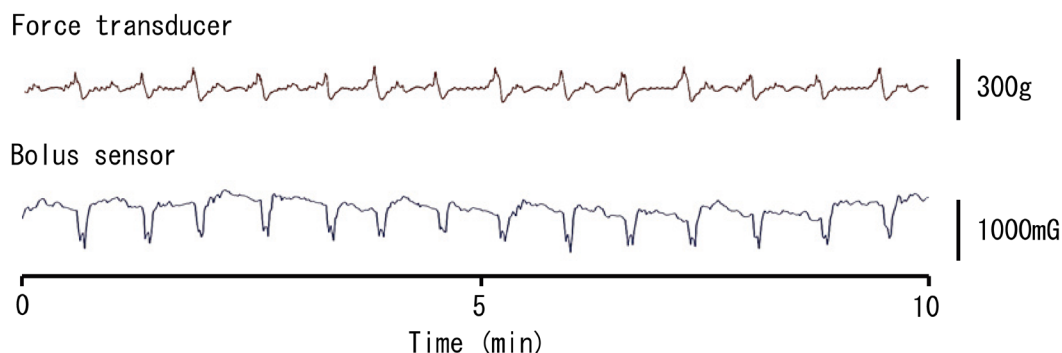


Fig. 3. Measurement results of ruminal motility obtained with the force transducer and the acceleration data obtained with the bolus sensor. The acceleration data are the y-axis.

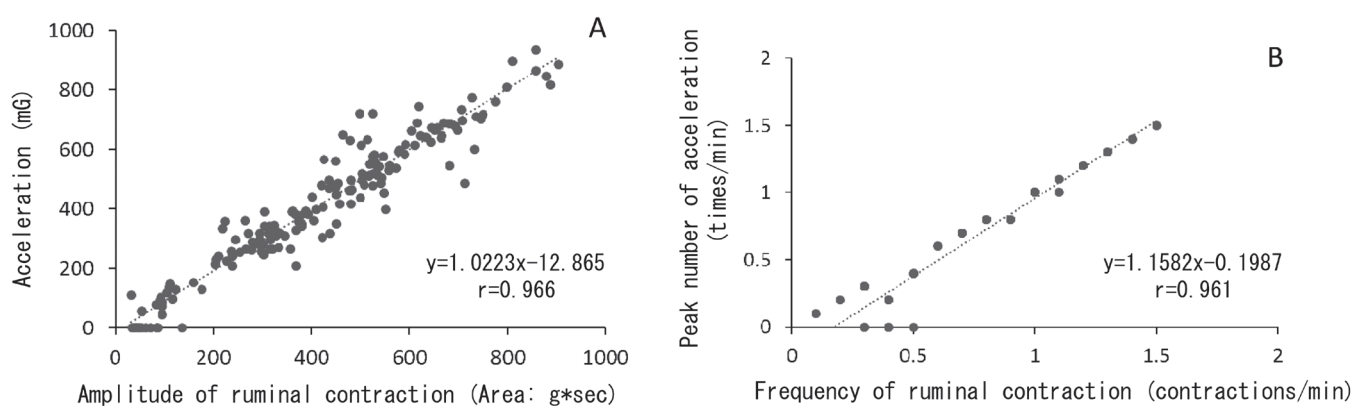


Fig. 4. A: The relationship between acceleration and the amplitude of ruminal contraction. B: The relationship between the peak number of acceleration and the frequency of ruminal contraction. Significant correlations were observed between the two methods (A: $r=0.966$, $P<0.01$, B: $r=0.961$, $P<0.01$).

Table 1. Measurement values of the bolus sensor and the force transducer during feeding and resting in cattle

Item	Bolus sensor		Force transducer	
	Feeding	Resting	Feeding	Resting
Acceleration (mG)	464 ± 168 ^{a)}	385 ± 109 ^{b)}	-	-
Amplitude of contraction (area: g × sec)	-	-	473 ± 127 ^{a)}	414 ± 88 ^{b)}
Peak number of acceleration (times/min)	1.5 ± 0.1 ^{a)}	1.1 ± 0.1 ^{b)}	-	-
Frequency of contraction (contractions/min)	-	-	1.5 ± 0.1 ^{a)}	1.1 ± 0.1 ^{b)}

Data are expressed as means ± SD. a, b) $P<0.01$.

at nearly the same time (Fig. 3), and patterns were clearly visible. The acceleration shown by the bolus sensor was significantly positively correlated with the amplitude of ruminal contraction shown by the force transducer ($P<0.01$, $r=0.966$) (Fig. 4). The peak number of accelerations obtained with the bolus sensor was significantly positively correlated with the frequency of ruminal contraction obtained with the force transducer ($P<0.01$, $r=0.961$) (Fig. 4). The acceleration data used the y-axis values.

Ruminal motility and acceleration data during feeding and resting

The acceleration data shown by the bolus sensor during feeding (464 ± 168 mG) was significantly higher than that shown during resting ($P<0.01$) (385 ± 109 mG) (Table 1). The amplitude of ruminal contraction measured by the force transducer during feeding (473 ± 127 g × sec) was significantly higher than that during resting ($P<0.01$) (414 ± 88 g × sec) (Table 1). The peak number of accelerations during feeding (1.5 ± 0.1 times/min) was significantly higher than that during resting ($P<0.01$) (1.1 ± 0.1 times/min) (Table 1). The frequency of ruminal contraction during feeding (1.5 ± 0.1 contractions/min) was significantly higher than that during resting ($P<0.01$) (1.1 ± 0.1 contractions/min) (Table 1). The acceleration data used the y-axis values.

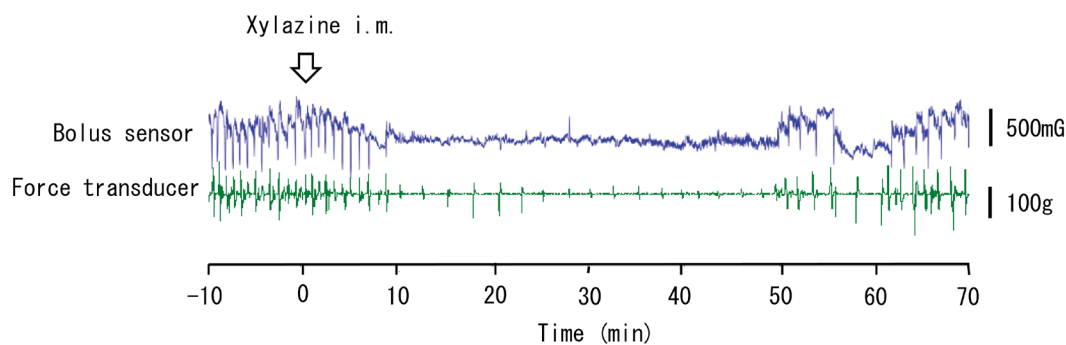


Fig. 5. Changes in ruminal motility and acceleration after the administration of xylazine hydrochloride in one of the four cattle. Top: Acceleration shown by the bolus sensor. Bottom: Ruminal motility shown by the force transducer.

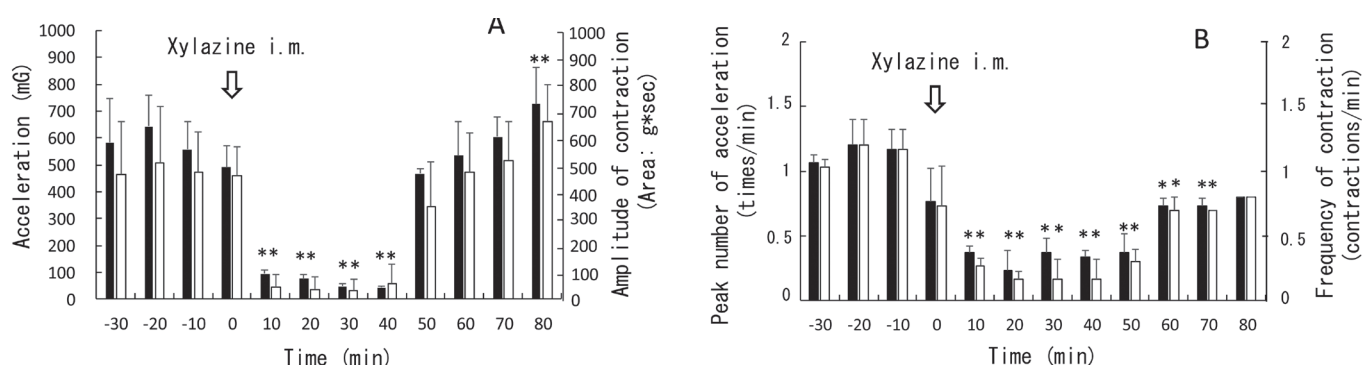


Fig. 6. A: Changes in the amplitude of contraction revealed by the force transducer and acceleration revealed by the bolus sensor after the administration of xylazine hydrochloride in cattle. B: Changes in the frequency of contraction revealed by the force transducer and the peak number of acceleration revealed by the bolus sensor after the administration of xylazine hydrochloride in cattle. * $P < 0.05$ compared to -10 min (before the administration of xylazine). ■, Force transducer; □, Bolus sensor.

Changes in ruminal motility and acceleration data after the administration of xylazine

After the administration of xylazine hydrochloride, the changes in the waveform of ruminal motility shown by the force transducer and those of acceleration shown by the bolus sensor were almost the same (Fig. 5). The ruminal atony occurred approximately 10 min after xylazine hydrochloride administration (Fig. 5). Compared to the -10 min values (before the xylazine hydrochloride administration), the acceleration and the amplitude of ruminal contraction were significantly decreased at 10–40 min after the xylazine hydrochloride administration ($P < 0.05$) and were then significantly increased at 80 min ($P < 0.05$) (Fig. 6). Compared to the -10 min values, the peak number of accelerations and the frequency of ruminal contractions were significantly decreased at 10–70 min after the administration of xylazine hydrochloride ($P < 0.05$) (Fig. 6). Regarding the cattle's clinical signs, ruminal tympany occurred at 30–40 min after the administration of xylazine hydrochloride and then recovered at 60–70 min.

DISCUSSION

The intended location of the bolus sensor in this study was the reticulum, which is a small compartment at the front of the rumen. The bolus-type wireless sensor that was inserted into the rumen was left continuously in the reticulum [5, 16, 22]. It seems that the bolus sensor is held in a comparatively free situation in digesta of the reticulum [16]. Since the accelerometer is subject to Earth's gravity, it is possible to monitor its orientation. We observed that the baseline y-axis acceleration data of the bolus sensor was kept level, whereas the baseline data of x- and z-axes showed a large curve. Once in its intended location in the reticulum, the probe is in an almost horizontal position with respect to the longitudinal axis. Acceleration measurements may be influenced by factors such as the flow of the contents of the reticulorumen and reticuloruminal motion [3, 15]. In the present study, there were many periods during which relatively clear data dominated the signal. The cylindrical shape of the probe allows it to rotate freely around its longitudinal axis, and this is reflected in the collected data (x- and z-axes). Probe rotations occur with varying frequency and tend to be concomitant with reticuloruminal motion. A bolus sensor can be confirmed to be located in the reticulum by palpation through the rumen cannula [3, 22]. It is also possible to determine the location of the probe from measurement data alone [3]. When inserted in the rumen, the probe will eventually (within a few days) spontaneously transfer from the rumen to

the reticulum, where it remains indefinitely. There appears to be a discernible difference in the movement pattern of acceleration between the rumen and the reticulum. The pattern in the reticulum exhibits more feature-rich movements, where each movement generally displays two or three local maximums, whereas the pattern in the rumen displays smoother movements with fewer maximums and a slightly different rhythm [3]. Our present analyses revealed more feature-rich movements of acceleration with two local maximums within 1 day after the oral administration of the bolus sensor in all four cattle.

We observed that the waveforms of ruminal motility and acceleration were almost the same, and a significant positive correlation was observed between the amplitude of ruminal contraction and the acceleration ($r=0.966$, $P<0.01$). A significant positive correlation was also revealed between the frequency of ruminal contraction and the peak number of acceleration ($r=0.961$, $P<0.01$). Thus, the contraction of the dorsal sac of the rumen and the acceleration signals in the reticulum occurred at nearly the same time. This phenomenon may be explained as follows: the flow of ruminal contents which occurred by compression of the dorsal sac of the rumen pushed and moved the bolus sensor in the reticulum. Braun *et al.* reported that the duration time of the contraction of the dorsal sac of the rumen was 8.2 ± 1.04 sec [7]. In the present study, the duration of the acceleration movement shown by the bolus sensor was about 8 sec. It seemed that the movement of the dorsal sac of the rumen and the movement of the acceleration of digesta in the reticulum were almost the same. The general pattern of reticuloruminal motility consists of regular contraction sequences [8, 24], that successively engage the various parts of the reticulum and rumen. There are primary and secondary contraction cycles; the former serves primarily to mix the ingesta, support optimal microbial fermentation, and transport ingesta into the omasum, whereas the latter cycles are involved in the eructation of gas [8, 9]. The primary cycles started with biphasic reticular contraction followed immediately by contraction of the ruminal atrium. The dorsal sac of the rumen, the caudodorsal blind sac and the left longitudinal groove contracted at practically the same time, after which contraction of the caudoventral blind sac, and the ventral sac of the rumen occurred. Secondary contraction cycles do not involve the reticulum or ruminal atrium; they consist of contraction of the dorsal sac and then the ventral sac of the rumen [7, 9]. In the present study, the movement of acceleration shown by the bolus sensor generally displayed two local maximums. Since the bolus sensor was located in the reticulum, these local maximums may be reflecting biphasic reticular contraction. It is likely that the major waveform of acceleration shown by the bolus sensor indicates the flow of ruminal contents which occurred by compression of the dorsal sac of the rumen, because a significant positive correlation was observed between the acceleration and ruminal motility.

It was reported that the frequency of contraction of the dorsal sac of the rumen was 1.1 ± 0.2 contractions/min during resting [7]. Herein we observed similar results obtained by the force transducer (1.1 ± 0.1 contractions/min) and the bolus sensor (1.1 ± 0.1 times/min). The frequency and amplitude of the ruminal contractions during feeding were significantly higher than those during resting. Similar results were obtained by another measurement methods [12]. Ruminal motility is also detectable by auscultation. Ruminal sounds can be heard with a stethoscope placed on the sublumbar triangle. Ruminal sounds are generated when a cow is fed a diet with high fiber content that moves along the ruminal wall during contraction of the rumen. High producing dairy cows fed a ration with relatively low fiber content produce fewer frictional ruminal sounds than cows fed hay [8, 17]. Because acceleration data measured by a bolus sensor indicate the flow of ruminal contents, the acceleration data may be reflecting ruminal sounds.

Our analyses demonstrated that ruminal atony occurred approximately 10 min after an administration of xylazine hydrochloride. The detection of ruminal atony by the bolus sensor was almost synchronous with that detected by the force transducer. Xylazine, an α_2 -adrenoreceptor agonist, is often used as a sedative for cattle. The pharmacologic effects of xylazine are an excessive depression of the central nervous system, ruminal atony and bradycardia [25]. In disorders of ruminal motility, general anesthesia and disease at any site that produces pain or fever can inhibit the hindbrain reflex centers responsible for evoking primary and secondary cycle contractions of the reticulorumen [17]. Clinical cases of ruminal stasis should be interpreted as being caused by a depression of gastric centers, a lack of excitatory reflex inputs, an increase in inhibitory reflex inputs, blockade of the motor pathways as in hypocalcemic animals but probably not in the case of vagus indigestion. In addition to their specific reflex inputs, the gastric centres are influenced by nervous activity in other parts of the central nervous system [17].

The bolus sensor used in the present study could detect impaired forestomach motility such as ruminal atony in real time. In addition, ruminal tympany occurred when the ruminal atony continued for 30–40 min. Ruminal tympany (bloat) is of particular significance in fattening beef cattle, but it may also be a problem in dairy herds on high concentrate rations [13]. In healthy cattle, gaseous distension of the reticulorumen reflex elicits an increase in the force and frequency of secondary cycles; it evokes the opening of the cardia and initiates the other respiratory, esophageal, pharyngeal and buccal actions of the eructation sequence. Normally the cardiac region is cleared when the dorsal ruminal sac contractions of secondary cycles force the gas layer forward, thereby depressing the fluid level below the level of the cardia. In cases of systemic disease in which ruminal hypomotility or stasis are secondary features, a persistent, mild bloat may be evident, because although the fermentation rate is probably low, the weak ruminal motility may be inadequate to move the gas layer and to clear the cardia [17]. We observed that the bolus sensor was useful for evaluating aspects of ruminal motility such as the frequency, amplitude, and timing of hypomotility. Evaluations of ruminal motility using a bolus sensor may be useful as a non-invasive method of investigating reticuloruminal stasis in cows with ruminal tympany, acidosis, fever or hypocalcaemia [2, 10, 17].

Since the bolus sensor is located continuously in the reticulum, the sensor probe should be durable for as long as possible. Our probe housing was made from PTFE, and the sensor could be recorded continuously for ≥ 1 –2 months. Several studies have described probe housing made from stainless steel or resin, and the studies' authors noted that the sensors used with this type of probe housing could be recorded continuously for several months [14, 23]. It has been unclear whether a sensor probe can have even more long-term (e.g., several years) durability and safety. Further investigations are needed to assess the durability and safety

of the bolus sensor described herein, in order to spread the uses of sensor technology for cattle.

In conclusion, the bolus sensor we have described can be orally administered without surgery, and it was left in the reticulum. The basic movement of acceleration of the y-axis shown by the bolus sensor appeared to have a very distinct vertical pattern. For the analyses of ruminal motility, the acceleration of the y-axis should be used. A significant positive correlation was observed between the ruminal contraction measured by the force transducer and the acceleration measured by the bolus sensor. The contraction of the dorsal sac of the rumen and the acceleration signals in the reticulum occurred at practically the same time. The bolus sensor also detected ruminal atony after the administration of xylazine. We therefore suggest that a bolus-type wireless sensor may be useful for the measurement of ruminal motility and for detecting dysfunctions of the rumen such as ruminal atony and ruminal tympany.

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