Evaluation of a telemetric gastrointestinal pill for continuous monitoring of gastrointestinal temperature in horses at rest and during exercise

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OBJECTIVE
To evaluate use of a telemetric gastrointestinal (GI) pill to continuously monitor GI temperature in horses at rest and during exercise and to compare time profiles of GI temperature and rectal temperature.

ANIMALS
8 Standardbred horses.

PROCEDURES
Accuracy and precision of the GI pill and a rectal probe were determined in vitro by comparing temperature measurements with values obtained by a certified resistance temperature detector (RTD) in water baths at various temperatures (37°C, 39°C, and 41°C). Subsequently, both GI and rectal temperature were recorded in vivo in 8 horses over 3 consecutive days. The GI temperature was recorded continuously, and rectal temperature was recorded for 3.5 hours daily. Comparisons were made between GI temperature and rectal temperature for horses at rest, during exercise, and after exercise.

RESULTS
Water bath evaluation revealed good agreement between the rectal probe and RTD. However, the GI pill systematically underestimated temperature by 0.14°C. In vivo, GI temperature data were captured with minimal difficulties. Most data loss occurred during the first 16 hours, after which the mean ± SD data loss was 8.6 ± 3.7%. The GI temperature was consistently and significantly higher than rectal temperature with an overall mean temperature difference across time of 0.27°C (range, 0.22°C to 0.32°C). Mean measurement cessation point for the GI pill was 5.1 ± 1.0 days after administration.

CONCLUSIONS AND CLINICAL RELEVANCE
This study revealed that the telemetric GI pill was a reliable and practical method for real-time monitoring of GI temperature in horses. (Am J Vet Res 2017;78:778–784)

The effect of exercise on body temperature in horses has been evaluated mainly indoors with controlled experimental conditions by use of treadmill exercise tests with body temperature recorded as blood temperature (obtained by inserting a thermal sensor into the pulmonary artery).1–9 However, to better understand the mechanisms by which exercising horses regulate body temperature in real-life conditions, there is a need to explore new techniques that can possibly be applied in field settings. Currently, intermittent measurement of rectal temperature of horses at rest is common practice throughout training and competition.

Continuous monitoring of body temperature during exercise may have several important advantages over intermittent measurements obtained from horses at rest. These include determining and monitoring body temperature patterns and maximum body temperature limits for individual exercising horses, allowing early intervention during competition, and evaluating body temperature patterns and effectiveness of postexercise cooling. Such data may improve well-being and performance of exercising horses. Skin,10 intrauterine,11 and eye12,13 temperature have also been explored as methods for assessing thermoregulation and for monitoring horses during competition. Eye temperature can only be measured intermittently in horses at rest,12,13 whereas skin10 and intrauterine11 temperature recordings can be obtained continuously during exercise. However, there are disadvantages with these techniques because skin temperature is not reflective of core body temperature10 and intrauterine temperature measurements can only be retrieved following removal of the device from the uterus and obviously can only be obtained from mares.11

ABBREVIATIONS
CI  Confidence interval
GI  Gastrointestinal
RTD  Resistance temperature detector

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A nondigestible temperature-sensitive pill that passes through the GI tract has been used for continuous monitoring of body temperature. This technology is minimally invasive and wireless, and it enables real-time display on a mobile device by use of Bluetooth technology. A GI pill has been evaluated and used for continuous monitoring of thermoregulation in human athletes during field and exercise studies. In addition, GI pills have been tested in resting and exercising dogs, elephants, cattle, and horses (while at rest and during transportation).

To our knowledge, there have been no reports of continuous body temperature monitoring of horses by use of a GI pill during field exercises, and the accuracy of tracking temperature changes in these circumstances by use of a GI pill currently is unknown. Therefore, the aim of the study reported here was to evaluate the use of a GI pill in exercising horses. Our objectives were to perform an in vitro assessment of the accuracy, precision, and agreement of results for a GI pill with those of a certified RTD as the reference method by use of a water bath system; to assess the feasibility for use of the GI pill as a means of continuous monitoring of GI temperature in resting and exercising horses; and to compare the time profile of GI temperature provided by use of the GI pill with rectal temperature of horses while at rest and during exercise.

Materials and Methods

Animals

Eight unconditioned Standardbred horses (7 mares and 1 gelding) were used in the study. Mean ± SD body weight was 465 ± 9.5 kg, mean body condition score was 4 (scale, 1 to 9), and age range was 4 to 10 years. Horses were examined and deemed to be healthy prior to the study. The horses were housed in individual yards (3.5 X 3.5 m) with ad libitum access to oat hay and water. The daily exercise protocol consisted of 30 minutes of exercise (10 minutes of walking followed by 20 minutes of lunging exercise at a fast trot). After exercise was completed, horses were provided drinking water (within 3 minutes after end of exercise) and walked by hand for 10 minutes. The study was approved by the University of Adelaide Animal Ethics Committee and was conducted at Roseworthy campus during the fall.

GI pill and rectal probe

A commercially available telemetric GI pill was used in the study. The pill was 8.7 mm in diameter and 23 mm in length, and it weighed 1.6 g. According to the manufacturer specifications, the GI pill had a temperature sensing range of 25° to 50°C, accuracy of ± 0.1°C between 32° and 42°C, and resolution of ± 0.01°C. The transmission range was reported as 1 m, with data recordings at 5- or 15-second intervals, depending on whether the older or updated version of the system was used. A rectal probe was also used.

In vitro evaluation

Temperature recordings for 8 GI pills and the rectal probe were compared with those obtained by use of a certified RTD. The GI pills were suspended in an open small plastic container. The GI pills, rectal probe, and RTD were submerged sequentially in water baths with recirculating water at 3 temperatures (37°, 39°, and 41°C); temperature for the 3 baths ranged from approximately 37° to 45°C. Once the sensors were activated, they were allowed to remain in each water bath until a plateau temperature was reached and held for a minimum of 3 minutes.

In vivo evaluation

A GI pill in 0.5 L of water was administered at 5 PM to each horse by nasogastric intubation. The GI temperature data recorded by the GI pill were transmitted at 40.68 MHz, and the signal was recorded every 5 to 15 seconds by a receiver located in a sensor belt system placed on each horse (Figure 1). Data from the GI pill were recorded continuously over 3 consecutive days. In addition, temperatures were measured with a rectal probe for 3.5 hours each day to enable us to make comparisons between GI temperature and rectal temperature recordings of horses at rest and during exercise. The rectal probe was inserted to a depth of approximately 30 cm proximal to the anal opening.

Figure 1—Photograph of a sensor belt adapted for use in horses. The belt has been placed around the girth, with the receiver positioned ventrally at the sternum and protected by padded covers.
sphincter. Rectal temperature was recorded for 120 minutes while horses were at rest, for 30 minutes during exercise, and for 1 hour after exercise. If it was expelled, the rectal probe was immediately replaced. A temperature logger\textsuperscript{4} was used to measure the ambient temperature and relative humidity, which were confirmed by recordings obtained at a local Bureau of Meteorology station.\textsuperscript{8}

Presence of each GI pill in the GI tract of each horse was evaluated daily with the data logger. The time point at which no temperature signal output could be detected (ie, the pills were expelled from the rectum) was recorded as the data log cessation time point. The GI pills were not retrieved from the feces.

**Statistical analysis**

Feasibility of use of the GI pill and of the quality of data retrieved was evaluated. The evaluation involved assessing the proportion of usable data collected by use of the GI pill with the receiver system (after removal of erroneous data), calculating data loss (total and 4-hour increments), and recording the cessation time of the GI pill.

The nature and magnitude of accuracy and precision\textsuperscript{31} were assessed during the in vitro evaluation. Temperature for the GI pill and rectal probe were compared with RTD temperature. The Lin concordance correlation coefficient was calculated by use of a statistical package.\textsuperscript{3} The Bland-Altman method was used to calculate the 95% limits of agreement (mean difference ± 1.96•SD) and the bias.\textsuperscript{32,33} Po
tential within-pill correlation (repeated measures) was investigated with a mixed linear regression model\textsuperscript{b} and estimation of the intraclass correlation. Variability explained by between-pill variation was negligible (intraclass correlation = 4.960 \times 10^{-20}), and measurements for each pill were deemed independent. Mean response time of the 8 GI pills was determined by recording the time required to reach equilibrium temperature in 2 water baths (39° and 41°C).\textsuperscript{14,24}

To determine whether the GI pill was an accurate measuring device in horses in a field setting, data from periods of rest and exercise were analyzed. The GI temperature data were adjusted for bias calculated during the in vitro water bath evaluation and then used for statistical analysis. One-minute values (mean and 95% CI) were calculated for GI and rectal temperature data of horses at rest (120 minutes), during exercise (30 minutes), and after exercise (60 minutes) for 3 days. Recorded temperatures were considered erroneous and excluded from analysis when values were associated with rectal probe expulsion, were outside the lower or upper limits of the body temperature range for horses (≤ 36.5° to 41°C), or changed by > 0.5°C in 30 seconds (ie, exceeded the sensor response rate).\textsuperscript{29,30} Measurements obtained during the first 15 minutes after insertion of the rectal probe and > 60 minutes after exercise were not included in the analysis. To account for repeated measures, a mixed effects linear regression model\textsuperscript{b} was used to investigate differences between GI and rectal temperatures over time, with horse and trial iteration within horse as random effects. Dependence among residual values (2 temperatures measured with a brief interval between measurements are more similar than 2 temperatures measured with a large interval between measurements) was accounted for by adding an autoregressive residual covariance matrix in the model. Difference between GI and rectal temperatures was reported as predicted mean values with 95% CIs and compared across activity periods; values were considered significant at \(P < 0.05\), with Bonferroni correction to account for multiple pairwise comparisons. The time for the mean GI temperature and rectal temperature to return to a preexercise cutoff value of 38.5°C after exercise was also recorded.

The time profile of total data loss for the GI pill was calculated for each horse as the number of missing data points divided by the total number of data points. Mean data loss for the 8 horses was calculated at 4-hour intervals, and total cumulative loss was calculated for the entire recording period (76 hours). Total data loss was analyzed by use of a univariate 1-way ANOVA with post hoc testing with the Fisher least significant difference test. Values were considered significant at \(P < 0.05\).

**Results**

**In vitro evaluation**

The in vitro evaluation revealed excellent correlation between measurements for the GI pill and RTD and between the rectal probe and RTD throughout the water bath trials. Calculated concordance correlation coefficients between GI temperature and RTD temperature and between rectal probe temperature and RTD temperature were 0.996 (95% CI, 0.993 to 0.999) and 0.999 (95% CI, 0.999 to 1.0), respectively, which illustrated good precision of the methods. Similarly, bias correction factors for the GI pill and rectal probe revealed excellent accuracy (0.997 and 1.0, respectively). The calculated systematic bias for the GI pill measurements was 0.140°C (95% limits of agreement, −0.277° to −0.004°C) and for the rectal probe measurements was 0.010°C (95% limits of agreement, −0.101° to 0.082°C; **Figure 2**). Variability explained by between-pill variation was negligible (intraclass correlation, 4.960 \times 10^{-20}), and measurements for the GI pills were deemed to be independent. Mean ± SD total time to equilibrium temperature (response time) in the 39° and 41°C water baths was 75 ± 72 seconds and 83 ± 95 seconds, respectively.

**In vivo evaluation**

One GI pill was inadvertently dropped on the floor and subsequently damaged during administration; thus, a second GI pill was administered to that horse 48 hours later. The rectal probe was regularly expelled by all horses and required replacement. Output data collected at those time points were consid-
Mean ± SD total data loss for the 8 horses was 16.5 ± 4.1% with a large interindividual variation (range, 3.2% to 37.3%). Data loss was mainly during the first 12 to 16 hours after GI pill administration, which was evident in the 4-hour data (Figure 3). Data loss significantly (P = 0.014) decreased as time progressed and reached a plateau at 16 hours after GI pill administration. Total data loss did not differ significantly (P = 0.056) between 16 and 72 hours after pill administration. Elimination of the first 16 hours of the recordings resulted in a mean data loss of 8.6 ± 3.7% (range, 1.1% to 32.6%).

In vivo GI temperatures were adjusted by adding the correction factor of 0.14°C (ie, bias obtained during the in vitro evaluation). Ambient temperature (mean ± SD minimum and maximum temperatures, 6.62 ± 0.7°C and 19 ± 0.9°C, respectively) and mean relative humidity (minimum and maximum values, 62.2 ± 3% to 90.7 ± 2.7%) were similar during the 3 days.

Differences between GI and rectal temperatures were compared for horses at rest, during exercise, and after exercise (Figure 4). Data were recorded for 7 horses, with differences in the number of trial iterations per horse (range, 1 to 3). The GI temperature consistently was significantly (P < 0.001) higher than the rectal temperature, with an overall mean temperature difference across time of 0.27°C (range, 0.22° to 0.32°C). This temperature difference did not differ significantly among the 3 time periods (at rest, during exercise and after exercise).

During the 120-minute rest period, mean GI and rectal temperatures were 37.94°C (95% CI, 37.82° to 38.06°C) and 37.63°C (95% CI, 37.50° to 37.77°C), respectively. Both GI and rectal temperatures increased during the exercise period and continued to increase after the end of exercise (Figure 4). Mean maximum GI temperature was 38.88°C (95% CI, 38.76° to 38.93°C) at 6 minutes after completion of exercise, whereas the mean maximum rectal temperature was 38.58°C (95% CI, 38.45° to 38.71°C) at 4 minutes after completion of exercise.

Mean ± SD cessation time point was 5.1 ± 1.0 days after administration. For 7 horses, the GI pill could not be detected after 5 days; however, the remaining horse expelled the GI pill at 12 days after administration.

**Discussion**

To our knowledge, the study reported here was the first that has been conducted to evaluate the feasibility of a GI pill for continuous monitoring of GI...
temperature in horses during exercise in a field setting. The GI pill and data logger system was found to be a minimally invasive and practical method for real-time monitoring of GI temperature during lunging exercise and has the potential to be adapted for use during exercise performed with a rider.1

Neither the use of a rectal probe nor pulmonary artery catheterization (the criterion-referenced standard) are suitable for use in measuring core temperature of horses in field settings because of expulsion of the rectal probe during defecation and the invasive nature of the catheterization procedure, respectively.1,7,9,29,34 Other methods (eg, implantable microchips) have provided no correlation with rectal temperature in steers28 or with rectal temperature or blood temperature in dogs.35 Measurement of intrauterine temperature by insertion of a temperature logger into the uterus has been used successfully to continuously monitor temperature in 9 mares during rest and exercise.11 Researchers of that study34 reported a similar but slightly lower temperature profile to that described for the present study. Disadvantages of the intrauterine method are that it is not a real-time measurement, it can only be used in mares, and there are no data on possible adverse effects on future reproduction. Additionally, similarly to rectal temperature, uterine temperature may lag behind body (core) temperature because of its peripheral location.

For the present study, the adjusted GI temperature was consistently higher than rectal temperature in horses at rest, which is in accordance with results of other studies. Investigators of 1 study29 reported small differences in the hourly mean temperature when comparing GI temperature with other temperature measurements; GI temperature was 0.5°C higher than rectal temperature and 1.0°C higher than blood temperature. Similarly, GI temperature and rectal temperature reported for the present study were significantly different during exercise, with only a small but uniform difference throughout the measurements, which suggested that random error between methods was acceptably small at GI temperatures. The GI temperature reached a higher maximum temperature than did the rectal temperature, which may suggest that GI temperature may be more reflective of changes in body temperature during exercise than is rectal temperature. Similarly, studies17,18,20,21,36,37 of humans conducted to compare GI temperature with other temperature measurements revealed an acceptable level of agreement with a consistent and significant bias existing between GI temperature and rectal temperature. Investigators of 1 study37 reported that pulmonary artery blood temperature and GI temperature measurements at the end of heat stress were similar, there was an extremely small bias for limits of agreement, and blood temperature and GI temperature were highly associated but the early GI temperature data were lower than blood temperature data. Similarly, there is a slower response of rectal temperature relative to GI and intraesophageal temperatures.14,16 In addition, there is a slower response of rectal temperature and GI temperature relative to the response of intraesophageal temperature during high-intensity exercise in humans.24

In the study reported here, GI temperature continued to increase after exercise, which is consistent with results of other studies6,7,9,34,38 conducted to evaluate rectal temperature of horses during treadmill exercise. This emphasizes the importance for continuous recording of temperature after exercise.6,29

Bland-Altman evaluation of results for the GI pill in water baths revealed reasonable precision with low variation and justified the use of the small bias as a reasonable correction factor to adjust GI temperature in the in vivo evaluation. Although reproducibility and repeatability were not directly assessed during the in vivo evaluation in the study reported here, an acceptable level of GI temperature reliability for humans has been reported.56,37 It has been suggested36 that an acceptable limit of agreement is 0.4°C (when comparing GI temperature and rectal temperature in humans), and an acceptable bias is > 0.1°C. Further investigations with higher water bath temperatures and higher-intensity exercise, long-term exercise, or exercise during hot conditions would be valuable to confirm reliable temperature measurement at higher body temperatures (eg, 42°C and 45°C).37

The GI pill response time was acceptable and confirmed the suitability for continuous monitoring of temperature patterns over time, especially when temperature patterns are more important than abso-
lute values. However, the response time and rate of change for the GI pill at the start of exercise or during periods of acceleration and deceleration may be less rapid than changes in blood temperature, which is a result similar to that reported for humans. Evaluation of the response time during rapid changes of body temperature is recommended, especially for animals that require a rapid response time (eg, racehorses). In the study reported here, data obtained during the first 15 minutes after insertion of the rectal probe (which was lubricated with cold gel) were removed because this would have falsely influenced the correlation between rectal and GI temperatures.

In the present study, data loss predominantly occurred during the first 16 hours after GI pill administration; therefore, it is recommended that the GI pill be administered to a horse approximately 16 hours before the time at which monitoring is required. Data loss (after elimination of the first 16 hours of data) was within acceptable limits and without extreme outliers, except for 1 horse. We have no explanation as to the reason that this occurred, specifically for that 1 horse. Possible reasons included damage to the GI pill or interference in the transfer of data from the GI pill. In general, data loss for the GI pill most likely occurs because of electromagnetic interference, the fact that the sensor may have a limited transfer range during movement of the GI pill through the GI tract, or temporary failure of the data logger. The use of GI pills in horses has been evaluated in other studies. Although the GI pill system used in those studies has not been evaluated during exercise, data loss in horses at rest was considerably higher than that recorded for the present study. Investigators of 1 study evaluated another GI pill system in 8 adult horses at rest. The GI pills were administered 17 hours before data collection, and mean data loss during the subsequent 6 hours of monitoring was 13.3 ± 4.7% for GI temperature, compared with mean data loss for the blood temperature (16.4 ± 12.5%). However, a much higher mean data loss (48.5 ± 4.7%) was reported during 2 days of monitoring of horses in stables and trailers. Furthermore, downloading of data with the system used in those studies is an extremely tedious task (in our experience), which suggests that the system is less practical. The pH, GI temperature, and luminal pressure were measured in 7 ponies by use of a modified GI pill system equipped with an extra antenna for the external receiver to enhance the transmission range. This intervention was needed to overcome the larger body size of the ponies, compared with the body size of humans. Data loss in the ponies with the modified receiver was approximately 15%, but the exact duration of data collection was not specified. In addition, other systems do not allow real-time viewing of temperature data.

The cessation time cannot be known exactly without collecting the GI pill from feces. Battery life of the device during active transmission is approximately 10 days. In the study reported here, we assumed that monitoring the signal from the GI pill was a sufficient method to determine whether the pill was still within the GI tract. The data log cessation time point differed greatly among horses, which is in accordance with results of other human and equine studies, and could have been attributable to factors such as interindividual differences in GI tract motility. Cessation time in other studies of horses ranged from 33 hours to >1 week. Cessation time in studies of humans ranged from 12.5 hours up to 5.6 days.

In the study reported here, real-time temperature monitoring by use of the GI pill in combination with a data logger in horses during exercise was found to be feasible. There was little data loss >16 hours after administration of the GI pill, and there was good correlation between GI and rectal temperatures. These findings may provide many avenues for future research on thermoregulation and exercise physiology of horses in field conditions. Better understanding of thermoregulation in horses will help to improve training protocols and to prevent exertional heat illness, which would be a major step with respect to well-being of horses.

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Footnotes
c. Thermal water bath, Model NBTH-P, Labec Laboratory Equipment, Marrickville, NSW, Australia.
g. Roseworthy weather station, Bureau of Meteorology, Roseworthy, SA, Australia.
h. Stata, version 14.1, StataCorp LLC, College Station, Tex.
i. SPSS software, version 19.0, IBM-SPSS, Chicago, Ill.

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3. Geor RJ, McCutcheon LJ, Ecker GL, et al. Thermal and cardiorespiratory responses of horses to submaximal exer-