Technical note: A facility for respiration measurements in cattle

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ABSTRACT

A respiration system consisting of 4 climate-controlled chambers and 1 set of flowmeters and analyzers was constructed and validated. Each chamber had volume of 21.10 m³ (3.68 × 2.56 × 2.24 m) and was made from steel with double-glazed windows on either side enabling visual contact between animals. The chambers are independently climate-controlled and can maintain temperature and relative humidity in a range from 5 to 45°C and 30 to 80%, respectively. A flow generator and mass flowmeter continuously pull air from each chamber and a slight negative pressure inside the chamber is ensured. Air from all chambers and ambient air share a common gas analysis and data acquisition system for monitoring O₂, CO₂, and CH₄ concentrations over the measurement period, with the cycle time set to 20 min. Analyzers are regularly calibrated and the chambers have mean recoveries of 99.0 and 98.0% for CO₂ and CH₄, respectively. The chambers are equipped with infrared cameras and electronic feed and water bins for intake measurements, as well as sensors for monitoring animal position and heart rate. Data acquisition and analysis software is used to calculate the rate of consumption of O₂ and production of CO₂ and CH₄. The dynamic respiration measurements are integrated with feed intake data and other sensors. The daily gas exchanges are estimated by integration to determine methane emission and heat production. We conducted a trial with 12 lactating 3/4 Holstein × 1/4 Gyr crossbred dairy cows (6 multiparous and 6 primiparous) under 2 feeding regimens (ad libitum or restricted) to validate the system. Two 22-h respiration measurements were obtained from each cow. Restricted-fed cows showed lower values for milk yield, methane emission, and heat production compared with ad libitum-fed animals. We found no difference between groups for CH₄ produced

per kilogram of dry matter intake. Repeatability for CH₄ emission and heat production was high (0.97 and 0.92, respectively). The respiration system described herein is a useful tool for measuring the dynamic and accumulated data of heat production, methane emission, and feed intake.

Key words: bioenergetics, energy, indirect calorimetry, methane

Technical Note

Historically, open-circuit respiration chambers have been widely used in North America and Europe for determination of feed evaluation and energy requirements for dairy and beef cattle (Yan et al., 1997; Derno et al., 2005). Over the last decade, the increased demand for finding strategies to mitigate methane emission by ruminant animals has renewed interest in respirometry studies around the world. In addition, there is a need to understand the mechanisms that regulate energy expenditure in beef and dairy cattle to improve the efficiency of production and animal health (Derno et al., 2009), and to identify variation in energy metabolism of more-efficient animals as a phenotypic feature for breeding programs (Arndt et al., 2015; Moraes et al., 2015). The search for knowledge about the effects of heat stress on animal metabolism also motivates the use of climate-controlled respiration chambers. The respiration chambers for cattle described herein were designed to allow the study of interactions and dynamics among feed intake, climatic conditions, methane emission, and energy metabolism. The aim of this technical note is to describe and validate this facility as a useful and repeatable tool for respiration measurements.

The respiration system is located in Bioenergetic Laboratory of Multi-use Complex on Livestock Bioefficiency and Sustainability of the Brazilian Agricultural Research Corporation, Embrapa (Coronel Pacheco, Minas Gerais, Brazil). All chambers are located in the same building and a dedicated level on the second floor contains the air-conditioning units. A separate air-conditioned room, annexed to the chamber build-

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Figure 1. General scheme of the respiration system. FK2K = flow meter and control, SS4 = sub-sampler pump, RH-300 = water vapor analyzer, CA-10 = CO₂ analyzer, MA-10 = CH₄ analyzer, FC-10 = O₂ analyzer, UI-2 = universal interface. All components are from Sable Systems International (Las Vegas, NV).

ing, houses the equipment for gas analysis, calibration, chamber control, and data acquisition and processing (Figure 1). The respiration system is configured in an open-circuit arrangement (Aguilera and Prieto, 1986) and consists of 4 chambers assembled in pairs. The net volume of each chamber is 21.10 m³, with dimensions (m) of 3.68 long × 2.56 wide × 2.24 high, containing a 2.26- × 1.26-m pen, which provides a safe environment for one animal and allows technicians walk around to manipulate it. The construction company was No Pollution Industrial Systems Ltd. (Edinburgh, UK). The chambers are made from steel with thermo-insulating and sound-insulating wall panels made from AISI 304 stainless steel sheets (CPC Inox S.P.A., Basiano, Italy), with polyurethane injected in between. Joints between panels were sealed with polyurethane sealant (Sikaflex, Sika S/A, São Paulo, Brazil). The chambers have large double-glazed windows (150 cm high, 150 cm wide) to guarantee visual communication between animals. Each chamber is fitted with one large back door for animal access and a smaller front door for operator access and for feeding, both fitted with rubber seals (Figure 2A). The floor is concrete painted with epoxy to prevent CO₂ exchange. An epoxy sealant ensures no leakage between the walls and concrete floor. A slurry grate located behind each animal is emptied twice a day by a flushing system operated from outside the chambers (Figure 2C). The slurry system is sealed with a wafer cast iron butterfly valve to prevent gas leaks. The pen

floor is covered with a Rubber Plus mat (WingFlex, Kraiburg TPE GmbH & Co., Waldkraiburg, Germany) to optimize the animal's comfort. Each chamber is fitted with an emergency hatch, which is closed by an electromagnet lock. In the event of a power failure, flooding due to a leak in the water supply system, extreme temperatures, or a CO₂ build-up to 10,000 ppm, the hatch is automatically opened, ensuring animal safety.

Chambers are climate-controlled and designed to keep ambient temperature and relative humidity (RH) from 5 to 45 ± 0.5°C and 30 to 80 ± 5%, respectively. The temperature and RH inside the chambers are continuously measured over the measurement period, and the climate control and climatic conditions are recorded using Metasys software (version 5.1.3.0400; Johnson Controls Inc., Milwaukee, WI). Each chamber has an independent regulation system, a separate air treatment unit with a recirculating fan (800–1,600 m³/h), and an air filter section, which is integrated to the chamber through 350-mm-diameter flexible thermo-insulating tubes. For recirculation, air leaves the chamber through openings at the bottom corners of the chambers. The air is then recycled into the chamber through openings at the front end of the chamber ceiling.

Four separate streams of ambient air are drawn through 75-mm-diameter polyvinyl chloride (PVC) pipes from outside the shed and are connected to each chamber's fresh air inlet in the front ceiling (Figure 1).

Figure 2. (A) Overview of the chambers; (B) chamber's interior view with the feed and water bins; (C) slurry grate for feces and urine. Color version available online.

Inside the chamber, the fresh air inlet presents a valve and a T-connection fitted with 2 horizontal PVC tubes (50 mm diameter $\times$ 1.5 m) punctured with 5-mm holes to avoid laminar flow, immediately above the feed bin and next to recirculating air entrance. At the same shed wall, next to the 4 outside spots, another 75-mm-diameter PVC pipe connected to an exhaust fan (Ventokit 80, Westaflex Tubos Flexíveis Ltda., Paraná, Brazil) is used to take the ambient air to a carboy next to the control room (Figure 1) so that more stable values of oxygen concentration can be obtained.

The chamber is fitted with an air outlet with a filter box (CSL-851-200HC, Solberg Manufacturing Inc., Itasca, IL), in the rear section of the ceiling, and the air is continuously drawn out through a 75-mm-diameter PVC pipe, which is reduced to 51-mm-diameter flexible polyurethane hose next to the analysis room and then connected directly to a mass flowmeter and flow generator (FlowKit model FK-2000, Sable International Systems, Las Vegas, NV) with a sealed rotary pump having a capacity range from 400 to 2,000 L/min. Flowmeters provide mass flow measurements of the atmospheric air corrected for standard temperature (273.5 K) and pressure (101.325 kPa) conditions (STP) and keep the set flow rates constant throughout the measurement period. The flow rate is chosen on the premise that the CO₂ level should not exceed 1.00% and measurement of O₂ consumption should still be possible. For lactating dairy cows, the flow rate usually used is 1.3 L/min for each kilogram of live BW, and for heifers and nonlactating dairy cows, the flow rate is 1.0 L/min for each kilogram of BW.

At the flow-through system described herein, the air is pulled and the flow rate measurement takes place downstream from the respiration chamber (in the excurrent air stream). This approach, together with adjustments in the fresh air inlet valve, always ensures a slight negative pressure (minimal 50 and maximal 100 Pa below ambient pressure) inside the chamber, thus preventing leakages out of the system. The pressure inside the chamber is measured with a digital pressure indicator (DPI 705, Druck Limited, Leicester, UK) every morning before starting the measurements.

The 4 chambers share a common gas analysis and data acquisition system (Sable Systems International). After the measurement of the flow rate, air leaving the chamber is continuously sampled at about 0.5 L/min by the flow meter's internal subsampling pump for analysis, and then the overflow is exhausted. The ambient air (baseline) is also continuously subsampled at about 0.5 L/min by a positive pressure pump (B-pump, Sable Systems International). A gas switching system with 8 channels (RM-8 Flow Multiplexer, Sable Systems International) controls the 4 chamber and baseline air samples, and delivers only one sample stream (from one of the chambers or baseline) to the analyzer set at any time by a means of a diaphragm subsampling pump (SS-4 Sub-Sampler Pump, Sable Systems International; Figure 1). Flow leaving the multiplexer at 0.5 L/min is pulled by the subsampling pump at 0.2 L/min through a sampling manifold (T-connection); then, the excess air escapes and the controlled flow (0.2 L/min) is pushed through the analysis chain. All tubing from the subsampling pumps to the gas analyzers uses Bev-

A-Line IV tubes, size B5 (Excelon, Long Hill Township, NJ).

The time interval at which the multiplexer switches the channels can be defined by the operator in the data acquisition software (Expedata Data Analysis Software 1.8.5, version PRO, Sable Systems International), based on the stability of the gas concentrations and the number of chambers in operation. At present, the system is configured to 200 s of measuring time for each channel (dwell time). With all 4 chambers working simultaneously, the switching sequence in each measurement cycle follows the pattern: baseline, chamber 1, chamber 2, baseline, chamber 3, chamber 4. Using this approach, the time required for a complete cycle through all chambers (cycle time) is 20 min and we have 3 measurements per hour for each chamber and 66 measurements in 1 d (considering a measurement period of 22 h/d).

The sample stream is delivered in sequence to the water vapor (RH-300 Water Vapor Analyzer), CO₂ (CA-10A Carbon Dioxide Analyzer), CH₄ (MA-10Methane Analyzer), and O₂ (FC-10 Oxygen Analyzer) analyzers (Figure 1; all from Sable Systems International). The lag time of each analyzer depends on the length of the Bev-A-Line tubes between the gas switching system and the respective analyzer, and on the subsampling rate. Using a subsampling rate of 0.2 L/min, the lag time of the water vapor, CO₂, CH₄, and O₂ analyzers are 9, 11, 16, and 23 s, respectively. Carbon dioxide and methane are measured using infrared technology, whereas oxygen is measured using fuel cell technology. The gas analyzers have an internal temperature control and barometric pressure compensation, so the readout is already corrected to STP conditions. The detection range for relative humidity, CO₂, CH₄, and O₂ are 0–100% (accuracy 2% absolute, resolution 0.001%), 0–10% (accuracy 1% of reading, resolution 0.0001%), 0–10% (accuracy 1% of reading, resolution 0.001%), and 0–100% (accuracy 0.1% of reading, resolution 0.0001%), respectively.

Calibration of the CO₂ and CH₄ analyzers (zero and span) is made before the beginning of each measurement. The O₂ and water vapor analyzers are calibrated once a week. For zeroing the CO₂, CH₄, and O₂ analyzers, nitrogen gas (99.999%) is used, and CO₂ and CH₄ are spanned by using a mixed gas (0.5% CO₂, 0.1% CH₄ in N₂ as carrier). The O₂ analyzer is spanned with dry ambient air, scrubbed from water by using magnesium perchlorate, as it shows an almost constant concentration of 20.95%. A zero value of the water vapor analyzer is achieved with the dry air, and the value for spanning is calculated following the Lighton (2008) equation:

$$WVP = BP \times [(F'iO_2 - FiO_2)/F'iO_2], \quad [1]$$

where WVP is the water vapor pressure in the same units as barometric pressure (kPa); BP is the barometric pressure; and F'iO₂ and FiO₂ are O₂ fractional concentrations of dry and wet ambient air, respectively.

A recovery test of the whole system was made by injection of known volumes of CO₂ and CH₄ in each chamber, by using a portable mass flowmeter with totalizer function (MC-50SLPM-D, Alicat Scientific Inc., Tucson, AZ). The average recoveries for CO₂ and CH₄ were (mean $\pm$ SD) 99.0 $\pm$ 2.1% and 98.0 $\pm$ 2.7%, respectively.

Each chamber contains a feed bin (0.7 m wide, 1.0 m high, and 0.5 m deep) made from stainless steel and equipped with load cells (100-kg weighing capacity with $\pm$ 25 g accuracy), an electronic gate for animal access control, and a registration device (Intergado Ltd., Minas Gerais, Brazil; Figure 2B). For each bin visit, the system records the duration and feed disappearance using a data collector via network cable and transfer to the Intergado web software via a general packet radio service. The feed bins are equipped with an automatic gate allowing feeding (release access to feed) without opening the chamber. Around 30 min after closing the chamber, the feed bin gate is opened and the evaluation of gaseous exchange and feed intake start. This waiting period following the door closure aims to minimize the measurement while the chamber air is transient; that is, the gas content is modified quickly by the animal.

Once a week, the feed system is calibrated with a 25-kg analytical precision weight (Intergado Ltd.), following the manufacturer's instructions. Water intake is registered by water meters equipped with electro-mechanical registration, and this system is checked periodically by removing a known volume of water from the bin to compare with the value registered. Animal position, depicted as standing or lying, is registered by a photoelectric switch (Intergado Ltd.). To monitor animal behavior and wellbeing, each chamber is equipped with an infrared camera (VM 310 IR, Intelbras S/A, Santa Catarina, Brazil) plugged into a video recording system, which enables animals to be observed from a video monitor located in the control room, as well as remote monitoring by staff members. The animal position registered by the photoelectric switch can be checked by the video recordings, when necessary. The animal's heart rate (**HR**) inside the chamber is recorded with a Polar transmitter and monitor (model RS800CX G3, Polar Electro Inc., Kempele, Finland).

Data acquisition and analysis software (ExpeData v.1.7.5, Sable Systems International) is used to record

gas concentration for O₂, CO₂, and CH₄; wet air outflow rate; temperature; barometric pressure; and water vapor pressure during the measurement period. The software, by means of a macro utility, corrects the effect of water vapor on flow rate and gas concentrations, performs lag time correction, response correction and drift correction. The gas concentration data are corrected for lag by deleting the first “n” seconds in that channel; that is, the time of each analyzer to encounter the air sample, and shifting all remaining data “n” seconds to the left. The gas concentrations are corrected for differences in response time by applying the instantaneous transform, also known as the Z-transform (Bartholomew et al., 1981; Lighton, 2008). Response correction coefficients were 0.134, 0.189, 0.047, and 0.137 for O₂, CO₂, water vapor, and CH₄, respectively. From the measurements of air entering (incurrent) and air leaving (excurrent) the chambers, the software calculates the exhaustion rates (L/min) of O₂ (**VO₂**), CO₂ (**VCO₂**), and CH₄ (**VCH₄**) from each chamber, using the following equations from Lighton (2008):

$$\begin{aligned} \text{VO}_2 = \text{FR} \times [& (\text{FiO}_2 - \text{FeO}_2) - \text{FiO}_2 \\ & \times (\text{FeCO}_2 - \text{FiCO}_2) - \text{FiO}_2 \\ & \times (\text{FeCH}_4 - \text{FiCH}_4)] / (1 - \text{FiO}_2), \end{aligned} \quad [2]$$

$$\begin{aligned} \text{VCO}_2 = \text{FR} \times [& (\text{FeCO}_2 - \text{FiCO}_2) + \text{FiCO}_2 \\ & \times (\text{FiO}_2 - \text{FeO}_2) + \text{FiCO}_2 \\ & \times (\text{FeCH}_4 - \text{FiCH}_4)] / (1 + \text{FiCO}_2), \end{aligned} \quad [3]$$

$$\begin{aligned} \text{VCH}_4 = \text{FR} \times [& (\text{FeCH}_4 - \text{FiCH}_4) + \text{FiCH}_4 \\ & \times (\text{FiO}_2 - \text{FeO}_2) + \text{FiCH}_4 \\ & \times (\text{FeCO}_2 - \text{FiCO}_2)] / (1 + \text{FiCH}_4), \end{aligned} \quad [4]$$

where FR is the flow rate; FiO₂, FiCO₂, and FiCH₄ are the fractional concentrations of O₂, CO₂, and CH₄ of the incurrent air; and FeO₂, FeCO₂, and FeCH₄ are the fractional excurrent concentrations of O₂, CO₂, and CH₄. After VO₂, VCO₂, and VCH₄ have been calculated for each sample point, the mean is taken for the central 180 consecutive samples of each 200-sample data section for each chamber during each measurement cycle of 20 min. Besides the rate of gas exhaustion from the chambers, the rate of change in gas content inside the chamber is also calculated as the difference in the volume of O₂, CO₂, and CH₄ between each measurement cycle; that is, the chamber gas concentrations are multiplied by the known volume of chamber corrected for pressure and temperature. The difference of chamber gas content between sequential measurements and the

gas exhaustion rate are then summed over each cycle to calculate the total gas exchange for O₂, CO₂, and CH₄, which means the rate of gas consumption by, and emission from, the animal. The data recorded over 24 h are exported and used as input for R for integration and data analysis using a R-dedicated package developed to this particular system, which allows easy data integration with all sensor platforms. Data between each measurement time and missing data when the chambers are open (for animal feeding and milking) are estimated by interpolation (penalized spline model). The daily gas exchanges are calculated by integration (spline/area under curve). Data of feeding and water intake, standing time, standing or lying position and HR are integrated to data of CH₄ emission and heat production (**HP**) calculated according to Brouwer (1965), and reports and graphics from R software are generated.

We conducted a trial with 12 lactating 3/4 Holstein × 1/4 Gyr crossbred dairy cows (6 multiparous and 6 primiparous) at 157.6 ± 6.9 DIM to evaluate the system. The cows were fed a TMR consisting of 443.1 g/kg maize silage, 79.1 g/kg Tifton hay, and 477.8 g/kg concentrate, on a DM basis (DM = 486.6 g/kg; CP = 177.8 g/kg; NE_L = 1.61 Mcal/kg). Cows were distributed in 2 feed regimens from 30 d postpartum: ad libitum (**AL**) or restricted to provide 80% of NE_L requirements (**RE**), according to NRC (2001). The cows were milked at 0630 and 1400 h and fed at 0700 and 1430 h. The daily milk yield and feed intake were recorded. Animals were halter-trained and adapted to handling and to respiration chambers before the trial began. Starting after the morning milking, two 22-h respiration measurements were obtained from each cow. For each respiration measurement, the cow was randomly allocated to one chamber. The feed intake and milk production inside the chamber were compared with the average feed intake and milk yield during the week before the respiration trial and, if these values dropped more than 5%, the respiration measurement was repeated. For this trial, urinary nitrogen was neglected in Brouwer's equation, because it gives a very small contribution to HP compared with O₂ and CO₂ (Versteegen et al., 1987). All animals were weighed on the way to and from the chambers. The circulated air inside the chambers was maintained at 55% RH and 22°C. A mixed model was used to examine the components of variation for all variables. The mixed model included fixed effects for feed regimen, day, and parity. Random effects included in the model were cow and day within cow. The estimated components of variation were used to calculate the coefficient of variation (b) within cow and between cows. Repeatability of CH₄ emission was calculated as the proportion of variance between animals with respect to the total variance.

Figure 3. Dynamics of accumulated feed intake (●), heat production (○), and methane emission (□), and standing time (shaded areas) of one cow during the respiration trial. Heat production and methane emission levels decreased around 1500 h because the chamber was opened for milking and feeding procedures.

The AL-fed multiparous and primiparous cows had an average live weight of 584 ± 41 kg and 544 ± 21 kg, respectively. The RE-fed multiparous and primiparous cows had an average live weight of 497 ± 22 kg and 455 ± 25 kg, respectively. All RE-fed cows showed similar feed intake the week before and during chamber stay, because there were no orts due to the limited feed supply. Three AL-fed cows, 2 primiparous and 1 multiparous, dropped more than 5% in DMI when they were transferred to the respiration chambers; therefore, it was necessary to take one more respiration measurement for these animals. Two cows (#1 and #7) under the AL regimen showed variation in DMI >5% (6.4 and 9.2%, respectively) between first and second day of evaluation inside the chambers. However, DMI recorded during the 2 respiration measurements was still within the admissible range regarding the average DMI observed the previous week outside the chambers for the respective cows.

The dynamics of heat production, CH_4 emission, feed intake, and position changes measured during the stay of one individual cow in one of the chambers is shown in Figure 3. Feed consumption, milk production, and components of energy expenditure data are presented in Table 1. As expected, RE-fed multiparous and primiparous cows showed lower values for methane emission and HP than AL-fed animals. No differences between primiparous and multiparous were observed for the parameters evaluated because the primiparous cows used in the present trial had already reached their mature weight. The 35% reduction in DMI for RE-fed multiparous compared with AL-fed multiparous cows led to reductions in CH_4 production and HP of 33 and 28%, respectively. The 31% reduction in DMI by RE-fed primiparous cows reduced the CH_4 production and HP by 29 and 21%, respectively. We detected no difference among groups for CH_4 produced per kilogram of DMI (Table 1). The within-animal (day-to-day

Table 1. Feed intake, milk yield, methane emission, heat production, and respiration quotient (RQ) in primiparous (P) and multiparous (M) dairy cows under 2 feeding regimens: ad libitum (AL) or restricted (RE)

Cow	Parity	Feeding regimen	Measured parameter													
			Chamber		DMI, kg		Milk yield, kg		CH ₄ , L		CH ₄ , L/kg of DMI		Heat production, kcal/kg ^{0.75} per day		RQ	
			Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
1	P	AL	4	1	22.8	20.9	20.9	19.3	573	561	25.1	26.9	245	244	1.17	1.13
2	P	AL	2	3	18.6	17.8	19.2	20.8	471	464	25.3	26.0	260	253	1.14	1.10
3	P	AL	2	4	18.1	18.5	16.6	15.7	529	519	29.2	28.1	227	228	1.14	1.14
Mean (SD)					19.4 (1.95)	18.8 (2.2)			519 (45)		26.8 (1.6)		243 (13)		1.14 (0.02)	
4	P	RE	3	4	13.7	13.7	17.2	17.5	404	394	29.4	28.7	196	194	1.16	1.16
5	P	RE	2	1	15.1	15.1	22.1	21.3	399	401	26.4	26.5	205	200	1.09	1.10
6	P	RE	3	4	11.1	11.1	12.9	13.4	298	303	26.8	27.3	177	177	1.05	1.08
Mean (SD)					13.3 (1.8)	17.4 (3.8)			367 (51)		27.5 (1.3)		191 (12)		1.11 (0.05)	
7	M	AL	2	4	20.7	22.1	20.3	19.5	571	608	27.5	27.5	249	259	1.11	1.13
8	M	AL	3	2	21.7	21.4	25.1	24.1	550	585	25.4	27.3	273	276	1.08	1.16
9	M	AL	3	4	20.6	20.0	22.0	22.8	497	491	24.1	24.5	249	239	1.09	1.14
Mean (SD)					21.1 (0.8)	22.3 (2.2)			550 (48)		26.1 (1.6)		258 (15)		1.12 (0.03)	
10	M	RE	2	1	14.8	14.8	19.0	19.9	398	385	27.0	26.1	185	175	1.12	1.13
11	M	RE	3	4	12.2	12.2	15.3	11.7	389	372	31.8	30.4	183	176	1.12	1.12
12	M	RE	1	2	14.0	14.0	14.3	16.5	330	335	23.5	23.8	194	197	1.05	1.10
Mean (SD)					13.7 (1.2)	16.1 (3)			368 (29)		27.1 (3.4)		185 (9)		1.11 (0.03)	
Within-animal variance					0.22	1.28			63.21		0.38		14.23		0.00	
Between-animal variance					2.49	8.68			2,264.47		5.08		168.14		0.00	
Total variance					2.70	9.96			2,327.68		5.46		182.38		0.00	
Repeatability					0.92	0.87			0.97		0.93		0.92		0.74	

variation) CV were 1.8 and 2.3% for CH₄ emissions measured in liters per day and liters per kilogram of DMI, respectively; and the between-animal CV were 10.6 and 8.4% for these parameters. For HP, the within- and between-animal CV were 1.7 and 5.9%, respectively. Estimates of repeatability (total variation/variation between animals) for CH₄ emission and heat production were high (Table 1). Repeatability for individual animals over time needs to be high to reliably detect high and low CH₄-emitting animals (Vlaming et al., 2008), as well as more- and less-efficient animals through respiration trials. The results presented here showed variation consistent with findings from the previous studies of Blaxter and Clapperton (1965) and Grainger et al. (2007), which obtained within-animal CV of 7.2 and 4.3%, respectively, for CH₄ measures using respiration chambers.

In conclusion, the respiration system described is a useful tool for measuring the dynamic and accumulated data of HP, methane emission, and feed intake and its interactions with animal genetics, nutritional management, and climatic conditions.

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