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Article

# Comparison of Methane Emissions from Dairy Cows Quantified by Maximum Amplitude of Eructation Peaks and other Concentration Metrics

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**Abstract** The aim of this study was to quantify methane (CH<sub>4</sub>) emissions from dairy cows during milking by maximum amplitude of eructation peaks and compare estimates with other metrics for CH<sub>4</sub> emissions. Spot measurements of CH<sub>4</sub> and carbon dioxide (CO<sub>2</sub>) emissions were recorded for at least 7 days of continuous sampling using an infrared gas analyser in a robotic milking station whilst cows were milked. Concentrations of CH<sub>4</sub> and CO<sub>2</sub> were measured at 1 second intervals. A total of 105,701 CH<sub>4</sub> spot measurements were obtained from 2,206 dairy cows on 18 farms. Methane emissions per individual cow were quantified by maximum amplitude of eructation peaks, average area under eructation peaks (integral of eructation), average concentration during milking and ratio of CH<sub>4</sub> to CO<sub>2</sub> concentration. There was a high correlation ( $r = 0.71$ ) between CH<sub>4</sub> emissions quantified by maximum amplitude and integral of eructation peaks. The correlation between maximum amplitude and average CH<sub>4</sub> concentration was low, and there was no correlation between maximum amplitude and ratio of CH<sub>4</sub> to CO<sub>2</sub>. As both approaches identify and extract eructation peaks to quantify enteric CH<sub>4</sub> emissions, the substantial association between maximum amplitude and eructation integral was expected.

**Keywords:** dairy cows; enteric methane; eructation; measurement

## 1. Introduction

During the last decade, several methods for quantifying CH<sub>4</sub> emissions from cattle have been proposed. A common approach used is the “sniffer method” which makes use of sensors that were initially created to find hazardous gas leaks [1]. The sniffer method samples gas at a place that the animal frequently visits such as a feed bin. The aim is to sample the air near the animal’s mouth and nostrils. Sniffer or breath sampling techniques have several advantages over other techniques for large-scale measurement of CH<sub>4</sub> emissions by individual animals. After the device is installed, animals are unaware of it and are in their normal surroundings, making sampling non-invasive. There is no need for training, handling, or dietary changes because animals follow their regular pattern, which includes feeding and milking. Equipment is often inexpensive, and operating costs are minimal [1].

Automatic milking stations provide an ideal location to measure CH<sub>4</sub> emissions on commercial farms given that all cows visit for milking several times per day and gas measurements can be obtained in a standard way at the feed bin [2]. Furthermore, infrared gas analysers are available that are generally mobile, durable and with high sensitivity (e.g. Nondispersive Infrared (NDIR), Fourier-transform infrared (FTIR), or photoacoustic infrared (PAIR)). Eructations produced by an animal can be detected as large peaks in CH<sub>4</sub> concentration by a gas analyser. Detection of peaks to quantify enteric CH<sub>4</sub> emissions shows good agreement with respiration chamber measurements of total CH<sub>4</sub> production from the same cows [3]. Bell et al. [4] found that CH<sub>4</sub> emissions for cows quantified by the integral of an eructation peak had higher repeatability and rank correlation compared to average

CH<sub>4</sub> concentration and CH<sub>4</sub> to CO<sub>2</sub> ratio during milking. To test the precision and adoption of eructation peak detection for spot measurement of CH<sub>4</sub> emissions, there is a need to evaluate performance of alternative CH<sub>4</sub> metrics.

The objective of this study was to quantify CH<sub>4</sub> emissions from dairy cows during milking by maximum amplitude of eructation peaks and compare estimates with other metrics for CH<sub>4</sub> emissions.

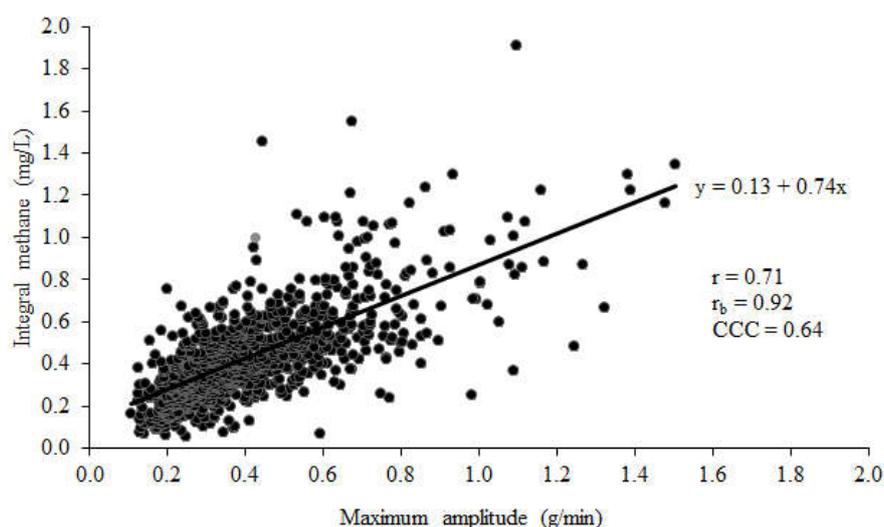
## 2. Results

Cows in the study had an average lactation number of  $2.6 \pm 1.9$ , were milked  $2.4 \pm 0.8$  times per day at robotic milking stations and produced  $30.4 \pm 9.7$  kg of milk per day (mean  $\pm$  standard deviation). Average CH<sub>4</sub> emissions for maximum amplitude of eructation peaks, average CH<sub>4</sub> concentration, integral of eructation peaks and ratio CH<sub>4</sub> to CO<sub>2</sub> are shown in Table 1. There was a higher coefficient of variation for CH<sub>4</sub> calculated by maximum amplitude of eructation peaks compared to other metrics.

**Table 1.** Average CH<sub>4</sub> expressed as maximum eructation amplitude, average CH<sub>4</sub> concentration, integral of eructation peaks and ratio of CH<sub>4</sub> to CO<sub>2</sub> concentrations.

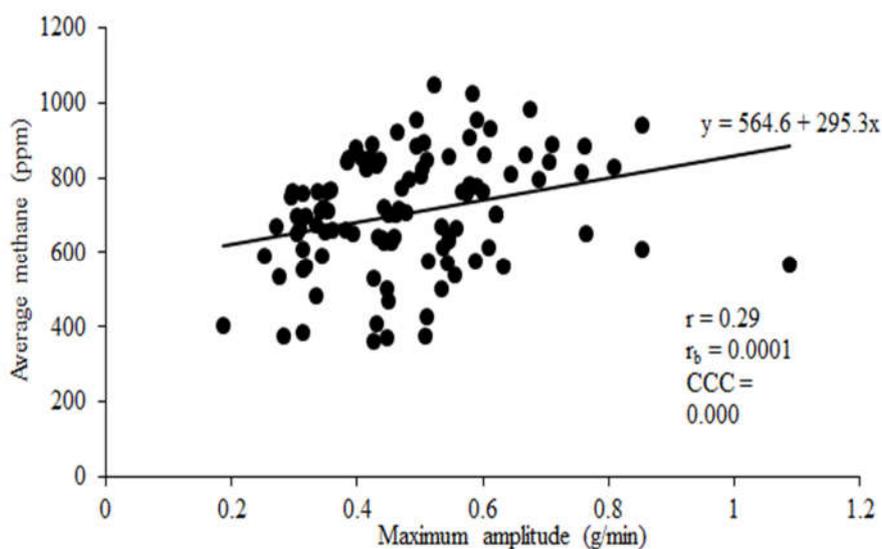
Measure	Units	Mean	SD	Minimum	Maximum	Coefficient of Variation (%)
Maximum amplitude of eructation peaks	g/min	0.48	0.15	0.19	1.09	31.3
Average CH <sub>4</sub> concentration	ppm	708	156	361	1046	22.0
Integral of eructation peaks	mg/l	0.46	0.1	0.24	0.69	21.7
Ratio CH <sub>4</sub> to CO <sub>2</sub>		0.09	0.02	0.05	0.16	22.2

There was a high correlation ( $r = 0.71$  and  $CCC = 0.64$ ) between CH<sub>4</sub> emissions calculated from integral of eructation peaks and maximum amplitude of eructation peaks (Figure 1).

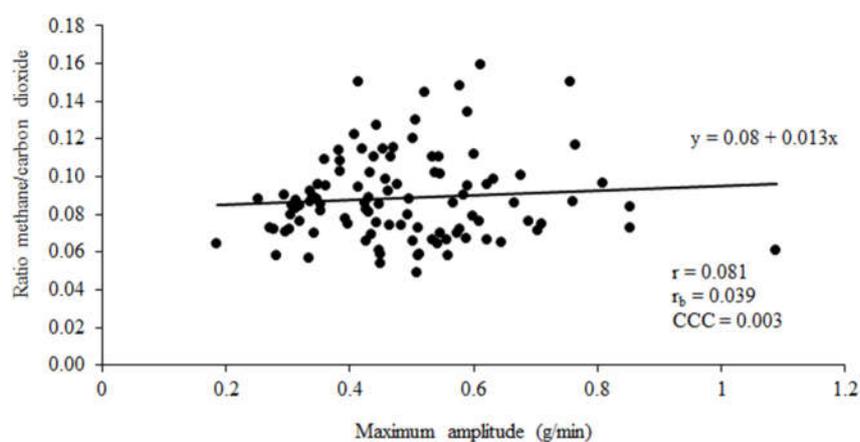


**Figure 1.** Relationship between integral CH<sub>4</sub> (mg/L) and maximum CH<sub>4</sub> amplitude (g/min) of eructation peaks. Data points are means for individual cows; line and equation are linear regression between variables;  $r$  = simple correlation coefficient;  $r_b$  = Lin's bias correction factor;  $CCC$  = Lin's concordance correlation coefficient.

There was no correlation between CH<sub>4</sub> emissions calculated from maximum amplitude of eructation peaks and average CH<sub>4</sub> concentration (Figure 2) or ratio of CH<sub>4</sub> to CO<sub>2</sub> (Figure 3).



**Figure 2.** Relationship between CH<sub>4</sub> emissions calculated from average CH<sub>4</sub> concentration (ppm) and maximum amplitude of eructation peaks (g/min). Data points are means for individual cows; line and equation are linear regression between variables;  $r$  = simple correlation coefficient;  $r_b$  = Lin's bias correction factor; CCC = Lin's concordance correlation coefficient.



**Figure 3.** Relationship between CH<sub>4</sub> emissions calculated from the ratio of CH<sub>4</sub> to CO<sub>2</sub> concentrations and maximum amplitude of eructation peaks (g/min). Data points are means for individual cows; line and equation are linear regression between variables;  $r$  = simple correlation coefficient;  $r_b$  = Lin's bias correction factor; CCC = Lin's concordance correlation coefficient.

### 3. Discussion

Using peak analysis techniques, enteric CH<sub>4</sub> obtained from integral and maximum amplitude of eructation peaks in the current study showed a strong association. The association between maximum eructation amplitude with average CH<sub>4</sub> concentration and ratio of CH<sub>4</sub> to CO<sub>2</sub> was weak. Both integral and maximum eructation amplitude use peak analysis approaches to extract features associated with the detection and shape of eructation peaks i.e. rise time and height. The correlation in the current study between average CH<sub>4</sub> concentration and ratio of CH<sub>4</sub> to CO<sub>2</sub> with maximum amplitude of eructation peaks was lower ( $r = 0.29$  and  $0.08$  respectively) than reported by Bell et al. [4] assessing the rank correlation of CH<sub>4</sub> measurements for average CH<sub>4</sub> concentration and ratio of CH<sub>4</sub> to CO<sub>2</sub> in cows fed on a commercial ration (ranging from  $r = 0.35$  to  $0.62$ ). The current study used

a larger dataset of 2,206 cows across multiple farms compared to the single experimental study of 36 cows by Bell et al. [4].

Approximately 87% to 93% of enteric CH<sub>4</sub> emissions, along with other volatile compounds such as CO<sub>2</sub>, are released by dairy cows through eructation from their mouths and nostrils. Ruminant animals expel rumen gas from digestion of food as large eructations on a regular basis. These emissions from fermentation of food are highest after feeding [5,6]. In the current study, the proximity of the animals' head to the sampling tube was not measured but the maximum peak amplitude assumes that the eructation produced by a cow, and with the greatest amplitude during a milking, represents the time when the mouth and nostrils of the cow are closest to the sampling tube. This approach therefore accounts for cow head position to obtain a representative spot measurement from the animal being sampled. This approach to eructation peak detection is based on the theory that CH<sub>4</sub> pulses expelled by the animal can produce a repeatable and reliable measure of individual CH<sub>4</sub> emissions from spot measurements when compared to respiration chamber measurements [3,7,8].

Garnsworthy et al. [3] noted differences in CH<sub>4</sub> concentration and frequency of eructation peaks between high and low CH<sub>4</sub>-emitting cows. Other studies using signal processing and detection of eructation peaks found that dairy cows with high and low enteric CH<sub>4</sub> production have distinct CH<sub>4</sub> profiles [9]. Cows that produce more CH<sub>4</sub> exhibit higher average CH<sub>4</sub> concentrations and more frequent eructation peaks than cows with lower CH<sub>4</sub> production [10]. To effectively analyse large datasets, identify hidden trends in CH<sub>4</sub> emissions, develop accurate estimation models, and facilitate real-time monitoring and updates, machine learning and artificial intelligence techniques hold significant potential [11–15].

#### 4. Materials and Methods

Approval for this study was obtained from the Animal Welfare and Ethical Review Body of the University of Nottingham (approval number 30/3210). Data used were from previous research collecting CH<sub>4</sub> measurements across commercial farms [16].

##### 4.1. Data

A total of 105,701 CH<sub>4</sub> spot measurements were collected from 2,206 dairy cows across 17 commercial farms (Farms A to Q) and the University of Nottingham (Farm R) in the UK (Table 2). Measurements were obtained between December 2009 and December 2013. The majority of the study's cows were Holstein-Friesian breeds. The diets provided to cows were categorised as either a partial mixed ration (PMR; conserved forage and concentrate feed) or a PMR with pasture that had been grazed. The CO<sub>2</sub> and CH<sub>4</sub> concentrations were only recorded simultaneously at farm R. The cows were fed *ad libitum*. During milking, concentrate feed was supplied to each cow to correspond with her daily milk production. Live weight, milk output, and robot concentrate consumption were recorded automatically at every milking. Eleven farms fed PMR and 7 farms fed a PMR with grazing (farms A to R).

##### 4.2. Gas Sampling

A sniffer approach was used to measure CH<sub>4</sub> and CO<sub>2</sub> concentrations in the feed bin of robotic milking stations whilst dairy cows was being milked (Figure 4). Gas measurements were recorded for at least 7 days continuously at 1 second intervals using a data logger (Simex SRD-99; Simex Sp. Z o.o., Gdańsk, Poland) connected to an infrared gas analyser (Guardian SP; Edinburgh Instruments Ltd., Livingston, UK). Before each monitoring period, each analyser was calibrated using standard mixtures of CH<sub>4</sub> in nitrogen (0.0, 0.25, 0.50, 0.75, and 1.0% CH<sub>4</sub>; Thames Restek UK Ltd., Saunderton, UK).

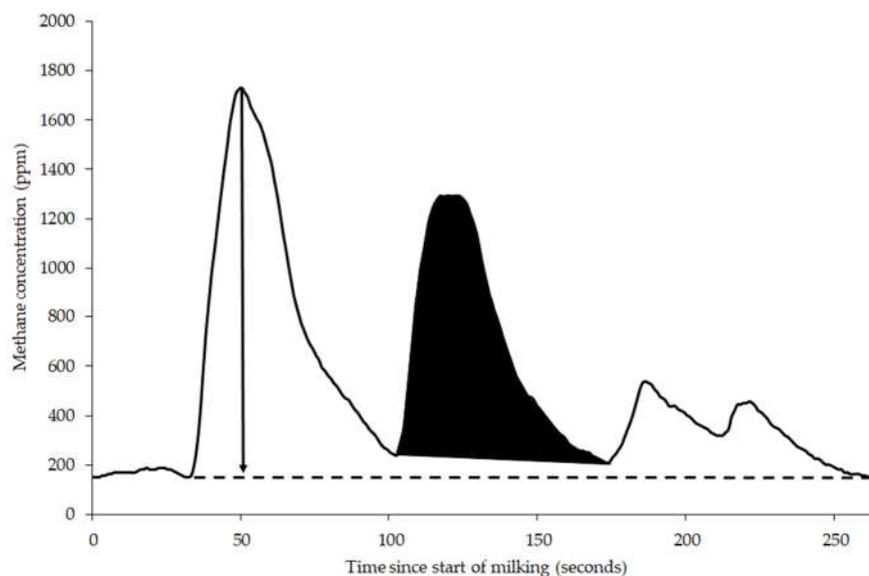


**Figure 4.** Spot measurements of enteric CH<sub>4</sub> emissions obtained in the feed bin of a robotic milking station whilst a cow is being milked.

Time series gas measurement during milking was aligned to when each individual cow visited the robotic milking station using milking station records. A single infrared CH<sub>4</sub> analyser was used with each automatic milking station. Each gas analyser had a range of 0 to 1% for CH<sub>4</sub> or 0 to 5% for CO<sub>2</sub> concentrations. Between the gas entry port and the analyser, an integrated pump drew air through the apparatus. A 3 m long, 8 mm diameter polyethylene tube attached to the analyser's gas inlet port was used to constantly sample air at a rate of 1 L/min from the feed bins in the milking stations. The analyser's exhaust port was vented into the atmosphere at least 3 metres away from every sample location. An inline combination particle filter and water separator (Air-Pro IF-14; Flotec Industrial Ltd., Loughborough, UK) was installed about 50 cm from the analyser inlet port on the sample tube. The sample tube's inlet end was placed at the back of the milking station's feed bin. Although feed bin design can vary in milking stations, all stations had a trough that was about 50 cm wide by 50 cm long and 25 cm deep into which concentrates were delivered by a chute that was about 8 cm in diameter.

#### 4.3. Gas Measurements

The maximum amplitude of eructation peaks, area under eructation peaks (integral of eructation), average CH<sub>4</sub> concentration and ratio of CH<sub>4</sub> to CO<sub>2</sub> were extracted from the time series gas concentration (Figure 5).



**Figure 5.** Maximum peak amplitude (solid black line with arrow) and area under peaks (solid black area) are shown on a CH<sub>4</sub> concentration profile in eructated gas for a single cow during milking. Within each milking period, background concentrations were retrieved (dashed black line), and average concentration during this time [5,9].

Maximum amplitude of eructation peaks, area under eructation peaks and average CH<sub>4</sub> concentration were obtained for all spot measurements. Concentration of CO<sub>2</sub> was only measured at Farm R and provided 2,474 spot measurements with CO<sub>2</sub> concentration measured at the same time as CH<sub>4</sub> concentration. Background concentration of both gases during milking was assumed to be the lowest gas concentration and were subtracted from the average concentration recorded.

#### 4.3.1. Maximum Eructation Amplitude

Maximum peak amplitude was extracted from measured CH<sub>4</sub> concentration using signal processing peak analysis tools in MatLab Signal Processing Toolbox (version R2018a, The MathWorks, Inc., Natick, United States). The rationale for this approach was that maximum amplitude should correspond to an eructation when the cow had its nose closest to the sampling tube, thus reducing variation in CH<sub>4</sub> measurements due to head position as proposed by Bell et al. [5]. The peak analysis tools identify eructation peaks using the findpeak function. Maximum peak amplitude of an eructation peak also removed background CH<sub>4</sub> concentration. Rise time to maximum peak was also determined. Filters were applied to data to prevent detection of the same peak more than once, with a minimum peak amplitude of 100 ppm and a minimum peak separation of 10 seconds. Given that the analyser needs 60 seconds to reach the "real" peak asymptote and finish processing the gas sample, all extracted emission rates (in grams per minute) during milking were scaled to estimated emissions based on the exponential increase in gas concentration and the extracted rise time for eructation peaks by Equation (1) as:

$$\text{CH}_4 \text{ emission rate (g/min)} = \text{maximum peak amplitude (ppm)} / [1 - \text{EXP}(-(\text{peak rise for amplitude in seconds} / 60))] \times 60 \times 0.706 \times 10^{-6} \quad (1)$$

Measurements were converted to emission rate in grams per minute by multiplying by 60 and density of CH<sub>4</sub>, assumed to be  $0.706 \times 10^{-6}$  g/L.

#### 4.3.2. Integral of Eructation

Average area under eructation peaks of three or more eructations per milking were calculated as the integral of peak concentrations in mg/L per minute multiplied by frequency of eructation peaks per minute to calculate concentration of CH<sub>4</sub> produced by the cow in mg/L. A custom-designed

program developed by Garnsworthy et al. [3] extracted the integral of peaks and peak frequency. Milkings with less than three eructation peaks were excluded from analysis. Peaks that rose less than 200 mg/kg above baseline were excluded. Eructation frequency and integral were calculated for every milking. The product of calculated mean integral and eructation frequency was used to compute CH<sub>4</sub> emission index during each milking per cow in mg/L [3].

#### 4.3.3. Average Concentration and Ratio of CH<sub>4</sub> to CO<sub>2</sub>

Average concentrations of CH<sub>4</sub> and CO<sub>2</sub> emitted in ppm during each milking were calculated by subtracting minimum concentration at the start of the milking from average concentration during each milking. Ratio of CH<sub>4</sub> to CO<sub>2</sub> concentrations was then calculated by dividing average CH<sub>4</sub> concentration by average CO<sub>2</sub> concentration.

#### 4.4. Statistical Analysis

Data were analysed using Genstat Version 21.1 (VSN International, Hemel Hempstead, UK) VSN, Hemel Hempstead, UK). Relationships between CH<sub>4</sub> spot measurement metrics were assessed using Pearson correlation coefficient (r), Lin's bias correction factor (rb), and concordance correlation coefficient (CCC). The concordance correlation coefficient (CCC) was obtained by multiplying coefficient r by Lin's bias correction factor (rb), which assesses how far the best-fit line deviates from the 45° line through the origin [17].

## 5. Conclusions

In this study, four enteric CH<sub>4</sub> emission metrics for dairy cow were compared. Methane emissions computed using maximum peak amplitude and integral of eructation peaks showed a high positive correlation. There was a low positive correlation between peak analysis measures and average CH<sub>4</sub> concentration or CH<sub>4</sub> to CO<sub>2</sub> ratio. The correlation between integral CH<sub>4</sub> peak analysis and maximum amplitude CH<sub>4</sub> peak analysis was anticipated given both methods detect and extract eructation peaks to estimate enteric CH<sub>4</sub> emissions.

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**Institutional Review Board Statement** All animal work was carried out under the authority of the UK Animals Scientific Procedures Act (1986), within Project Licence number 30/3210. Approval for the work was obtained prior to commencement, from the University of Nottingham Animal Welfare and Ethical Review Body.

**Informed Consent Statement:** Although this study did not involve human subjects, informed consent was obtained from all farmers for use of their anonymised farm data in analyses.

**Data Availability Statement:** The datasets analysed are available from the corresponding author on request.

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**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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