Assessing the Prediction of Human CO_2 Emissions for IAQ Applications

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ABSTRACT

The field of building ventilation and indoor air quality (IAQ) often employs indoor CO_2 concentrations as an indicator of outdoor air ventilation rates and, in some cases, as a contaminant impacting human health and comfort. Many of these applications require CO_2 emission rates from building occupants (VCO_2), which can be predicted based on occupant characteristics (e.g., body mass, sex, age) and activity level (e.g., sleeping, exercise, resting). In some applications, this information is fairly well known. However, in many other cases, the occupant characteristics and activity levels that impact the values of VCO_2 are difficult to know with much precision, thereby requiring assumptions about the occupants and their activity levels. The ability to use literature-based values for the required input is particularly important during the building design phase when there are no actual occupants to characterize or when considering occupied spaces where it is not practical to characterize the occupants. Whether these inputs are known or not, it is important to characterize the predictive accuracy of calculated VCO_2 values to aid in interpreting indoor CO_2 concentrations.

This study leverages data from whole-room indirect calorimeter chamber measurements of VCO_2 to evaluate the accuracy of two VCO_2 estimation approaches—ASHRAE Fundamentals Handbook (2021) and Persily and De Jonge (2017). The chamber experiments involved 50 healthy, non-smoking individuals aged 20 to 64 years, engaged in activities such as sleeping, stationary cycling, and sitting (performing sedentary tasks like reading or watching television). Metabolic parameters such as VCO_2, rate of oxygen consumption (VO_2), basal metabolic rate (BMR), respiratory quotient (RQ), and energy expenditure (EE) were collected during these activities. The validation exercise is performed using two types of input values to estimate VCO2— measured data from the chamber experiments and data from the literature. The results indicate that whether using either type of input values, the Persily and de Jonge (PdJ) predictive values are closer to the measured VCO_2 than the values calculated using the ASHRAE approach. PdJ predictions exhibit an absolute mean error of 6 % when using measured inputs, smaller than the ASHRAE predictive error of 28 %. When utilizing literature inputs, the mean predictive error of PdJ is 19 %, comparable to 28 % for the ASHRAE approach.

KEYWORDS

human CO_2 emissions; indoor air quality; indoor CO_2; prediction; ventilation VCO2?

1 INTRODUCTION

IAQ and ventilation assessments have long involved indoor CO_2 concentrations (Persily, 1997; ASTM 2024), although, in practice, many of these applications are implemented without a sound understanding of the underlying technical concepts and the assumptions involved (ASHRAE, 2022). More specifically, many applications require the CO_2 emission rates of building occupants (VCO_2), which are calculated using the expression in the ASHRAE Handbook - Fundamentals (ASHRAE, 2021) given by Equation 1,

$$VCO_2 = VO_2 \,.\, RQ = \frac{0.00276 A_D M RQ}{(0.23RQ + 0.77)} \tag{1}$$

where:

VCO_2 = rate of CO_2 generation (L/s),

VO_2 = rate of O_2 consumption (L/s),

RQ = respiratory quotient (dimensionless)

M = metabolic rate (met), or level of physical activity,

A_D = DuBois surface area (m^2), calculated from height H in m and body mass W in kg as follows:

$$A_D = 0.202H^{0.725}W^{0.425} \tag{2}$$

The respiratory quotient RQ in Equation 1 is equal to the ratio of VCO_2 to VO_2. This equation, which first appeared in the Thermal Comfort chapter of the ASHRAE Handbook in 1989, does not discuss the basis of the equation nor provide references and does not directly account for key occupant characteristics that affect CO_2 generation, e.g., age and sex. The ASHRAE presentation of these VCO_2 calculations also provides met rates (a metric of the level of physical activity) for various activities, which are based on references predominantly from the 1960s.

Recognizing these limitations, Persily and de Jonge (2017) proposed an alternative approach (herein referred to as PdJ) for predicting VCO_2 based on concepts from the fields of human metabolism and exercise physiology, which is given by Equation 3,

$$V_{CO2} = \mathrm{RQ} \cdot \mathrm{BMR} \cdot \mathrm{M}\left({}^{T}/{}_{P}\right) 0.000211 \tag{3}$$

where BMR is the basal metabolic rate (MJ/day), and T and P are the air temperature (K) and pressure (kPa) in the occupied space, respectively. This approach incorporates occupant characteristics, specifically age, sex, and body mass, which are used to calculate BMR. However, both the ASHRAE and PdJ approaches require detailed occupant information that can be challenging to obtain in real-world settings, for example, in actual occupied spaces as opposed to test chambers where the test participants can be well characterized. Also, some applications of indoor CO_2 involve spaces that are still in the design phase or otherwise for which the input data are not available; in these cases, assumptions need to be made about the occupants and their activities.

This study evaluates the predictive accuracy of the ASHRAE and PdJ approaches to estimating VCO_2 using two types of input data: first, when input values are not available and must be based on literature values. In the second case, measured values of the inputs from chamber experiments are used. Sample calculations are presented for one chamber study dataset, but similar analyses are currently underway with other datasets. By understanding the uncertainties or predictive errors of these estimating approaches, we can make more informed decisions about their application in IAQ assessments and building ventilation design.

2 METHODS

In collaboration with researchers at the National Institute for Health and Care Research (NIHR) Cambridge Clinical Research Facility, we obtained experimental data from indirect whole-body calorimetry chamber studies. These studies focused on energy expenditure, substrate oxidation, and macronutrient intake from food consumption, with the experimental methods documented in Murgatroyd et al. (1999). The chamber study was ethically reviewed by a local ethics committee, and all participants provided written informed consent.

The study involved fifty (50) healthy non-smokers aged between 20 and 64 years. Participants were provided with balanced meals designed to meet their energy requirements, consisting of 50 % to 55 % carbohydrates, 30 % to 35 % fat, and 12 % to 15 % protein by energy content. Each participant stayed in the calorimetry chamber for three days, following a strict schedule that included sleeping, cycling at 50 W with a cadence of 40 to 60 RPM, and engaging in sedentary activities such as reading, sitting, or watching television. During their stay, the following parameters were collected at 30-minute intervals: VO_2, VCO_2, BMR, RQ, and total energy expenditure (EE). Additionally, anonymized anthropometric data were gathered, including sex, age, body mass, height, and body mass index (BMI). The collected data enabled a comparison between measured VCO_2 values and predictions made using the ASHRAE and PdJ approaches. The predicted VCO_2 values using chamber data are then compared with predicted VCO_2 values using literature data.

2.1 Data Analysis

Predicted VCO_2 using input parameters from experimental measurements: First, the Schofield equations are used to estimate BMR based on an individual's age, sex, and body weight as described in Persily and de Jonge (2017). The general form of the Schofield equations is:

Males: BMR = [a × weight (kg)] + b;

Females: BMR = [c × weight (kg)] + d (4)

where a, b, c, and d, are constants that vary depending on the age of the individual. Once the BMR is calculated using these equations, the EE value is divided by BMR to estimate the metabolic rate (met). Then, the value of RQ is estimated by dividing the measured VCO_2 by the measured VO_2. These parameters are subsequently input into the ASHRAE and PdJ expressions using Equations 1 and 2.

Predicted VCO_2 using input parameters from literature values: The VCO_2 prediction based on literature values utilized several established sources. The value of BMR was estimated using the Schofield equations (Equation 4). RQ values were derived from energy requirement values reported by the Food and Agricultural Organization of the United Nations (FAO, 2001). Additionally, metabolic rates were obtained from an online compendium of physical activities (Ainsworth et al., 2011).

The comparison between the predicted VCO_2 using input parameters from direct experimental measurements and literature values aims to provide a basis for evaluating the applicability of the ASHRAE and PdJ equations in scenarios where direct measurements of the inputs are unavailable.

3 RESULTS AND DISCUSSION

Table 1 presents the mean and absolute percentage differences between predicted and measured VCO_2 values using literature and measured inputs using the ASHRAE and PdJ approaches. These percentage differences are calculated relative to the mean of the measured and predicted values. For the chamber data used in this study, the absolute percentage mean VCO_2 prediction error using the ASHRAE approach with literature inputs is 28 %, which is identical to the error using measured inputs. In contrast, the prediction error using literature inputs with the PdJ approach is 19 % and 7 % when using measured input values. In both scenarios, the PdJ approach exhibits smaller prediction errors than the ASHRAE approach. Notably, the ASHRAE approach consistently underestimates the VCO_2 measurements, regardless of whether literature-based or measured inputs are used.

Table 1. Percentage differences between measured and predicted VCO_2 values

	ASHRAE		PdJ	
	Mean difference	Mean absolute difference	Mean difference	Mean absolute difference
Literature inputs	-28 %	28 %	-19 %	19 %
Measured inputs	-28 %	28 %	-7 %	7 %

Bland-Altman plots were generated to evaluate the bias between measured and predicted VCO_2 values (Bland and Altman, 1986 and 1999) for the ASHRAE and PdJ approaches, as shown in Figures 1 through 4. The X-axis is the mean of the measured and predicted VCO_2 values, while the Y-axis is the percentage difference between these values. The black horizontal solid line at zero percent on the vertical axis is the reference line for "no difference" between the measured and predicted VCO_2 values. The red line represents the mean of the differences for all the data points. The further this line deviates from the zero-reference line, the greater the bias. The red dashed lines are the 95 % confidence intervals for the mean of the differences, based on normality assumptions. If the red solid line falls within this confidence interval, it indicates that the mean difference between the measured and predicted values is not statistically significant from zero, i.e., no statistically significant bias. The blue dashed lines represent the 95 % lower and upper limits of agreement, showing the range within which most differences between the measured and predicted values lie.

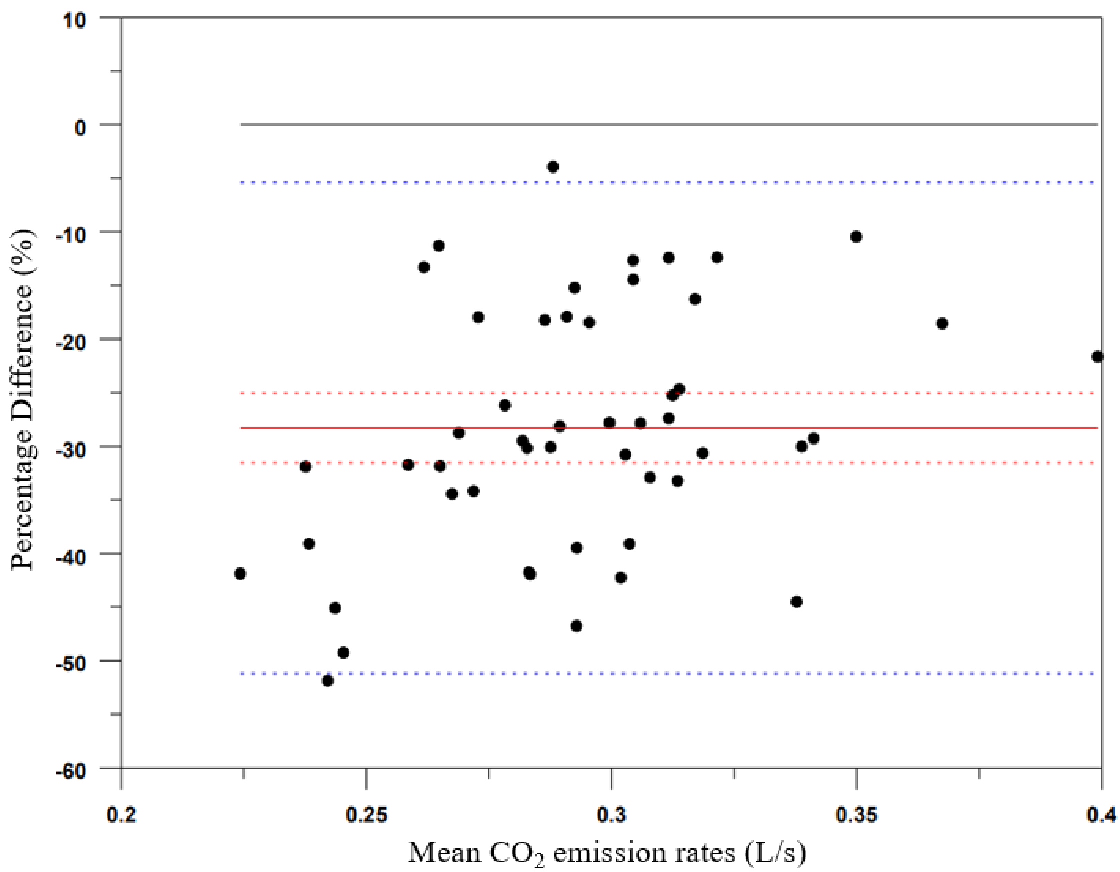

Figure 1: Bland-Altman plot comparing measured VCO_2 to ASHRAE predictions using chamber inputs. The black line at zero represents no difference, the red line shows the mean difference, and the red dashed lines indicate the 95 % confidence intervals. The blue dashed lines are the 95 % limits of agreement.

The Bland-Altman plots for predicted VCO_2 values using the ASHRAE equation for both chamber inputs (Figure 1) and literature inputs (Figure 2) demonstrate that the mean difference line is significantly below the zero-reference line, and the confidence limits for the mean difference do not contain the zero-reference line. This result indicates evidence of a significant systematic bias. In addition, both predictions indicate a consistent underestimation of the measured CO_2 emission rates, with the degree of underestimation varying across the emission rate range. Specifically, when using chamber input values, the predicted average VCO_2 was 28 % (±9 %) lower than the measured VCO_2 (Figure 1). Similarly, predictions using literature input values were 28 % (±11 %) lower than the measured VCO_2 (Figure 2). The blue dashed lines in Figures 1 and 2 show that the majority of the values lie within the upper and lower limits of agreement (mean bias ± 1.96 SD).

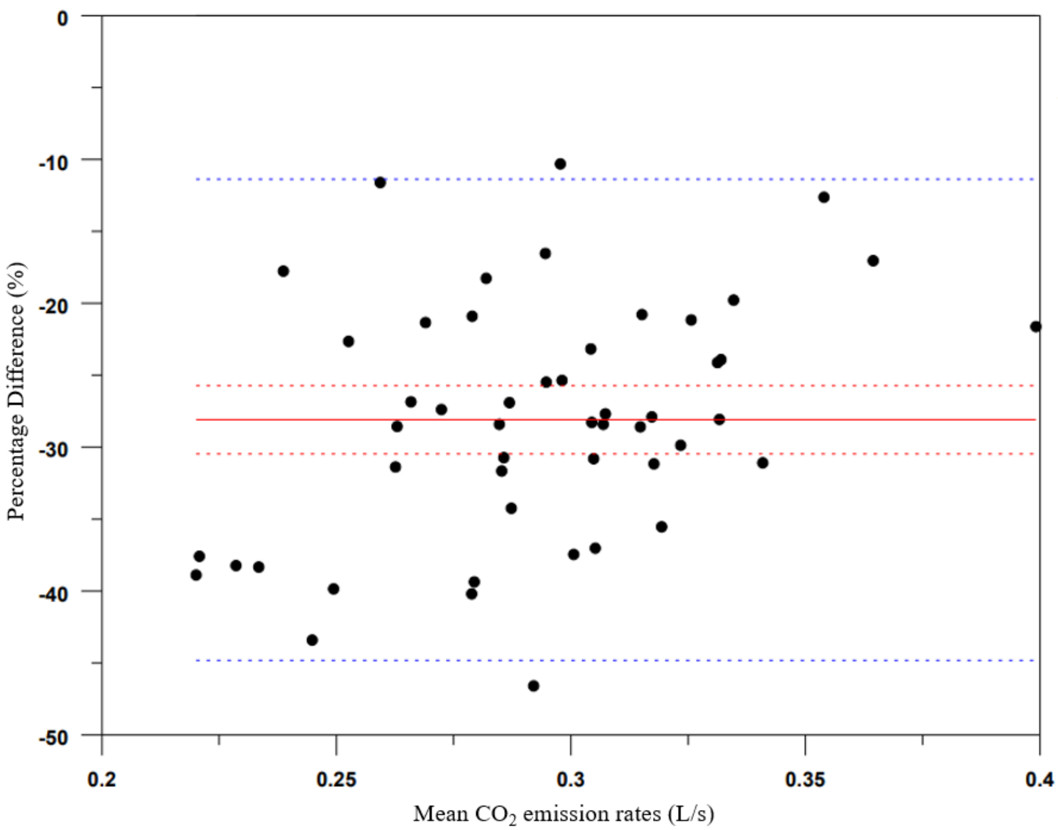

Figure 2: Bland-Altman plot comparing measured VCO_2 to ASHRAE predictions using literature inputs. The black line at zero represents no difference, the red line shows the mean difference, and the red dashed lines indicate the 95 % confidence intervals. The blue dashed lines are the 95 % limits of agreement.

Figure 3 shows the comparison between measured VCO_2 and predicted VCO_2 using chamber-measured input values with the PdJ approach. There is also significant bias in this case, but the data points exhibit a relatively narrow spread around the mean difference line, suggesting consistent agreement between the measured and predicted values with low variability. For this dataset, the plot reveals a percentage mean difference of -7 % (±2 %). Most data points fall within the limits of agreement, indicating that the predicted VCO_2 values generally align well with the measured values. Figure 4 compares the measured VCO_2 with predicted VCO_2 using the literature input values with the PdJ approach. The plot shows evidence of a significant systematic bias, and the predicted VCO_2 values are 19 % (± 2 %) lower than the measured values, with most data points within the limits of agreement.

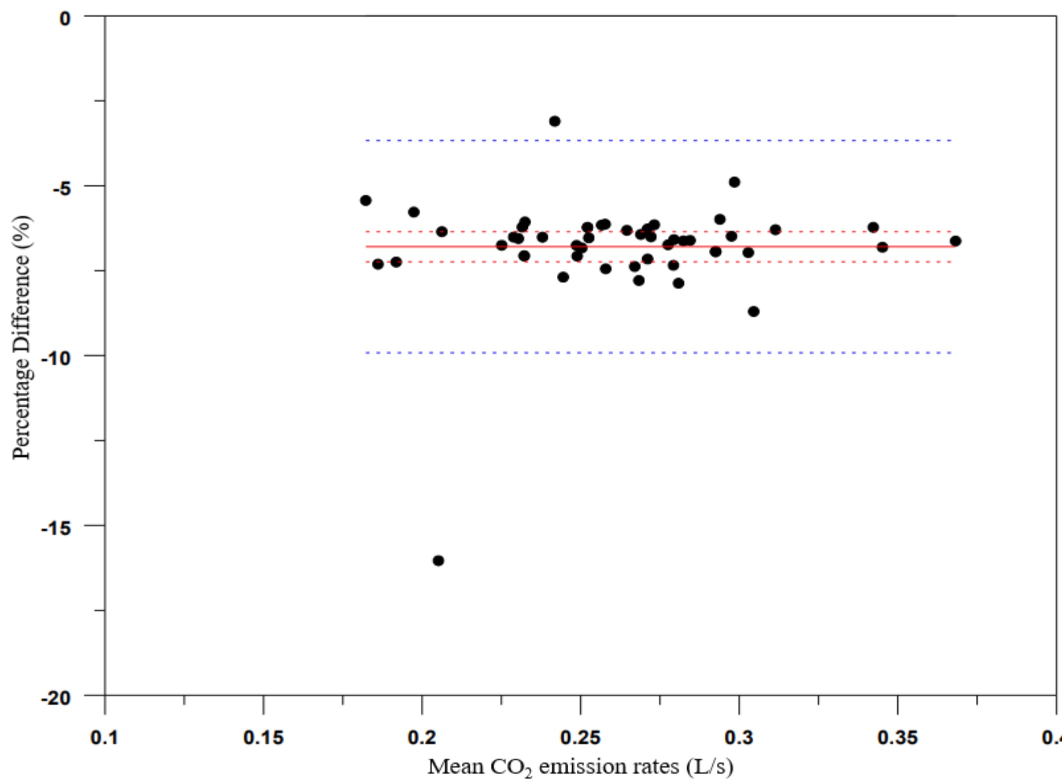

Figure 3: Bland-Altman plot comparing measured VCO_2 to PdJ predictions using chamber inputs. The black line at zero represents no difference, the red line shows the mean difference, and the red dashed lines indicate the 95 % confidence intervals. The blue dashed lines are the 95 % limits of agreement.

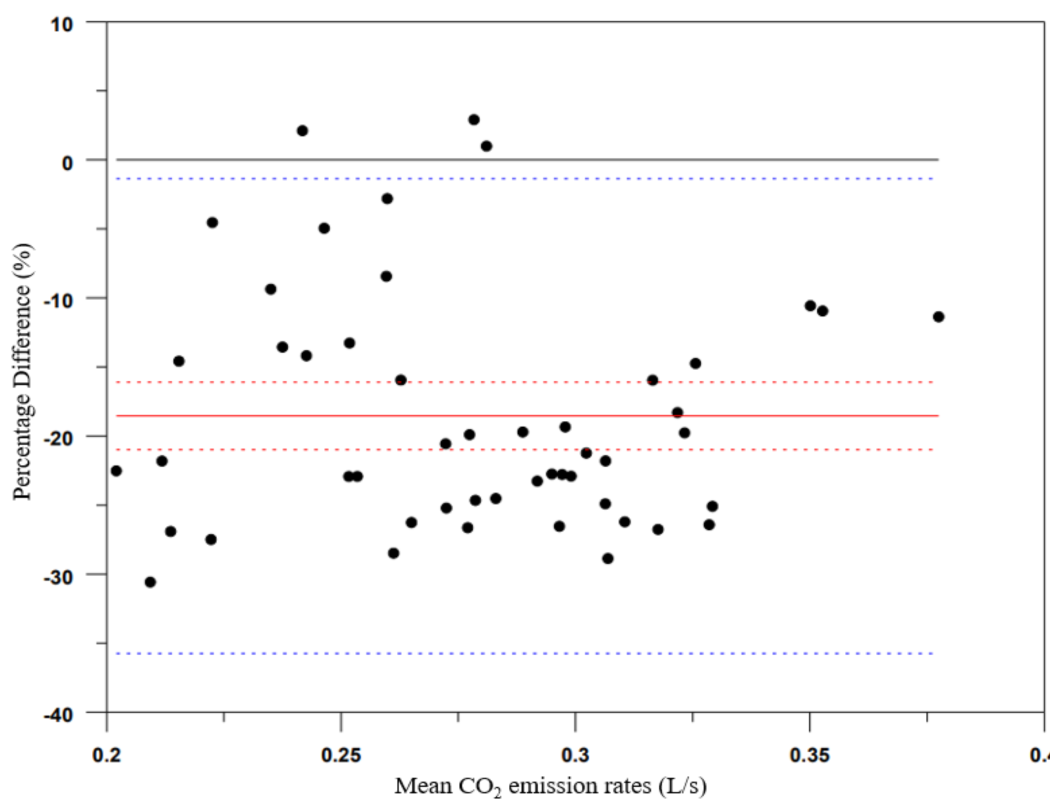

Figure 4: Bland-Altman plot comparing measured VCO_2 to PdJ predictions using literature inputs. The black line at zero represents no difference, the red line shows the mean difference, and the red dashed lines indicate the 95 % confidence intervals. The blue dashed lines are the 95 % limits of agreement.

4 CONCLUSIONS

For the dataset considered here, the PdJ and ASHRAE approaches underestimate the VCO_2 measurements, regardless of whether literature-based or measured inputs are used. However, the predicted VCO_2 values using the PdJ approach are, on average, within 20 % or less of the measured data, exhibiting smaller prediction errors than the ASHRAE approach. While other datasets are being studied for presentation in future publications, these results are encouraging given that BMR values, RQ, and met rates are not generally available except in chamber studies. These additional datasets sometimes include measured quantities other than those considered here (e.g., BMR), different activities, and different test durations. The ability to use literature-based values for BMR, RQ, and met rate is particularly important during the building design phase when there are no actual occupants to characterize or when considering occupied spaces where it is not practical to characterize the occupants. Also, there are applications in which expected CO_2 concentrations are calculated as a function of ventilation rate, occupancy, and other factors to understand various aspects of IAQ, and these efforts require reliable values of VCO_2. Addressing these challenges in predicting VCO_2 is critical to interpreting indoor CO_2 concentrations and will be the focus of future work.

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The National Institute of Standards and Technology Institutional Review Board reviewed and approved the protocol for this project and all subjects provided informed consent in accordance with 15CFR27, the Common Rule for the Protection of Human Subjects.

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