An evaluation of CO_2 emission rates by Chilean school children

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ABSTRACT

The predicted and measured carbon dioxide (CO_2) emitted by human respiration into an occupied space has been used as an indicator for controlling buildings' ventilation rates. However, this application assumes a constant emission rate for the entire population. Conversely, new knowledge has shown that this variable depends on the number of people in the room and their sex, diet, height, and above all, body mass and metabolic rate. This paper applies the latter model and a previously used sampling approach to identify the variability of CO2 emission rates and excess CO2 concentrations in school classrooms in Chile, and compares them with those in the USA. This time, we collected data from local sources and public databases to model an evidence-based average classroom of 29 students –15 men and 14 women– following the Chilean regulations and the ASHRAE 62.1 and SHRAE 241 standards for ventilation. Then, using Python and a Monte Carlo sampling approach, we calculated the emission rates for the local population in the classrooms of children between 5 and 18 years old. Results show that the mean body weights of the USA and Chilean child populations are statistically different, but the excess CO_2 concentrations can vary by only 4% between demographics. The difference in excess CO2 concentrations between countries reflects their differences in occupancy densities. Finally, there is a significant difference in excess CO_2 concentrations for the two standards but little difference between countries for the same standard.

KEYWORDS

CO_2 concentrations; ventilation; indoor air quality; proxy indicator

1 INTRODUCTION

Carbon dioxide (CO_2) is a product of respiration and so is emitted in any spaces where people are present. Indoor CO_2 concentrations have long been used as a proxy indicator of the *per capita* ventilation rates, and a model of CO_2 generation rates has been developed that is based on principles of human metabolism and exercise physiology. It explicitly accounts for age, sex, and body mass (Persily & de Jong 2017). CO_2 has, however, been used without an adequate understanding or explanation of the limitations of doing so, and so ASHRAE (Laue, J., 2018) recently outlined key limitations. It states that when using CO_2 as an indicator of the outdoor air, ventilation rate, space type, occupant density, and occupant characteristics must be considered as factors into any analysis. Occupant characteristics include age, body mass (which is a function of sex), and activity levels. A recent investigation of uncertainty in the relationship between indoor steady-state CO_2 concentrations and ventilation rates in US school classrooms looked at the variation in emission rate of US children aged between 4 to 19 years (Molina et al. 2021). It showed that the rate of change and uncertainty in body mass is most significant in children between the ages of 4 and 14 years old. Furthermore, a global sensitivity analysis determined that the most important input into the emission rate model of Persily & de Jong is body mass. This means that standards and guidelines should use existing body mass data used by health services to determine appropriate values of mean emission rate to represent a local population. Molina *et al.* determined CO_2 emission rates for US children using government-published weight-for-age percentiles and sex ratios, and representative values of child metabolic rates in schools. The emission rates varied between 3.1 and 5.1 cm^3 per person (or ppm m^3 s^{-1} per person).

As the body mass of US school children may not be comparable to those in other countries, the emission rates derived for them may not apply in other countries. Therefore, this study aims to determine if physiological data for another country may produce different emission rates, using Chilean school-age children as an example.

2 METHOD

A steady state indoor CO_2 concentration, $C_{i,ss}$, can be used to evaluate a *per capita* ventilation rate.

$$Q_o = \dot{V}_{CO_2}\left(C_{i,ss} - C_o\right)^{-1} = \dot{V}_{CO_2} C_{e,ss}^{-1} \tag{1}$$

Here, Q_o is the outdoor air ventilation rate per capita (m^3 s^{-1} per person), $\dot{V}_{CO_2}$ is the generation rate of CO_2 *per capita* (cm^3 s^{-1} per person), $C_{i,ss}$ is the steady-state indoor CO_2 concentration (ppm), and C_o is the outdoor CO_2 concentration (ppm). The difference between $C_{i,ss}$ and C_o is known as the *excess CO_2* steady-state concentration $C_{e,ss}$ (ppm), which is typically a more useful metric because C_o varies by location and diurnally, and is steadily increasing over time. Here we note that ppm, which is equivalent to one μL of CO_2 per L of air, is used herein for CO_2 concentrations.

2.1 Model of CO_2 emission rates

A full description of Persily and de Jong's CO_2 emission rate model is given elsewhere (Persily & de Jong, 2017) and so only a summary is given here. The generation rate of CO_2 per capita (cm^3 s^{-1} per person) is given by

$$\dot{V}_{CO_2} = \text{BMR}\, M\, \text{RQ}\, \dot{V}_{O_2}\, T\, P^{-1} \tag{2}$$

Here, BMR is the essential energy a person requires to sustain life, known as the *basal metabolic rate* (J s^{-1} per person). We assumed it is a linear function of body mass requiring sex and age dependent gradients and intercepts, which are given in Table 1 of Persily & de Jong (2017). M is a dimensionless metabolic rate that describes the ratio of a person's energy demand required to complete a specific physical activity relative to their BMR. RQ is the ratio of the volumetric rate at which CO_2 is produced to the rate at which oxygen is consumed, known as the *respiratory quotient*. For well-nourished people in a normal weight range, its primary determinant is diet. Fractions of dietary carbohydrates, fats, proteins, and alcohol by sex are derived from the US National Health and Nutrition Examination Surveys (Wright & Wang, 2010). They are assumed to be constant because uncertainties in these values are not given, and we also assume that children do not consume alcohol. $\dot{V}_{O_2}$ is a person's rate of oxygen consumption (cm^3 J^{-1}) and implicitly assumes that 1 kcal (4.2 J) of energy use requires 206 cm^3 of oxygen consumption. Finally, T is the ratio of the air temperature to 273.15 K, and P is the ratio of the air pressure to 101.325 kPa. We assume indoor temperatures and pressures are 293.15 K and 101.325 Pa, respectively, so T and P are 1.07 and 1.00, respectively, throughout.

2.2 Sources of information and assumptions

Child body mass and BMI values are sampled by age, and extracted from the standardized growth patterns for the child and adolescent population issued by the Chilean Ministry of Health (MINSAL, 2018). The corresponding age was allocated for each school grade following the grades given by the Ministry of Education of Chile. Each grade is mixed-sex and each class has 29 students, comprising 15 males and 14 females, reflecting the Chilean population sex ratios between 1950 and 2020.

The metabolic rate, M, is determined as a function of age, and three activities of different physical intensities are considered to occur in a classroom: *playing on the computer*, *watching*

TV, and *household chores*, with a time-weighted ratio of 0.75:0.15:0.1, respectively, to give a weighted M. This weighted factor accounts for high-intensity activities that do not usually occur for prolonged periods. Therefore, its values are higher than those used by Molina et al. (2020), and Equation (2) shows that this should increase the value of $\dot{V}_{CO_2}$. M is then calculated by age band following Pfeiffer (2017). Pfeiffer's analysis is for the US child population, so we compared the two population samples using the T-test.

An appropriate value of RQ for well-nourished children is around 0.85, following Wright *et al*. (2010). However, only around 37% of children in Chile can be considered *well nourished* (Lira, M., 2022)., and so we assume it is normally distributed with a mean of 0.82 and a standard deviation of 0.07.

2.3 Sampling method

The sampling method uses a Monte Carlo (MC) approach written in Python code to interrogate the probability space. The model requires input variates that are specified deterministically or are described by continuous probability distributions. They are applied to the $\dot{V}_{CO_2}$ model and,

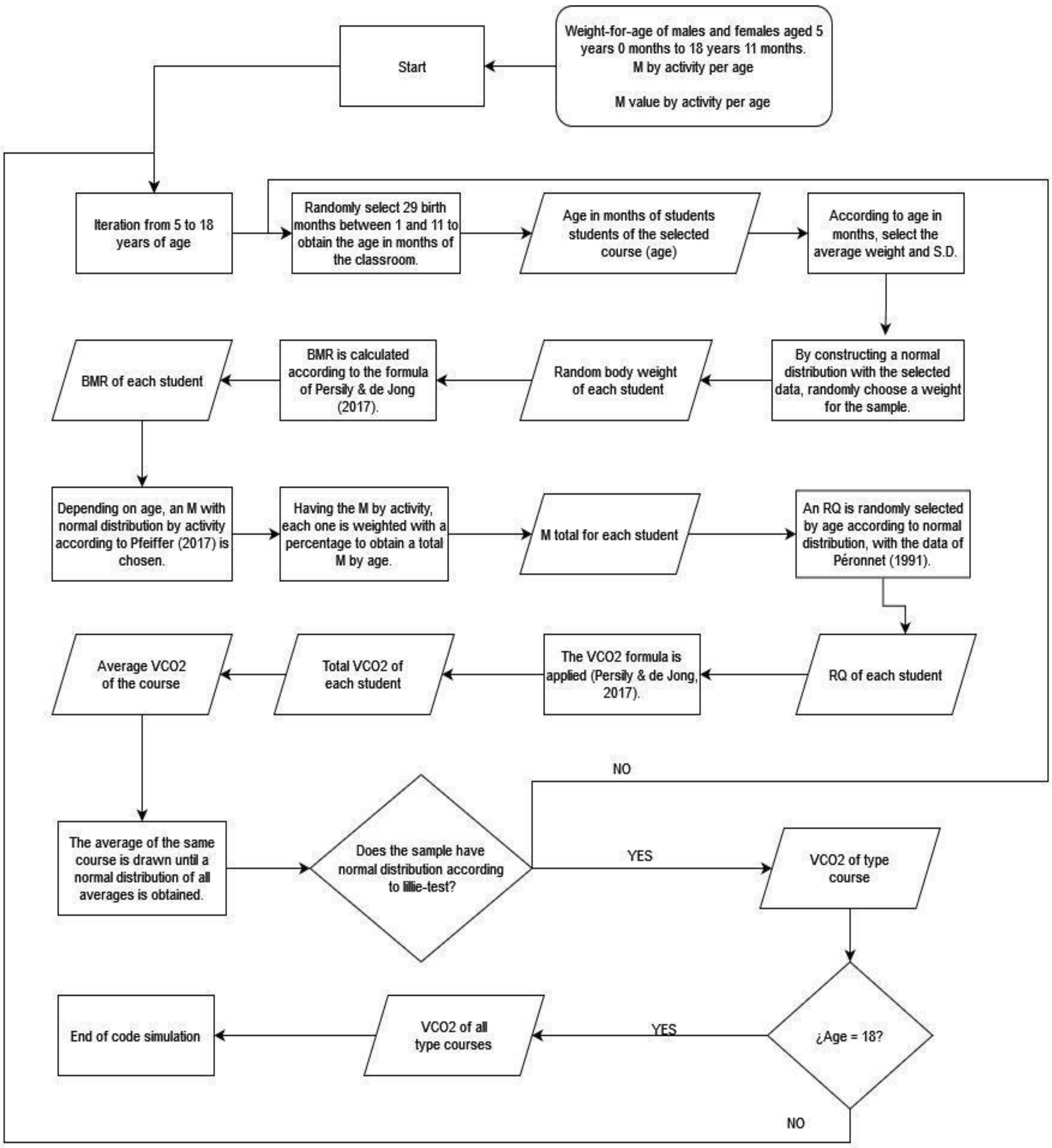

Figure 1: Model system diagram

by systematically varying the variates and running multiple simulations, distributions of $\dot{V}_{CO_2}$ are generated that quantify the uncertainty in $\dot{V}_{CO_2}$. The modeling approach is shown in Figure 1.

Inputs were sampled to form a class of children for each age group. The Python code was run until a normal distribution of the means of each age class was obtained. A Lillie test is used to confirm the normality of the sampling distribution of means.

2.4. Comparison to standards

Classrooms in the US use ASHRAE standards 62.1. to determine outdoor air delivery rates, which comprise the sum of a *per capita* air flow rate and a flow rate of 0.6L/s per unit floor area. The *per capita* air flow rate and classroom occupancy density are different for children aged 5 to 8 years and those aged 9 or more years old. ASHRAE Standard 241 gives airflow rates designed to control of infectious aerosols, requiring 20L/s per person. Equation 1 is used to determine the excess concentration $C_{e,ss}$ and are compared for each age group and each standard (using default occupancy densities for 62.1).

3 RESULTS AND DISCUSSION

Figure 1 shows the distributions of $\dot{V}_{CO_2}$ by age group. The change is non-linear, plateauing as the children reach around 14 years of age. It also shows a clear difference between 5 and 18-year-old children. This is reflected by the relationship between $\dot{V}_{CO_2}$ and body mass, shown in Figure 3. The body weights of the USA and Chilean child populations are found to be different at a statistically significant level by using the T-test.

Figure 2 shows that the distributions of $\dot{V}_{CO_2}$ are not normal, which agrees with the findings of Molina *et al*. Therefore, an appropriate representative statistic is the median, and so these are given in Table 1 for each age band.

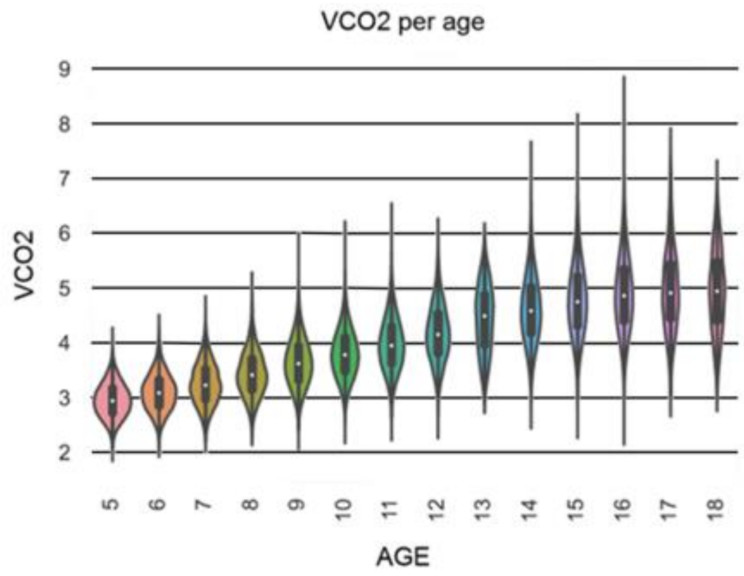

Figure 2: Distribution of $\dot{V}_{CO_2}$ emission by age group

Table 1 also gives the excess concentrations $C_{e,ss}$ for each age group and for each standard (using default occupancy densities for 62.1) applying Equation 1. This shows that there is a significant difference in $C_{e,ss}$ for the two standards (T-test, p << .01; Cohen´s *d*, *strong* effect for both countries), but there is very little difference between countries for the same standard (Cohen's *d*; *above the minimum* for the ASHRAE 62.1, and *no effect* for the ASHRAE 241).

Table 1: $\dot{V}_{CO_2}$ and $C_{e,ss}$ for ASHRAE standards governing classrooms. All values given to 2 significant figures.

Age	Median $\dot{V}_{CO_2}$		Excess concentration, $C_{e,ss}$			
			ASHRAE 62.1		ASHRAE 241	
	USA	Chile	USA	Chile	USA	Chile
5	3.1	3.0	420	490	160	150
6	3.3	3.1	440	510	160	160
7	3.4	3.2	460	540	170	160
8	3.6	3.4	490	570	180	170
9	3.9	3.6	580	600	200	180
10	3.9	3.8	580	630	200	190
11	4.1	4.0	610	660	210	200
12	4.3	4.2	640	700	220	210
13	4.5	4.4	670	740	230	220
14	4.8	4.6	720	760	240	230
15	5.0	4.8	750	790	250	240
16	4.9	4.9	730	810	250	240
17	5.0	5.0	750	830	250	250
18	5.1	5.0	760	830	260	250

The reason for the higher excess concentrations in Chilean classrooms, despite their lower emission rates, is because occupancy densities are different, at around 60 people per 100m^2 as opposed to the 25 and 35 people per 100m^2 in the US for 5-8 year olds and over 9 year olds, respectively. This shows that standardized values of $C_{e,ss}$ need to be country specific if the occupancy densities differ.

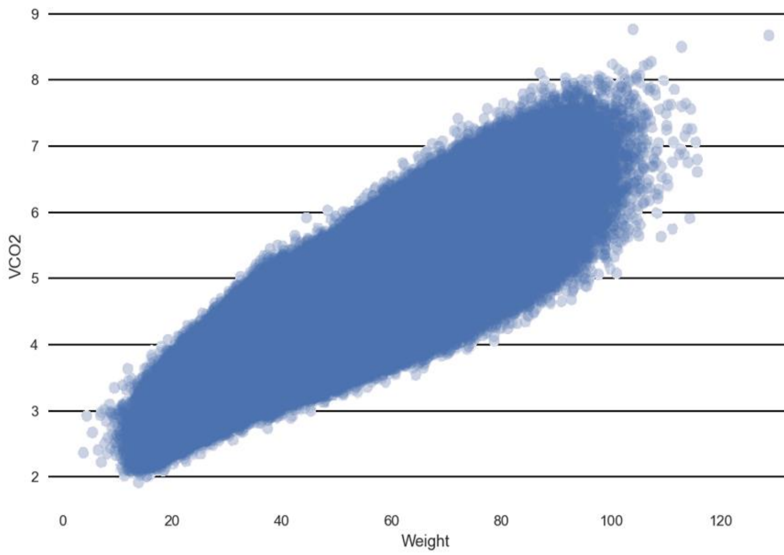

Figure 3: The relationship between $\dot{V}_{CO_2}$ and body weight for both sexes combined.

The differences in $C_{e,ss}$ and $\dot{V}_{CO_2}$ for the age bands of each country are small. The magnitude of $\dot{V}_{CO_2}$ is heavily dependent on the body mass of the children. The difference between the distributions of body mass for each age band for each country is tested using a T-test to show that there is not enough evidence to conclude that their means are different ($p > .05$). When considering emission rates for other countries, if the body mass of the new population is like those used for existing calculations of $\dot{V}_{CO_2}$, there is no need to revise them.

Finally, when a building is run in infection risk mitigation mode when ASHRAE Standard 241 applies, then an excess concentration of 150 ppm ensures the children of all age groups meet its requirements.

3.1 Limitations

When this same model was used by Molina et al. (2021) for the calculation of the US population, extensive databases were found with information on inputs, such as body mass, height, and BMI. For Chile, however, information on the nutritional status of the child and the adolescent population is scarce and unavailable to the general public. The Ministry of Health of Chile has some limited public reports, but they do not cover all age groups. It does project the body mass, height, and BMI of the child and adolescent population to compare them against the same projections made by the World Health Organisation.

4 CONCLUSIONS

Metabolic CO_2 emission rates for US and Chilean children for the same activities in school classrooms are broadly similar, and they follow the same age-related trends. This is because differences in the body mass of both populations of children are statistically insignificant. The existing uncertainties in estimating a per capita ventilation rate from a steady state carbon dioxide concentration mean that it is possible for other countries whose distributions of child body mass broadly agree with those in the US to use the emission rates derived for the US.

There are differences between the CO_2 emission rates of 5- and 18-year-old students, which range between 3 and 5 $cm^3\ s^{-1}$ per person. If the age of students is unknown, or if they may vary over some period, the smaller value should be used to determine an excess steady-state concentration threshold.

Finally, excess steady-state concentration thresholds should be determined locally if the standardized airflow rates are a function of the classroom floor area. This is because occupancy densities are inconsistent.

6. References

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