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Carbon dioxide generation rates for building occupants

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Abstract

Indoor carbon dioxide (CO_2) concentrations have been used for decades to characterize building ventilation and indoor air quality. Many of these applications require rates of CO_2 generation from the building occupants, which are currently based on approaches and data that are several decades old. However, CO_2 generation rates can be derived from well-established concepts within the fields of human metabolism and exercise physiology, which relate these rates to body size and composition, diet, and level of physical activity. This paper reviews how CO_2 generation rates have been estimated in the past and discusses how they can be characterized more accurately. Based on this information, a new approach to estimating CO_2 generation rates is presented, which is based on the described concepts from the fields of human metabolism and exercise physiology. Using this approach and more recent data on body mass and physical activity, values of CO_2 generation rates from building occupants are presented along with the variability that may occur based on body mass and activity data.

KEYWORDS
carbon dioxide, human metabolism, indoor air quality, standards, ventilation

1 | INTRODUCTION

Indoor CO_2 concentrations have been prominent in discussions of building ventilation and indoor air quality (IAQ) since the 18th century when Lavoisier suggested that CO_2 build-up rather than oxygen depletion was responsible for “bad air” indoors.[1] About one hundred years later, von Pettenkofer suggested that bioeffluents from human occupants were causing indoor air problems, not CO_2. Discussions of CO_2 in relation to IAQ and ventilation have continued to evolve, focusing on the impacts of CO_2 on building occupants, how CO_2 concentrations relate to occupant perception of bioeffluents, the use of CO_2 to control outdoor air ventilation rates, and its use for estimating building ventilation rates.[2] The rate at which building occupants generate CO_2 is a key factor in these discussions, but the generation rates currently being used in the IAQ and ventilation fields are not based on recent references or a thorough consideration of individual occupant characteristics.

The fields of human metabolism and exercise physiology have studied human activity for many decades, including rates of energy expenditures, oxygen consumption, and CO_2 generation, as well as the individual factors that affect these rates. These factors include sex, age, height, weight, and body composition, with fitness level and diet composition also affecting energy expenditure and the ratio of O_2 consumed to CO_2 produced.

The objectives of this paper were first to explain the generation of CO_2 from building occupants using concepts from the fields of human metabolism and exercise physiology, and second to describe a new method for estimating these rates using basal metabolic rates and levels of physical activity for application to building ventilation and IAQ. The paper begins with a summary of previous discussions of CO_2 in the fields of ventilation and IAQ. That summary includes a description of the approach currently used to estimate CO_2 generation rates from building occupants. The next major section of the paper presents relevant work on human metabolism that serves as the basis for the new approach, which is presented in the section that follows. The paper concludes with a short discussion of the variation in CO_2 generation rates based on known variations in body mass, followed by a general discussion section that speaks to application of the new approach as well as issues that merit additional study in the future.

2 | PREVIOUS DISCUSSIONS OF CO_2, VENTILATION, AND INDOOR AIR QUALITY

Indoor CO_2 has had a prominent place in discussions of ventilation and IAQ for many years.[2,3] The relevant issues include the impacts of CO_2 on building occupants (including how CO_2 concentrations relate to occupant perception of bioeffluents), the use of CO_2 to control outdoor air ventilation rates, CO_2 monitoring as an indicator of IAQ conditions, and the use of indoor CO_2 to estimate building ventilation rates. This section reviews these applications, as well as the approach currently used in the ventilation and IAQ fields for estimating CO_2 generation rates.

2.1 | Application of indoor CO_2 to ventilation and IAQ

Several studies of bioeffluent odor perception in chambers show correlations between dissatisfaction with these odors and both ventilation rate per person and CO_2 level.[4-6] The results of these studies have been used for decades in the development of outdoor air ventilation requirements in standards.[2] More recent studies have shown associations of elevated CO_2 levels with symptoms, absenteeism, and other outcomes[7-9]; however, these associations are likely due to lower ventilation rates elevating the concentrations of other contaminants with health and comfort impacts at the same time they are elevating CO_2. There have been some recent studies of individuals completing computer-based tests showing decreases in decision-making performance at CO_2 concentrations as low as 1800 mg/m^3.[10-12] However, another recent study did not observe an impact of similar CO_2 levels on occupant performance.[13]

Another application of indoor CO_2 concentrations is the control of outdoor air intake rates in ventilation systems, referred to as demand control ventilation (DCV). Ventilation and IAQ standards allow the use of DCV,[14] and it is required under some circumstances in energy efficiency standards.[15] The CO_2 concentration used as a set point in applying DCV depends on the ventilation rate requirement of the space of interest, as well as the CO_2 generation rate of the occupants. Indoor CO_2 concentrations have also been proposed for monitoring IAQ conditions for verifying proper ventilation system operation and building usage. This application is described briefly in ASTM D6245,[16] with a more detailed explanation by Lawrence.[17]

It is also quite common to use indoor CO_2 concentrations to estimate ventilation rates per person based on a single-zone mass balance of CO_2, although in many cases without acknowledgement of the assumptions on which it is based.[3,16] In a ventilated space with a uniform CO_2 concentration, the ventilation rate and CO_2 concentration are related under steady-state conditions, assuming that the generation rate, ventilation rate, and outdoor CO_2 concentration are all constant over the mass balance analysis period. This relationship has been discussed in ASHRAE Standard 62 since 1981,[18] in which the steady-state equation is presented as follows:

$$Q_o = \frac{G}{C_{in,ss} - C_{out}} \tag{1}$$

where Q_o is the outdoor air ventilation rate per person, G is the CO_2 generation rate per person, $C_{in,ss}$ is the steady-state indoor CO_2 concentration, and C_{out} is the outdoor CO_2 concentration. This steady-state relationship, sometimes referred as the peak CO_2 approach, is essentially an application of the constant injection tracer gas method as described in ASTM E741.[19] It must therefore abide by the following assumptions to yield a valid air change rate: The CO_2 generation rate is known, constant, and uniform throughout the building being tested; the CO_2 concentration is uniform throughout the building and has achieved steady state; the outdoor CO_2 concentration is known and constant; and the outdoor air ventilation rate is constant.

Indoor CO_2 concentrations have also been used to characterize IAQ conditions in buildings and the adequacy of outdoor air ventilation, again without a full appreciation of the links between indoor CO_2 and ventilation. As described in the most recent version of ASHRAE Standard 62.1,[14] for a ventilation rate of 7.5 L/s per person (a common value in many ventilation standards) and an assumed CO_2 generation rate of 0.005 L/s, the indoor CO_2 concentration will be about 1200 mg/m^3 above outdoors. Using an approximate value for the outdoor CO_2 concentration of 600 mg/m^3, one arrives at an indoor CO_2 concentration of 1800 mg/m^3 (about 1000 ppm) which has become a de facto CO_2 concentration guideline value over the years based on this relationship, but not based on any health effects associated with CO_2. Note that outdoor CO_2 values are typically higher than 600 mg/m^3, particularly in urban areas. Note also that these discussions of ventilation rates and the resulting CO_2 concentrations have not typically considered the properties of air temperature or pressure and their effects on volumetric airflow rates.

Practical Implications

- Indoor carbon dioxide concentrations have many applications in the fields of ventilation and indoor air quality, many of which require CO_2 generation rates for the building occupants. However, the CO_2 generation rates employed currently are based on calculation methods and data that are several decades old, and which do not account for individual occupant characteristics such as age, sex, and body size. This paper provides updated methods and data for estimating CO_2 generation rates, which will improve the application of indoor CO_2 concentrations.

2.2 | Current approach to estimating CO_2 generation rates

This section describes the approach that is currently used in the ventilation and IAQ fields to estimate CO_2 generation rates from building occupants. The ASHRAE Fundamentals Handbook [20] and ASTM D6245 [16] describe the estimation of CO_2 generation rates as follows. The rate of oxygen consumption V_{O_2} in L/s per person is given by Equation 2,

$$V_{O_2} = \frac{0.00276 A_D M}{(0.23\,\mathrm{RQ} + 0.77)} \tag{2}$$

where:

A_D=DuBois surface area (m^2),

M=metabolic rate (met), and

RQ=respiratory quotient (dimensionless).

A_D is calculated from height H in m and the body mass W in kg as follows:

$$A_D = 0.202 H^{0.725} W^{0.425} \tag{3}$$

M is level of physical activity, sometimes referred to as the metabolic rate, in units of met, and is discussed in more detail later in this paper. That later discussion addresses the common conversion of 1 met to 58.2 W/m^2, which is not accurate as it depends on the individual being considered. The respiratory quotient, RQ, is the ratio of the volumetric rate at which CO_2 is produced to the rate at which oxygen is consumed, and its value depends primarily on diet.[21] Based on data on human nutrition in the USA, specifically the ratios of fat, protein, and carbohydrate intake,[22] RQ equals about 0.85. The value of RQ tends to increase for values of M corresponding to strenuous activity (greater than about 2 met), but the dependence is not straightforward or well described in the literature and will be a function of the fitness level of the individual among other factors. Therefore, the calculations in this paper employ a single value of RQ (0.85). The variation in the level of physical activity has a much larger effect on CO_2 generation rates than does the variation in RQ.

The rate of CO_2 generation V_{CO_2} in L/s per person is given by Equation 4,

$$V_{CO_2} = V_{O_2}\,\mathrm{RQ} = \frac{0.00276 A_D M\,\mathrm{RQ}}{(0.23\,\mathrm{RQ} + 0.77)} \tag{4}$$

Equation 2 first appeared in the Thermal Comfort chapter of the ASHRAE Fundamentals Handbook in 1989. That discussion, as well as the current discussion in the handbook, references Nishi,[23] which presents that equation as a means of measuring the metabolic rate of an individual. Nishi does not discuss the basis of this equation nor provide references. ISO Standard 8996 also includes this approach in describing methods for measuring metabolic rates.[24]

The ASHRAE Fundamentals Handbook also contains a table of metabolic rates for various activities, which has remained unchanged since the 1977 edition.[20] These values are based on references predominantly from the 1960s,[25–27] although some are even older. The same metabolic rate values are contained in the ASHRAE thermal comfort standard,[28] with very similar data contained in ISO standard 8996.[24] As noted later in this paper, there are much more recent and comprehensive sources of metabolic rate data.

The above equations and data have been used to estimate CO_2 generation rates. For example, ASTM D6245 notes that for an average-sized adult (A_D=1.8 m^3) engaged in office work at 1.2 met, the corresponding CO_2 generation rate is 0.0052 L/s.[16] For a child (A_D=1 m^2) at the same level of physical activity, the corresponding CO_2 generation rate is 0.0029 L/s. Note that discussions of the application of Equation 4 to ventilation and IAQ do not generally consider effects of air density of CO_2 generation rates, simply presenting these rates in volumetric units without specifying the air temperature or pressure.

Equation 4 was recently shown to overestimate CO_2 generation rates in a group of 44 Chinese subjects (ages 19 to 30 years) by just under 25% in females and 16% in males.[29] That paper suggests that the equation should include a correction factor for estimating CO_2 generation rates for Chinese people under low-activity conditions. As discussed later in this paper, the updated approaches to estimating CO_2 generation rates described below provide values that better match the measurements in the study group without the use of a correction factor.

3 | RELEVANT WORK ON HUMAN METABOLISM

This section of the paper is intended to provide relevant background from the fields of human metabolism and exercise physiology to support the approach described later for estimating CO_2 generation rates from building occupants. In order to function, our bodies use the energy derived from the breakdown of macronutrients. These processes lead to the generation of mechanical power and work, as well as the production of heat. The science that quantifies this production of heat from metabolism is called calorimetry, which can be divided into two main methods: direct calorimetry and indirect calorimetry. With direct calorimetry, the production of heat by the body is directly measured. Indirect calorimetry involves calculation of heat production through other measurements such as oxygen consumption and is more commonly used than direct calorimetry. The analysis of expired air dates back to the work of Bischoff and Voit in 1860,[30] and Rubner, Atwater, and Benedict around 1900.[31,32] Bischoff and Voit reported calculations describing the caloric and respiratory gas exchange involved in the combustion of certain foods as well as individual nutrients.[30] A chemical reaction equation exists for the combustion of each individual nutrient, and the combination of these equations forms the basis for indirect calorimetry. The equations that represent the combustion of a representative carbohydrate (glucose) and fat (palmitic acid), along with the value of RQ for each process, are shown below:

Oxidation of a mole of carbohydrate (glucose):

$$\begin{gathered} 6O_2 + C_6H_{12}O_6 \rightarrow 6CO_2 + 6H_2O + 2760\,\mathrm{kJ} \\ \mathrm{RQ} = V_{CO_2}/V_{O_2} \rightarrow 6CO_2/6O_2 = 1.0 \end{gathered} \tag{5}$$

Oxidation of a mole of fat (palmitic acid):

$$\begin{aligned} 23O_2 + C_{16}H_{32}O_2 \rightarrow 16CO_2 + 16H_2O + 11090\,\text{kJ} \\ RQ = V_{CO_2}/V_{O_2} \rightarrow 16CO_2/23O_2 = 0.7 \end{aligned} \tag{6}$$

While the study of human energy and metabolism is not new, interest has increased significantly in recent decades as a result of the increasing prevalence of obesity worldwide. While the original research mainly focused on the determinants of energy expenditure at rest and the development of equations to predict resting energy expenditure based on easy-to-perform measurements such as height, weight, and age,[33-35] the focus has shifted to a more individualized approach.[36] The decrease in cost and the easier access to equipment have stimulated an interest in the accuracy and applicability of the established equations for individual use. This research has shown that although these equations performed reasonably well for population studies, they were not useful for establishing an individual's metabolic rate.

In addition, metabolism research has moved away from being centered on overall energy balance toward individual macronutrient balances, especially carbohydrates and fats.[37] Aided by the improvement of instrumentation used for indirect calorimetry, an increasing amount of research has investigated the factors that can affect the balance between fat and carbohydrate oxidation, expressed by RQ, with an RQ closer to 1.0 representing a larger fraction of energy expenditure due to carbohydrate oxidation with an RQ closer to 0.7 representing a higher percentage of fat oxidation. In light of this research, focusing on the most effective ways of weight loss as well as the prevention of weight gain, scientists have been searching for ways to increase fat oxidation over carbohydrate oxidation through changes in diet as well as in activity level.

The primary determinant of RQ is the dietary composition of an individual, which has been shown to be the same as the RQ of the diet (ie, the food quotient [FQ]) for individuals who are well nourished and in weight equilibrium.[21] This was an important finding as the calculation of FQ is much less labor-intensive and requires no sophisticated equipment as compared to the actual measurement of RQ. When diet composition is known, FQ can be calculated using the following equation[38]:

$$FQ = 1.0 \times CA + 0.7 \times F + 0.79 \times P + 0.66 \times A \tag{7}$$

where CA is the percent of energy in the diet consisting of carbohydrates, F is the percent that is fat, P is the percent protein, and A is the percent alcohol. Data on human macronutrient intake for the USA, based on the National Health and Nutrition Examination Surveys (NHANES), are available in Wright and Wang.[22] Using these data, that is, 47.9% carbohydrates, 33.6% fat, and 15.9% protein for men and 50.5% carbohydrates, 33.5% fat, and 15.9% protein for women, Equation 7 corresponds to RQ values of 0.84 and 0.86, respectively, for men and women. There are other factors that have been shown to influence RQ, but these tend to be second- and third-order effects relative to macronutrient intake. They are summarized in a table in the Supporting Information.

Another key concept in the field of human metabolism concerns the energy required for different physical activities, reflected by the variable M in Equation 4. A key reference for characterizing energy requirements for different activities is a report prepared by the Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO), and the United Nations University (UNU).[39] This report discusses energy requirements as a function of age (from infancy to >90 years) and other individual characteristics, including sex, pregnancy, and lactation. It defines energy requirement as "the amount of food energy needed to balance energy expenditure in order to maintain body size, body composition and a level of necessary and desirable physical activity consistent with long-term good health," and notes that variability will exist in the energy requirements for a group of otherwise identical individuals of the same sex, size, body composition, and physical activity. A key component of the energy requirements is the energy essential for life, for example, cell function and replacement, maintenance of body temperature, brain function, and cardiac and respiratory function, and is referred to as basal metabolism with an energy requirement called the basal metabolic rate (BMR). BMR is typically measured under conditions of being awake in a supine position after 10 to 12 hours of fasting and 8 hours of physical rest in an environment that does not lead to the generation or dissipation of body heat. BMR typically constitutes 45% to 70% of daily energy expenditure and is primarily a function of age, sex, body size, and body composition. After basal metabolism, the second largest component of daily energy expenditure, and the most variable, is associated with physical activity. The energy use associated with growth is important during the first three months of life, constituting roughly 35 % of the total, but falls rapidly after that. After the second year of life, energy for growth is only 1% or 2% of the total until the middle of adolescence and is negligible starting in the late teens.[39]

Equations for estimating BMR values as a function of sex, age, and body mass are presented in Schofield,[40] as well as in the FAO report, and are shown in Table 1. For example, the BMR for an 85-kg male between 30 and 60 year old is 7.73 MJ/day (89.5 W) and 6.09 MJ/day (70.5 W) for a 75-kg female in this same age range.

In addition to the BMR value, the level of physical activity must be considered in establishing human energy requirements. There are two primary references for obtaining information on energy requirements for different physical activities. The first is the FAO report mentioned earlier.[39] The second is a web-based compendium of physical activities.[41,42] The rate of energy use of an individual, or group of individuals, engaged in a specific activity is estimated by multiplying the BMR value for that individual or group by a factor that characterizes the

TABLE 1 Schofield BMR values.[39,40] (m is body mass in units of kg)

	BMR: MJ/day	
Age (y)	**Males**	**Females**
<3	0.249 m–0.127	0.244 m–0.130
3 to 10	0.095 m+2.110	0.085 m+2.033
10 to 18	0.074 m+2.754	0.056 m+2.898
18 to 30	0.063 m+2.896	0.062 m+2.036
30 to 60	0.048 m+3.653	0.034 m+3.538
>=60	0.049 m+2.459	0.038 m+2.755

specific activity. The FAO report refers to this factor as the physical activity ratio (PAR), while the web-based compendium refers it as the metabolic equivalent using the term MET. In this paper, the variable *M* (in dimensionless units of met) is used to describe the ratio of the human energy use associated with a particular physical activity to the BMR of that individual, referring to it as the metabolic rate as in the discussion of Equation 2.

Table 2 contains selected PAR values for various activities from Annex 5 of the FAO report. The average PAR values in the table are averages across multiple studies, when such data exist. Ranges are provided when there are multiple studies available for an activity. Table 3 contains selected physical activity values from the web-based compendium of physical activities. Unlike the FAO report, the compendium values are not presented separately for males and females. Both the FAO report and the web-based compendium contain many additional activities, primarily of a much more vigorous nature such as those associated with manual labor, agriculture, and manufacturing. Henceforth, this paper refers to these values using the variable *M* (units of met) and does not use the PAR or MET terminology.

These two data sources, the WHO report and the web-based compendium, constitute an important resource by providing more comprehensive and up-to-date data on human energy requirements associated with a wide range of physical activities. This advance is particularly notable given that data from the 1960s and older are currently being used in the fields of ventilation and IAQ.[20] The WHO report was developed to provide information on human food and nutrient requirements in response to a key mandate of the FAO to assess “the calorie and nutrient requirements of human beings” in order to determine “whether food supplies are adequate to meet a population’s nutritional needs”.[39] In the case of the compendium, it was developed “for use in epidemiologic studies to standardize the assignment of MET intensities in physical activity questionnaires,” because different studies were using different metrics, leading to inconsistencies and confusion.[41] The FAO database is based on a series of workshops involving experts in the field of human energy requirements, while the developers of the compendium considered several hundred studies of physical activity in developing this database. As noted on the compendium website, the values “… do not estimate the energy cost of physical activity in individuals in ways that account for differences in body mass, adiposity, age, sex …” The FAO contains a similar caveat about using its energy requirement values for single individuals. However, using these values in combination with BMR values based on body mass, age, and sex, as

TABLE 2 PAR values for various activities from FAO report [39]

	Males		Females	
Activity	Average PAR	PAR Range	Average PAR	PAR Range
Aerobic dancing—low intensity	3.51		4.24	
Aerobic dancing—high intensity	7.93		8.31	
Calisthenics	5.44			
Child care (unspecified)			2.5	
Climbing stairs	5.0			
Dancing	5.0		5.09	
Eating and drinking	1.4		1.6	
Housework (unspecified)			2.8	2.5 to 3.0
Office worker—Filing	1.3		1.5	
Office worker—Reading	1.3		1.5	
Office worker—Sitting at desk	1.3			
Office worker—Standing/ moving around	1.6			
Office worker—Typing	1.8		1.8	
Office worker—Writing	1.4		1.4	
Reading	1.22		1.25	
Sleeping	1.0		1.0	
Sitting quietly	1.2		1.2	
Sitting on a bus/train	1.2			
Standing	1.4		1.5	
Walking around/strolling	2.1	2.0 to 2.2	2.5	2.1 to 2.9
Walking quickly	3.8			
Walking slowly	2.8	2.8 to 3.0	3.0	

TABLE 3 Values of physical activity levels (*M*) from compendium [41]

Activity	*M* (met)	Range
Calisthenics—light effort	2.8	
Calisthenics—moderate effort	3.8	
Calisthenics—vigorous effort	8.0	
Child care		2.0 to 3.0
Cleaning, sweeping—moderate effort	3.8	
Custodial work—light	2.3	
Dancing—aerobic, general	7.3	
Dancing—general	7.8	
Health club exercise classes—general	5.0	
Kitchen activity—moderate effort	3.3	
Lying or sitting quietly		1.0 to 1.3
Sitting reading, writing, typing	1.3	
Sitting at sporting event as spectator	1.5	
Sitting tasks, light effort (e.g, office work)	1.5	
Sitting quietly in religious service	1.3	
Sleeping	0.95	
Standing quietly	1.3	
Standing tasks, light effort (e.g, store clerk, filing)	3.0	
Walking, less than 2 mph, level surface, very slow	2.0	
Walking, 2.8 mph to 3.2 mph, level surface, moderate pace	3.5	

described in this paper, allows one to more accurately quantify energy use and CO_2 generation of a group of individuals.

It should be noted that a new compendium is under development to provide detailed energy requirement for youth. A number of studies have recently been published that will provide data for this youth compendium,[43] which will be available online at http://www.nccor.org/nccor-tools/youth-energy-expenditure-compendium/.

Based on the above discussion, the fields of human metabolism and exercise physiology provide concepts and data needed to characterize human energy requirements and the resulting levels of CO_2 production. It is worth noting that these fields are focused primarily on energy requirements as they relate to the adequacy of nutrition and their link to obesity. They use O_2 consumption based on it being directly linked to energy use, but do not typically focus on CO_2 generation.

As noted earlier, the met unit for quantifying the level of physical activity is often presented as being equivalent to 58.2 W/m^2;[16,20] however, the conversion actually depends on the body size of the individual being considered. As described earlier in this paper, 1 met is a level of physical activity corresponding to the BMR of the individual being considered. Table 1 provides a set of equations for estimating BMR in units of MJ/day based on sex, age, and body mass,[40] which can be converted to W by multiplying by 11.6. Dividing by the body surface area in m^2 yields W/m^2. For the case of a 75-kg male between 30 and 60 year of age (BMR=7.73 MJ/day) with a DuBois surface area of 1.8 m^2, 1 met corresponds to 49.8 W/m^2, which is 16% less than the conversion value noted in the above references. However, for a 32-kg male child (between 3 and 10 years old) and a surface area of 1 m^2, 1 met corresponds to 59.7 W/m^2, closer but still not equal to the 58.2 W/m^2 conversion commonly employed.

4 | ESTIMATION OF CO_2 GENERATION RATES

This section describes a new approach to estimating CO_2 generation rates from building occupants based on the previously described information from the fields of human metabolism and exercise physiology. This approach uses the basal metabolic rate of the individual(s) of interest combined with their level of physical activity, in contrast to Equation 4, which only considers body surface area and level of physical activity.

The first step in estimating the CO_2 generation rate is to determine the BMR of the individuals of interest as described in the previous section, with Table 1 providing equations to calculate BMR based on sex, age, and body mass (*m*). The next step is to estimate their level of physical activity, also described in the previous section, in terms of the value of *M* that corresponds to the activities in which they are involved. If these activities are varying with time and location in the building, the estimation should consider those variations, but this description is based on the occupants being characterized by only a single physical activity.

Once the BMR value and the value of *M* for the relevant activity have been determined, their product in units of MJ/day is converted to L of oxygen consumed per unit time. This conversion is based on the conversion of 1 kcal (0.0042 MJ) of energy use to 0.206 L of oxygen consumption.[44] The exact conversion depends on the relative oxidation of carbohydrates and fat, but given the variation in the factors used in calculating CO_2 generation rates, a value of 0.206 L is a reasonable approximation. This conversion results in 1 MJ/day of energy use corresponding to 0.00057 L/s of oxygen consumption, which based on a respiratory quotient of 0.85 (discussed above) corresponds to 0.00048 L/s of CO_2 production. A BMR value of 7.73 MJ/day, mentioned above for an 85-kg male between 30 and 60 year of age, therefore corresponds to 0.0037 L/s of CO_2 production. Using the physical activity level of 1.5 met for "sitting tasks, light effort (eg, office work)" in Table 3 results in a CO_2 generation rate of 0.0056 L/s, which is close to the value of 0.0052 L/s cited in ASHRAE Standard 62.1 and ASTM D6245 for an adult.

Historically, CO_2 generation rates have been presented in volumetric units, for example, L/s or cfm, often without discussing the effects of air pressure and temperature. These two variables need to be provided to fully characterize the generation rate, or the rates can be presented in units of mass or moles per unit time to avoid the need to consider air density. The volumetric CO_2 generation rates presented in this paper are based on an air pressure of 101 kPa and an air temperature of 273 K. Under these conditions, a CO_2 generation rate of 1 L/s equals 0.0446 moles/s or 1.965 g/s. If the volumetric generation rates in this paper are to be used under another set of conditions, the rate must be adjusted for air density using the ideal gas law. These adjustments, as well as the conversion of volumetric concentration units (eg, ppm or mole fraction) to mass units (eg, mg/m^3) as a function of air density, are discussed in the Supporting Information.

The CO_2 generation rate is expressed in L/s as follows, at an air pressure of 101 kPa and a temperature of 273 K, with BMR in units of MJ/day and M in met:

$$V_{CO_2} = \mathrm{RQ}\ \mathrm{BMR}\ M\ 0.000569 \tag{8}$$

Assuming RQ equals 0.85, Equation 8 can be expressed as:

$$V_{CO_2} = \mathrm{BMR}\ M\ 0.000484 \tag{9}$$

These equations can be applied to calculate the CO_2 generation rate at other air pressures and temperatures using the following equations:

$$V_{CO_2} = \mathrm{RQ}\ \mathrm{BMR}\ M\ (T/P)\ 0.000211 \tag{10}$$

Assuming RQ equals 0.85, Equation 10 can be expressed as:

$$V_{CO_2} = \mathrm{BMR}\ M\ (T/P)\ 0.000179 \tag{11}$$

where T is the air temperature in K and P is the pressure in kPa. The derivation of equations 8 through 11 is described in the Supporting Information.

In order to facilitate use of these calculations, Table 4 contains CO_2 generation rates for a number of M values over a range of ages for both males and females. The mean body mass values are based on data in the EPA Exposure Factors Handbook, specifically the values in tables 8-4 for males and 8-5 for females.[45] As noted earlier, these values are most accurate, but still inherently approximate, when applied to a group of individuals and will not generally be accurate for a single individual.

TABLE 4 CO_2 generation rates at 273 K and 101 kPa for ranges of ages and level of physical activity (based on mean body mass in each age group)

			CO_2 generation rate (L/s)						
			Level of physical activity (met)						
Age (y)	**Mean body mass (kg)**	**BMR (MJ/day)**	**1.0**	**1.2**	**1.4**	**1.6**	**2.0**	**3.0**	**4.0**
Males									
<1	8.0	1.86	0.0009	0.0011	0.0013	0.0014	0.0018	0.0027	0.0036
1 to <3	12.8	3.05	0.0015	0.0018	0.0021	0.0024	0.0030	0.0044	0.0059
3 to <6	18.8	3.90	0.0019	0.0023	0.0026	0.0030	0.0038	0.0057	0.0075
6 to < 11	31.9	5.14	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0100
11 to <16	57.6	7.02	0.0034	0.0041	0.0048	0.0054	0.0068	0.0102	0.0136
16 to <21	77.3	7.77	0.0037	0.0045	0.0053	0.0060	0.0075	0.0113	0.0150
21 to < 30	84.9	8.24	0.0039	0.0048	0.0056	0.0064	0.0080	0.0120	0.0160
30 to <40	87.0	7.83	0.0037	0.0046	0.0053	0.0061	0.0076	0.0114	0.0152
40 to <50	90.5	8.00	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0155
50 to <60	89.5	7.95	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0154
60 to <70	89.5	6.84	0.0033	0.0040	0.0046	0.0053	0.0066	0.0099	0.0133
70 to <80	83.9	6.57	0.0031	0.0038	0.0045	0.0051	0.0064	0.0095	0.0127
≥80	76.1	6.19	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
Females									
<1	7.7	1.75	0.0008	0.0010	0.0012	0.0014	0.0017	0.0025	0.0034
1 to <3	12.3	2.88	0.0014	0.0017	0.0020	0.0022	0.0028	0.0042	0.0056
3 to <6	18.3	3.59	0.0017	0.0021	0.0024	0.0028	0.0035	0.0052	0.0070
6 to < 11	31.7	4.73	0.0023	0.0027	0.0032	0.0037	0.0046	0.0069	0.0092
11 to < 16	55.9	6.03	0.0029	0.0035	0.0041	0.0047	0.0058	0.0088	0.0117
16 to <21	65.9	6.12	0.0029	0.0036	0.0042	0.0047	0.0059	0.0089	0.0119
21 to < 30	71.9	6.49	0.0031	0.0038	0.0044	0.0050	0.0063	0.0094	0.0126
30 to < 40	74.8	6.08	0.0029	0.0035	0.0041	0.0047	0.0059	0.0088	0.0118
40 to <50	77.1	6.16	0.0029	0.0036	0.0042	0.0048	0.0060	0.0090	0.0119
50 to <60	77.5	6.17	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
60 to <70	76.8	5.67	0.0027	0.0033	0.0038	0.0044	0.0055	0.0082	0.0110
70 to <80	70.8	5.45	0.0026	0.0032	0.0037	0.0042	0.0053	0.0079	0.0106
≥80	64.1	5.19	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0101

5 | VARIATION IN CO_2 GENERATION RATES

While Table 4 is useful in providing CO_2 generation rates for different ages and levels of physical activity *M*, it uses the mean body mass for each age group and does not reflect the variation in body mass. The body mass data in the EPA Exposure Factors Handbook cited above provide values in the form of percentiles in each age group for both males and females. Figures 1 and 2 present CO_2 generation rates for males and females, respectively, in a form that reflects the variation in body mass. For each age group along the horizontal axes, a box-whisker plot is provided for six different values of *M* (1, 1.2, 1.4, 2, 3, and 4 met) which shows the 10th, 25th, 50th, 75th, and 90th percentile values of the CO_2 generation rate. These plots show that the CO_2 generation rate increases with age (for the same met value) up to about 30 year of age, at which point it decreases gradually with age. This trend reflects the dependence of BMR on age. For values of *M* less than 2 met, the impact of the variation in the body mass is less than the impact at higher values of M.

It is also useful to consider CO_2 generation rates for different space types of interest. Table 5 presents summary data for several space types, using the default occupancy levels and outdoor air ventilation rates from ASHRAE Standard 62.1,[14] as well as assumed air change rates for a dwelling, and met values from Tables 2 and 3. For the spaces covered by Standard 62.1 and the assumed occupancies, the average CO_2 generation rates per person range from about 0.003 to 0.006 L/s, primarily based on the assumed occupant ages and activity levels. The CO_2 generation rates in this table are based on the mean body mass for the

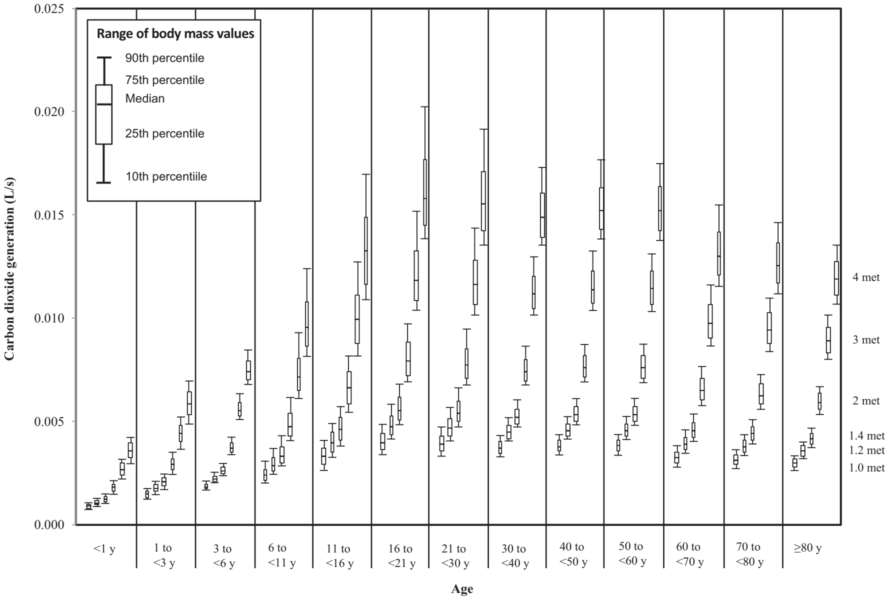

FIGURE 1 Variation in CO_2 generation rate at 273 K and 101 kPa associated with variation in age, body mass, and level of physical activity for males

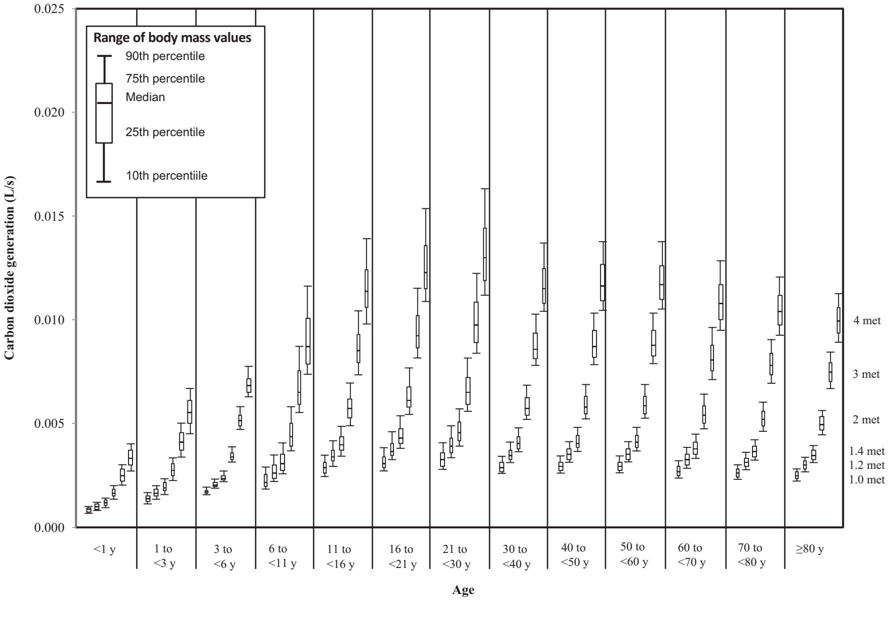

FIGURE 2 Variation in CO_2 generation rate at 273 K and 101 kPa associated with variation in age, body mass, and level of physical activity for females

TABLE 5 CO_2 generation rates and steady-state concentrations at 273 K and 101 kPa for selected spaces of interest (calculations based on the mean body mass in each noted age range)

Space type	Average CO_2 generation rate (L/s•person)	Outdoor air ventilation rate based on Standard 62.1 default occupancy (L/s•person)	Steady-state CO_2 concentration above outdoors (ppm(v))
Office[a]	0.0048	7.5	568
Conference room[a]	0.0048	3.1	1557
Educational (5 to 8 y)[b]	0.0030	7.4	408
Lecture classroom[c]	0.0042	4.3	970
Lecture hall, fixed seats[d]	0.0041	4.0	1036
Lobby[e]	0.0055	2.7	2042
Auditorium seating area[f]	0.0048	2.7	1787
		Outdoor air ventilation rate (h^{-1}) and (L/s•person)	
Residence[g]	0.0040	0.2 (6.1)	660
	0.0040	0.35 (10.7)	377
	0.0040	0.5 (15.3)	264
Adult bedroom[h]	0.0036	0.2 (1.8)	1988
	0.0036	0.35 (3.2)	1136
	0.0036	0.5 (4.5)	795
Child's bedroom[i]	0.0025	0.2 (2.5)	1014
	0.0025	0.35 (4.3)	579
	0.0025	0.5 (6.2)	406

[a] 50% male and 50% female, five occupants per 100 m^2, ages 21 to 60 y; 1.4 met.
[b] 24 children at 1.4 met (50% male and 50% female), one adult female, 21 to 60 y; 1.6 met.
[c] 64 students at 1.2 met (50% male and 50% female, 16 to 20 y), one adult female, 21 to 60 y; 1.4 met.
[d] 148 students at 1.2 met (50% male and 50% female, 16 to 20 y), one adult female, 21 to 60 y; 1.4 met.
[e] 150 adults at 1.6 met (50% male and 50% female, 21 to 60 y); 1.6 met.
[f] 150 adults at 1.6 met (50% male and 50% female, 21 to 60 y); 1.4 met.
[g] One male and one female, age 31 y to 40 y; one male and one female, age 6 y to 11 y; 1.4 met; dwelling volume 440 m^3.
[h] One male and one female, age 31 to 40 y; 1.0 met; bedroom volume 65 m^3; outdoor air ventilation uniformly distributed throughout dwelling.
[i] One male or one female, age 6 to 11 y; 1.0 met; bedroom volume 44 m^3; outdoor air ventilation uniformly distributed throughout dwelling.
[Correction added on 13 June 2017, after first online publication: steady-state CO_2 concentration above outdoors unit has been changed from mg/m^3 to ppm(v) in the column heading. And also, the values for office, conference room, adult bedroom have been altered from 643, 1577, 1958 to 568, 1557, 1988 respectively.]

assumed occupants in the noted age ranges; they do not account for the variation in body mass within these age ranges. Using the outdoor air ventilation requirements from Standard 62.1, the steady-state CO_2 concentrations above outdoors range from about 400 to 2000 ppm(v). [Correction added on 13 June 2017, after first online publication: steady-state CO_2 concentration above outdoors unit has been changed from mg/m3 to ppm(v).]. Note that these steady-state concentrations will only be achieved if conditions, including occupancy, are constant for sufficiently long periods of time. The amount of time depends on the inverse of the air change rate, that is, the time constant of the space, with three time constants required to achieve about 95% of the steady-state concentrations. For a space with a low air change rate, the occupancy may not be constant for long enough to achieve steady state. CO_2 generation rates and steady-state CO_2 concentrations are also shown in Table 5 for some residential cases, specifically whole house values for three different air changes rates (0.2, 0.35, and 0.5 hour^{-1}). Note that for the assumed size and occupancy of this residence, ASHRAE Standard 62.2-2013 would require at outdoor air ventilation rate of 0.34 hour^{-1}.[46]

6 | DISCUSSION

The approach described in this paper for estimating CO_2 generation rates from individuals is based on concepts from the fields of human metabolism and exercise physiology, as well as more recent data that are currently used in the fields of ventilation and IAQ. It is intended to replace the equation that has been used for decades within the ventilation and IAQ communities (Equation 4 in this paper) and offers important advantages. First, it is worth noting that the currently used equation is based on a 1981 reference that provides no explanation of its basis, while the new approach is clearly derived using principles of human metabolism and energy expenditure. Also, the new approach characterizes body size using mass rather than surface area, which in practice is estimated not measured. Body mass is easily measured and data on body mass distributions are readily available. The new approach also explicitly accounts for the sex and age of the individuals being considered, which is not the case with Equation 4. As new data on body mass become available, these data can be used to adjust CO_2 generation rates accordingly. Similarly, new research results on BMR values and new approaches to their estimation can also be easily applied to these calculations.

The approach described in this paper was used to reanalyze the CO_2 generation rate data collected by Qi et al.[29] referred to earlier, in which they noted that the 1981 Nishi equation (Equation 4 in this paper) tended to overestimate the CO_2 generation rates relative to their measurements. Based on the body mass values in that paper, the BMR for each test subject was calculated using the equations in Table 1. As noted in the Qi paper, the measured CO_2 generation rates were on average 23% and 24% lower for females sitting and standing, and 16% and 16% lower for males sitting and standing, relative to the values predicted with Equation 4. Using the approach described in this paper, with values of *M* for sitting and standing of 1.2 and 1.3 (based on Tables 2 and 3) and RQ equal to 0.85, the mean differences between the measured and predicted CO_2 generation rates decrease to −7%, 3%, −10%, and 0%. Therefore, the conclusion of Qi et al. [29] that Equation 2 should be adjusted with a correction factor when applied to Chinese subjects more likely reflects the use of the older calculation method and data rather than a fundamental difference for the test subjects. That said, the BMR values of Chinese adults have been shown to be lower than predicted using available equations, which may explain some of the observed differences between the predictions and measurements.[47] However, the BMR values calculated using the equations in Liu et al. do not result in significantly better agreement between predicted CO_2 generation rates and those measured by Qi et al.

Fan et al. [48] report measured CO_2 generation rates in a naturally ventilated room, and compare them to predictions using the approach embodied in Equation 4 of this paper. For the six subjects in the Fan et al. study (three males and three females in their mid-twenties), the measured generation rates were on average 17% and 25% lower than those predicted by Equation 4 for the male and female subjects, respectively. Using the BMR-based calculation presented in this paper in Equation 9, with a value of 1.1 met as employed by Fan et al., the measured rates were on average 2% and 8% higher than the calculated rates for the male and female subjects, respectively, again demonstrating the improved accuracy of this estimation method. Other than these two studies (Qi and Fan), there is very little published data on measured CO_2 generation rates from people. Additional data will be helpful in assessing the estimation method presented in this paper.

The CO_2 generation rate estimation method described here is applicable to groups of individuals, as the theory behind the method and the data are based on groups, not single individuals. As noted earlier, if the rate of energy consumption or CO_2 generation of a specific individual is needed, it has to be measured for that individual to account for differences that can exist due to that person's body composition, diet, genetics, and other factors. When considering a population of individuals in a building or space, the average values derived using the described approach will be more reliable than for a single individual. However, that reliability should be increased by characterizing the specific population of interest in terms of sex, age, body mass, and activity level. Methods for performing such characterizations in a standardized fashion are not described in this paper. The increased accuracy of CO_2 generation estimates that may be achieved by doing so have not been studied, but additional research will be useful to demonstrate the value of such methods.

The energy requirement values in the FAO report and the compendium cover a wide range of activities, but they only provide single values or ranges of values for particular activities (eg, those associated with office work), which may not capture the variability in the activities that occur in different building environments. It should be possible to use these general values to convert detailed activity schedules into more accurate estimates of energy requirements for specific building occupants, but methods for doing so are not described in this paper. While the application of such schedule-based approaches has not been studied, they certainly have merit. Future research to demonstrate and quantify the improvement in the accuracy of estimated CO_2 generation rates using activity schedules will be of interest. Additional work is also needed to examine the uncertainty associated with these estimates of CO_2 generation for groups as a function of the number of individuals in the group, as well as for individuals.

7 | CONCLUSIONS

This paper presents an approach to estimating CO_2 generation rates from building occupants for use in the fields of IAQ and ventilation. The approach and data are based on concepts from the fields of human metabolism and exercise physiology. They constitute a significant advance in the analysis of IAQ and ventilation and should be considered in future applications of CO_2 in ventilation and IAQ studies and standards. In addition, the sources of physical activity data identified should be incorporated into the references that currently use older and much more limited data sources, that is, ASHRAE Standard 55, the ASHRAE Fundamentals Handbook, ISO Standard 8996, and ASTM D6245.[16,20,24,28] In addition, guidance on CO_2 set points for the application of demand control ventilation should be updated to reflect the information in this paper.

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SUPPORTING INFORMATION

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