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Carbon Dioxide Generation Rates from Building Occupants

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SUMMARY
Indoor carbon dioxide (CO_2) concentrations have been used in the fields of building ventilation and indoor air quality (IAQ) for decades to estimate ventilation rates, to control outdoor air ventilation rates, and to assess IAQ. These applications employ CO_2 generation rates for the building occupants, which historically and currently are based on approaches and data from the literature that are many decades old. CO_2 generation rates depend on an individual's level of physical activity, as well as their sex, age and body size. These dependencies have been studied for decades within the fields of human metabolism and exercise physiology, but that knowledge has not been incorporated by the IAQ community. This paper describes a more robust and up-to-date method for estimating CO_2 generation rates for use in ventilation and IAQ analyses.

KEYWORDS
Carbon dioxide; human metabolism; physical activity

1 INTRODUCTION
Indoor CO_2 concentrations have been prominent in discussions of building ventilation and indoor air quality (IAQ) since the 18th century. More recent discussions have focused on the impacts of CO_2 on building occupants and the use of indoor CO_2 to estimate ventilation rates and to control outdoor air ventilation rates (Persily, 2015). While the rates at which building occupants generate CO_2 are key to these applications, the generation rates currently in use are not based on recent references or a thorough consideration of the impacts of occupant characteristics.

The fields of human metabolism and exercise physiology have studied human activity for many decades, focusing on 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.

This paper summarizes current approaches to estimating CO_2 generation rates and outlines an updated approach described in detail in Persily and de Jonge (2017).

2 CURRENT APPROACH TO ESTIMATE CO_2 GENERATION RATES

The ventilation and IAQ fields use the following equation to estimate CO_2 generation rates from building occupants (ASHRAE, 2013b):

$$V_{CO2} = \frac{0.00276\, A_D\, M\, RQ}{(0.23 RQ + 0.77)} \tag{1}$$

where V_{CO2} is the CO_2 generation rate per person (L/s); A_D is the DuBois surface area of the individual (m^2); M is the level of physical activity, sometimes referred to as the metabolic rate (met); and RQ is the respiratory quotient. A_D is calculated from height H in m and the body mass W in kg as follows:

$$A_D = 0.203 H^{0.725} W^{0.425} \tag{2}$$

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 (Black et al., 1986). Based on data on human nutrition in the U.S, specifically the ratios of fat, protein and carbohydrate intake (Wright and Wang, 2010), RQ equals about 0.85.

Equation 1 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 (1981), 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. The ASHRAE Fundamentals Handbook also contains a table of metabolic rates for various activities, which has remained unchanged since the 1977 edition (ASHRAE, 2013b). These values are based on references predominantly from the 1960s, though some are even older. The same metabolic rate values are contained in the ASHRAE thermal comfort standard (ASHRAE, 2013a), with similar data contained in ISO standard 8996 (ISO, 2004). As noted later in this paper, there are more recent and comprehensive sources of metabolic rate data.

The above equations and data are currently being 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 (ASTM, 2012). 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 1 to ventilation and IAQ do not generally consider effects of air density on CO_2 generation rates, simply presenting these rates in volumetric units without specifying the air temperature or pressure.

3 ESTMATION OF CO_2 GENERATION RATES

This section describes a new approach to estimating CO_2 generation rates from building occupants based on the information from the fields of human metabolism and exercise physiology, as described in much more detail in Persily and de Jonge (2017). This approach uses the basal metabolic rate (*BMR*) of the individual(s) of interest combined with their level of physical activity. This contrasts with Equation 1, which only considers their 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. Equations for estimating *BMR* values as a function of sex, age and body mass are presented in Schofield (1985) and are shown in Table 1. For example, the *BMR* of an 85 kg male between 30 y and 60 y old is 7.73 MJ/day and 6.09 MJ/day for a 75 kg female in this same age range. The next step is to estimate their level of physical activity in terms of the value of *M* that corresponds to the activities in which they are involved.

Table 1. *BMR* values (Schofield, 1985). (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

There are two primary references for obtaining information on energy requirements for different physical activities. The first 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), which discusses human energy requirements as a function of age and other individual characteristics (FAO, 2001). The second is a web-based compendium of physical activities (Ainsworth et al., 2011b; Ainsworth et al., 2011a). 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 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. Persily and de Jonge (2017) contains tables of values of *M* for various activities from the FAO report and from the web-based compendium.

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 (Lusk, 1924). 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 *RQ* 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 y and 60 y 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 (e.g. office work) 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.

Based on the approach just described, the CO_2 generation rate is expressed in L/s at an air pressure of 101 kPa and a temperature of 273 K, with *BMR* in units of MJ/day and *M* in met, using Equations (3) and (4). Adjustments to other values of air pressure and temperature are described in Persily and de Jonge (2017).

$$V_{CO2} = RQ\ BMR\ M\ 0.000569 \tag{3}$$

Assuming RQ equals 0.85, Equation 3 can be expressed as:

$$V_{CO2} = BMR\ M\ 0.000484 \tag{4}$$

In order to facilitate use of these calculations, Table 2 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 (EPA, 2011). 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 2. CO_2 generation rates for ranges of ages and level of physical activity

			CO_2 generation rate (L/s)						
Age (y)	**Mean mass (kg)**	***BMR* (MJ/day)**	Level of physical activity (met)						
			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

4 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 than those 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 1 in this paper) and offers important advantages. First, it is worth noting that the previous equation is based on a 1981 reference that provides no explanation of its basis, while the new approach is 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 1. 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 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. If the rate of energy consumption or CO_2 generation of a specific individual is needed, it must 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 would be useful to demonstrate their value.

5 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, i.e., ASHRAE Standard 55, the ASHRAE Fundamentals Handbook, ISO Standard 8996, and ASTM D6245 (ASHRAE, 2013b; ISO, 2004; ASTM, 2012; ASHRAE, 2013a).

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