

Accuracy Improvement for Estimating Indoor Carbon Dioxide Concentration Produced by Occupants

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ABSTRACT

Carbon dioxide included in exhaled breath is often used as a tracer gas when estimation of ventilation aspect in buildings with occupants is performed. Indoor carbon dioxide concentration is also adopted evaluation of ventilation commonly. It is needed for these investigations to grasp occupants' carbon dioxide production rate accurately.

In previous studies by the authors (2014, 2016), equations for calculating carbon dioxide production rate based on Japanese subjects' exhaled breath data obtained by using Douglas bag method have been shown. These equations, whose variables are occupant's height & weight, gender, age and *Met*, have been validated by measuring concentration of carbon dioxide in ventilated single zones with occupants.

This paper describes about investigated results of accuracy using one of the equations. Moreover, aiming at improving the precision in estimating indoor carbon dioxide concentration, estimation of *Met* value utilising wearable triaxial accelerometer or pulse rate monitor is examined and shown experimental results.

KEYWORDS

Ventilation, Exhaled breath, Carbon dioxide concentration, Single Zone, Estimation accuracy, Activity meter

1 INTRODUCTION

Carbon dioxide included in exhaled breath is often used as a tracer gas when estimation of ventilation aspect in buildings with occupants is performed. Indoor carbon dioxide concentration is also adopted evaluation of ventilation commonly. It is needed for these investigations to grasp occupants' carbon dioxide production rate accurately.

In previous studies by the authors (Tajima 2014, 2016), equations for calculating carbon dioxide production rate based on Japanese subjects' exhaled breath data obtained by using Douglas bag method have been shown. These equations, whose variables are occupant's height & weight, gender, age and *Met*, have been validated by measuring concentration of carbon dioxide in ventilated single zones with occupants. The calculation accuracy of the equations can be improved if occupant's *Met* value, which is generally substituted for designed value or referenced value, is estimated more accurately. Hence this paper describes about investigated results of calculating accuracy of indoor carbon dioxide concentration utilising activity meters.

2 METHODOLOGY

In order to improve the precision in estimating indoor carbon dioxide concentration using occupants' exhaled breath, the following 2 investigations are executed in this study.

(1) Accuracy tests for estimation accuracy of *Met* value

Occupants' *Met* value is one of the most important elements for calculating indoor carbon dioxide concentration. In previous studies on accuracy check in calculating indoor carbon dioxide concentration by the authors, *Met* values were set as referenced value (e.g.

ASHARAE, 2013/ SHASE, 2010) determined by visual judgement. By obtaining *Met* value utilising a wearable activity meter or a pulse rate monitor, accuracy of occupants' *Met* value is checked by comparing with Douglas bag method in this study.

(2) Accuracy tests for estimation of carbon dioxide concentration in ventilated rooms

Measurement of indoor carbon dioxide concentration in ventilated single zone are handled aiming at accuracy check of calculated concentration by using proposed equation for occupant's carbon dioxide production rate. Occupants' *Met* values are obtained by measuring devices also in the measurements.

3 ESTIMATING EQUATION FOR CARBON DIOXIDE PRODUCTION RATE

Occupants' carbon dioxide production rate which is investigated based on Japanese subjects' exhaled breath are given as equation (1) (Tajima, 2014) and equation (2) (Tajima, 2016) which is revised from equation (1). Japanese body surface area A_D is given by equation (3). The age coefficient C_a , which was determined by using data given by Ministry of Health, Labour and Welfare of Japan, is shown in Table1. In these previous studies, compared with carbon dioxide production rate shown in JIS (Japanese Industrial Standard Committee, 2010) or ASTM D6245-12 (ASTM, 2012), the indoor carbon dioxide concentration using the equations showed the closest value to the measured value within the *Met* value was 3. Figure 1 represents the relationships between the estimated value using the equation (1) & (2) and measured value obtained by Douglas bag method. The R^2 of the equation (2) is 0.8525 and higher than equation (1). Therefore, equation (2) can be considered that it is reliable expression for estimating Japanese carbon dioxide production rate.

$$P_{CO_2} = 1.589 \times 10^{-4} \times (94.4A_D \times 83.9Met \times 21.0C_g - 149.7) \quad (1)$$

$$P_{CO_2} = 1.601 \times 10^{-4} \times (60.63 \times A_D \times Met \times C_G \times C_a) \quad (2)$$

$$A_D = 0.007246 \times W^{0.425} \times H^{0.725} \quad (3)$$

Where:

P_{CO_2} is the carbon dioxide production rate [m^3/h]

A_D is the body surface area [m^2]

Met is the metabolic rate [-]

C_a is the age coefficient (See Table1)

C_G is the coefficient of gender Female 0, Male 1 (For equation (1))

C_g is the gender factor Female 0.73, Male 1.00 (For equation (2))

H is the height [cm]

W is the body weight [kg]

Table1 : The ratio of basal metabolic rate and basal metabolic rate by age

Age	Basal Metabolic Rate [kcal/day] (Ratio of Basal Metabolic Rate C_a)	
	Male	Female
18-29	1520 (1.00)	1110 (1.00)
30-49	1530 (1.01)	1150 (1.04)
50-69	1400 (0.92)	1100 (0.99)
70-	1290 (0.85)	1020 (0.92)

The ratio of the basal metabolic rate is based on the value of 18 to 29 years old
The grey part in the table represents the subjects' age and gender in the validation

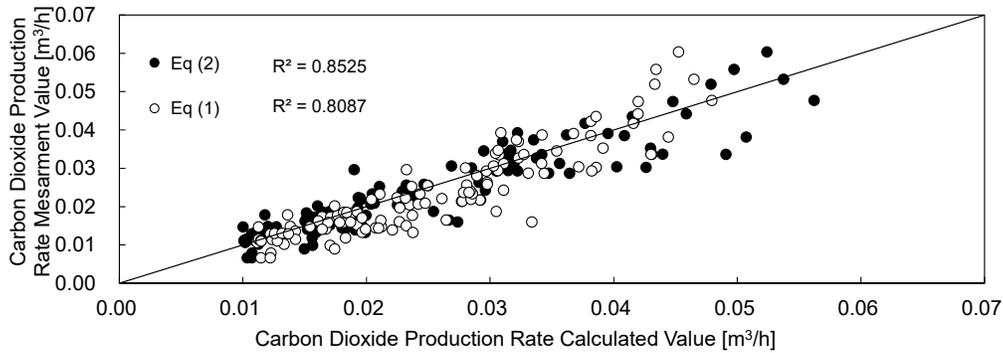


Figure 1: Measured and calculated carbon dioxide production rate

4 ACCURACY TESTS FOR ESTIMATION ACCURACY OF MET VALUE

Accuracy check in measurement of *Met* values of wearable devices are executed by comparing with the value measured by Douglas bag method.

4.1 Measurement of *Met* Value

Two wearable devices for measuring *Met* value shown in Table 2, Photo 1 and Photo 2 are used. The activity meter which employs triaxial accelerometer can directly measure *Met* value. The pulse rate monitor measures pulse rate, therefore additional conversion into *Met* value is required. Moreover, *Met* values considered to be correct were obtained by using Douglas bag method, whose measuring instruments are shown in Table 3. The experimental conditions are shown in Table 4. Table 4 also contains referenced *Met* values (ASHRAE, 2013/ Ainsworth, 2011).

Table 2: Wearable devices for measuring *Met*

Activity meter	Measurement Range: $\pm 6G$ 1.0-18.0 METs (0.1METs Notch)	OMRON Active style PRO HJA-750c
Pulse rate monitor*	Measurement range Pulse Rate 30 - 220 beat	MIO ALPHA 53PBLK-INT

* An additional conversion into *Met* value is required



Photo1: Activity meter



Photo2: Pulse rate monitor

Table 3: Testing instruments for Douglas bag method

Douglas bag	Volume: 100L	TAKEI TK-11288
Gas analyser	CO ₂ NDIR 0-5/10/20 vol% O ₂ zirconia process 0-5/10/25 vol%	HORIBA PG-240

Table 4: Experimental conditions

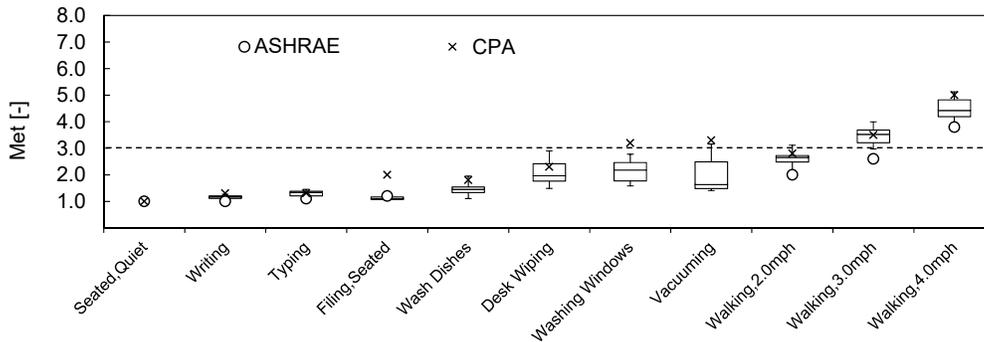
Action	Activity period	Referenced Value			Number of Subjects	
		ASHRAE	CPA*			
			METs	Code		
Seated, Quiet		1.0	1.0	07010	15	
Office Activities	5 minutes	Writing	1.0	1.3	09040	7
		Typing	1.1			10
		Filing, Seated	1.2	2.0	11763	15
Home Activities	4 minutes	Wash Dishes	2.0 - 3.4	1.8	05041	11
		Desk Wiping		2.3	05032	14
		Washing Windows		3.2	05022	11
		Vacuuming		3.3	05043	11
Walking (on level surface)	3 minutes	2.0 mph (3.2 km/h)	2.0	2.8	17152	11
		3.0 mph (4.8 km/h)	2.6	3.5	11792	13
		4.0 mph (6.4 km/h)	3.8	5.0	17220	12

* CPA: The 2011 Compendium of Physical Activities

4.2 Results and Discussion

Totally 130 subjects in 10 actions experimental results were obtained. Measurement results of Douglas bag method is shown in Figure 2. Figure 2 describes referenced value also. Figure 3 describes the standard error of *Met* values. *Met_a*(mean) represents mean value obtained by activity meter. *Met_{bpm}* represents calculated value by substituting heart beat rate into subject's personal equation like as shown in Figure 4 or 5. CPA (Ainsworth, 2011) and ASHRAE (ASHRAE, 2013) are referenced values.

The activity meter method shows totally most accurate. The standard error of *Met* value using the activity meter is 0.03. The pulse monitor method requires slightly complicated arrangement which needs personal relational expression of pulse rate and *Met* value. The personal expressions include individual differences shown in Figure 4 and 5. The referenced values show relatively correct results totally in Figure 3, however some actions such as vacuuming or walking have larger error. Therefore, the activity meter method is recommended to estimate *Met* values with relatively small error.



CPA: The 2011 Compendium of Physical Activities

Figure 2: *Met* value obtained by Douglas bag method and referenced value

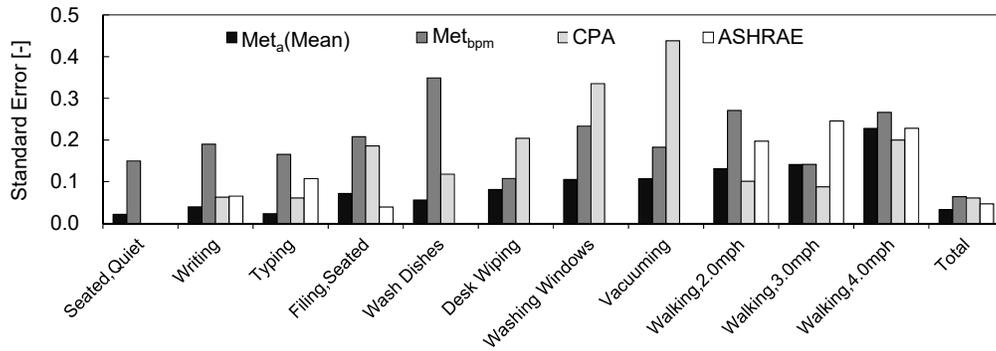


Figure 3: Standard error of *Met* value

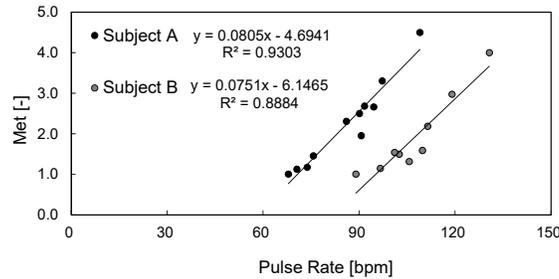


Figure 4: Pulse Rate and *Met* Value (larger R^2)

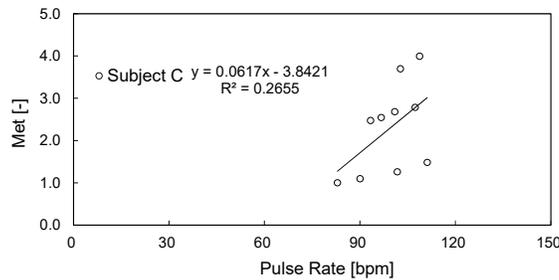


Figure 5: Pulse Rate and *Met* Value (smaller R^2)

5 ACCURACY TESTS FOR ESTIMATION OF CARBON DIOXIDE CONCENTRATION IN VENTILATED ROOMS

5.1 Experimental

As shown in above, utilising activity meter shows most accurate estimating result of *Met* value. Hence, calculating accuracy in indoor carbon dioxide concentration of ventilated rooms which are considered as single zone is handled with utilising the activity meter. Measurement conditions are shown in Figure 6 and Table 5. The experimental was carried out with four occupants wearing the activity meter. The measurement interval was set as 10 seconds.

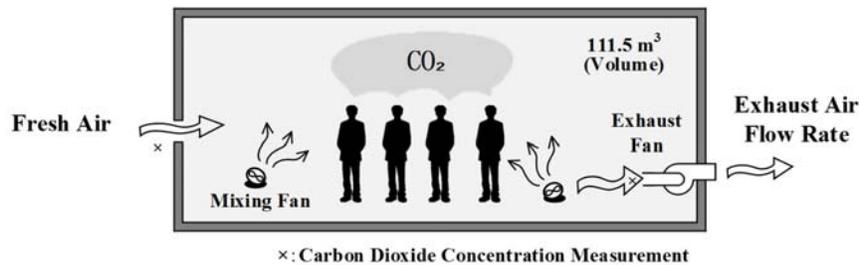


Figure 6 Experimental condition

Table 5: Condition of experimental measurement in single zone

Case	Ventilation Rate*	Measurement Period	Activity	
A-1	80m ³ /h	30 minutes	Seated, Quiet	
A-2			60 minutes	Seated, Quiet/Study
A-3				30 minutes
A-4		Filing, Seated		
A-5		Study		
A-6		Desk wiping		
A-7		Vacuuming		
A-8		Walking		
A-9				
A-10				
A-11				
A-12				

* Number of occupants is four, (20m³/h•person)

5.2 Results and Discussion

Totally 12 cases and 2318 points indoor carbon dioxide concentration data were obtained. Calculated results of indoor carbon dioxide concentration by equation (4) using equation (2) with *Met* values measured by activity meter as production rate P_{CO_2} are compared with referenced values. The *Met* values are determined by not only mean value but also instantaneous, mode and median value. Measured and calculated indoor carbon dioxide concentrations are shown in Figure 7, 8 and 9 as examples. The RMSE of estimated indoor carbon dioxide concentrations are shown in Table 6. The standard error of estimated indoor concentrations is shown in Figure 10.

The calculated results include using referenced values approximately agree with the measured value shown in Figure 7 and 8. However, In Figure 9, the calculated result using referenced value has a certain error. The standard errors of calculated concentrations are totally small as less than 2.0 ppm shown in Figure 10. Especially using both Met_a (mean) and Met_a (Instantaneous), the standard errors are both 1.0. These results suggest that calculation method using equation (2) can give accurate indoor carbon dioxide concentration and can ensure more correct calculation results utilising the activity meters.

$$\frac{dC_i}{dt} V_i = \sum_{j=1}^4 P_{CO_2j} + Q_{io}(C_o - C_i) \quad (4)$$

Where

C_i is the concentration of carbon dioxide of target room [m³/m³]

C_o is the concentration of carbon dioxide of outdoor [m³/m³]

Q_{io} is the ventilation rate [m³/h]

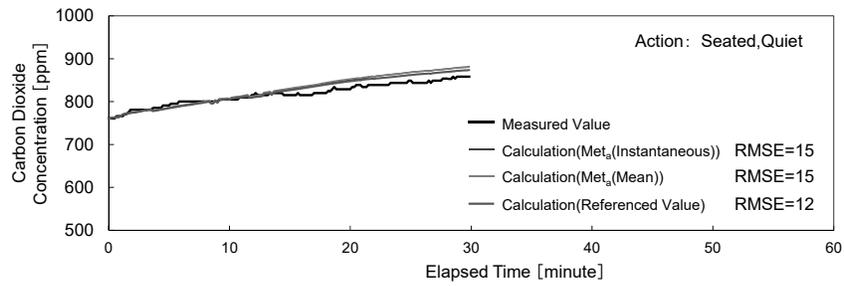


Figure 7: Measurement and Calculation Result of Indoor CO₂ Concentration (A-1)

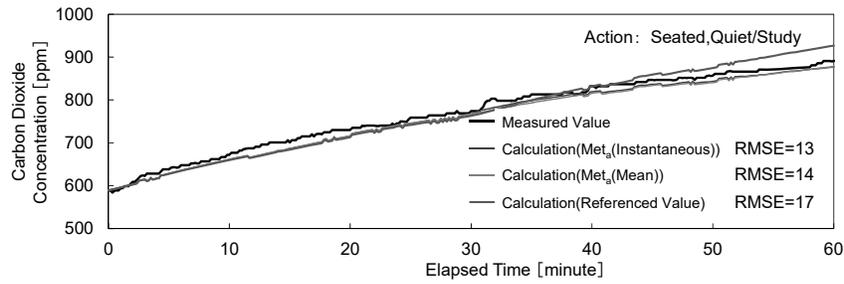


Figure 8: Measurement and Calculation Result of Indoor CO₂ Concentration (A-3)

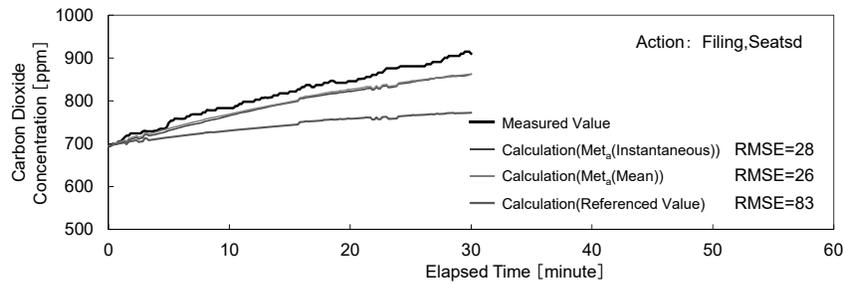


Figure 9: Measurement and Calculation Result of Indoor CO₂ Concentration (A-6)

Table 6: Measurement Result of *Met* Value and Carbon Dioxide Concentration

Case	<i>Met</i>				RMSE of CO ₂ Concentration [ppm]				
	Referenced value	<i>Met_a</i>			Referenced value	<i>Met_a</i>			
		Mean	Mode	Median		Instantaneous	Mean	Mode	Median
A-1	1.0	1.03	1.0	1.0	12.0	15.3	15.9	12.0	12.0
A-2		1.04	1.0	1.0	20.7	15.6	14.6	20.7	20.7
A-3	1.0/1.3* ²	1.05	1.0	1.0	17.1	12.5	13.6	22.7	22.7
A-4	1.1* ¹	1.07	1.0	1.0	30.5	34.6	34.2	43.9	43.9
A-5		1.04	1.0	1.0	13.3	21.6	21.6	28.0	28.0
A-6	1.2* ¹	1.64	1.5	1.6	82.7	28.2	25.6	43.3	30.2
A-7		1.29	1.2	1.2	13.7	5.7	3.5	13.7	13.7
A-8	1.3* ²	1.18	1.0	1.1	16.3	11.5	13.6	35.5	22.2
A-9		1.33	1.0	1.2	5.7	8.3	7.8	40.0	13.0
A-10	2.3* ²	2.28	2.4	2.3	19.4	15.0	16.9	33.5	19.4
A-11	2.3/3.2* ²	2.57	2.8	2.6	34.9	32.3	30.3	14.0	36.4
A-12	1.7* ¹	2.29	2.3	2.3	133.5	58.3	58.1	57.3	57.3

Met_a: measured by activity meter, *¹: ASHRAE HANDBOOK. *²: The 2011 Compendium of Physical Activities

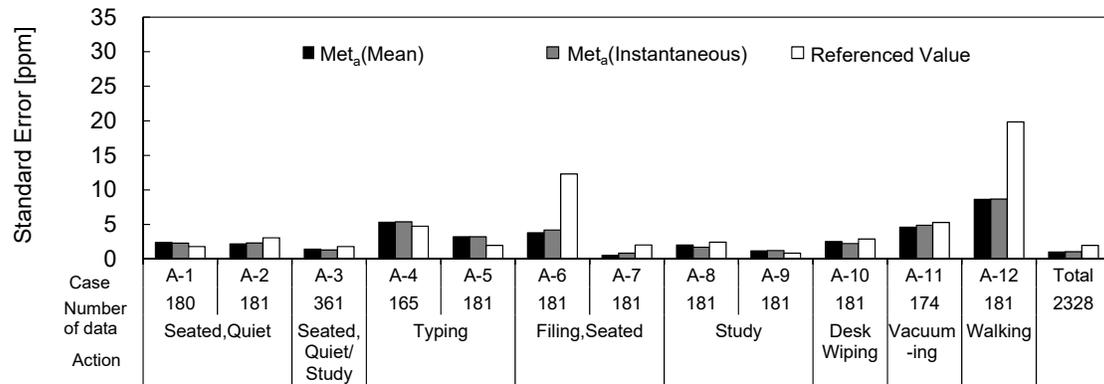


Figure 10: Standard Error of Indoor Carbon Dioxide Concentration

6 CONCLUSION

In order to improve the precision in estimating indoor carbon dioxide concentration using occupants' exhaled breath, accuracy tests for estimation accuracy of *Met* value and accuracy tests for estimation of carbon dioxide concentration in ventilated rooms have been executed.

From the experimental results on estimation accuracy of *Met* value, the *Met* values obtained by a wearable triaxial accelerometer (activity meter) give the closest values to the values by Douglas bag method. Based on totally 130 subjects and 10 actions data, the standard error of estimated *Met* value using the activity meter is 0.03.

From the experimental results on estimation of carbon dioxide concentration in ventilated rooms, calculation method using equation (2) can give accurate indoor carbon dioxide concentration and can ensure more correct calculation results utilising activity meters. Based on Totally 12 cases and 2318 points indoor carbon dioxide concentration data, the standard error of calculated result using equation (2) with *Met* values obtained by the activity meter is 1.0 ppm.

7 REFERENCES

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