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A Simple Method for Estimating Ventilation Volume Based on Equivalent Continuous A- Weighted Sound Pressure Level and Subjective Evaluation

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ABSTRACT

Ventilation rate estimation by leveraging carbon dioxide (CO_2) concentration as a tracer gas, a vital indoor environmental indicator, is very common. In office settings, CO_2 emissions predominantly arise from workers' exhalation. Notably, these emissions escalate during conversations, and the corresponding sound levels can also rise based on the work engagement. This compelling relationship between the equivalent sound pressure levels and CO_2 emissions is correlated, and it can be applied as a practical method of estimating ventilation rates. We conducted measurements across six open-plan office spaces, integrating data on equivalent sound pressure levels, average conversation time among workers, and their subjective evaluations of perceived indoor air quality. By applying multiple regression analysis to the gathered data, our results indicate that ventilation rates can be estimated with a maximum error of 29.9% using the average equivalent sound pressure level in conjunction with the inverse of the estimated conversation time. Furthermore, we significantly refined our ventilation rate estimation formula by incorporating workers' subjective indoor air quality assessments as an explanatory variable. This enhanced model can improve to an adjusted R^2 value of 0.786, drastically reducing the maximum error to 24.1%. These findings underscore the potential of this method to improve indoor air quality assessments and promote healthier work environments.

INTRODUCTION

In evaluating indoor air quality, it is crucial to understand the air conditioning and ventilation volume. Estimating the ventilation volume using the CO_2 exhalation volume from continuous measurements with a CO_2 sensor is relatively easy. However, continuous measurements may not be appropriate in facilities where people stay 24 hours a day, leading to inaccurate estimations. Conversely, living sounds like conversations are generated in occupied spaces. The CO_2 exhalation volume of talking workers increases the spatial CO_2 concentration and the equivalent continuous A-weighted sound pressure level simultaneously, suggesting a potential method for estimating ventilation volume and evaluating indoor air quality. If the main factor affecting the equivalent sound pressure level is workers' conversations, this increases CO_2 exhalation volume, i.e., the amount of CO_2 generated. Furthermore, if the ventilation volume remains constant, the amount of CO_2 generated and the CO_2 concentration are proportional, indicating a correlation between the equivalent sound level and the ventilation volume.

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SURVEYED BUILDINGS AND THE MEASUREMENT OVERVIEW

Overview of the Measurement Buildings

Table 1 provides an overview of the surveyed buildings. Buildings A, B, and C are office buildings with a total floor area of 3,000 m^2 or more and are comprehensively managed by a building maintenance company. This comprehensive management includes operating the air conditioning, monitoring operations using Building Automation, cleaning, etc., and ensuring data reliability. Meanwhile, buildings D, E, and F have packaged air conditioners and separate ventilation systems.

Table 1 Outline of the surveyed buildings

	Location	latitude	longitude	Total Floor Area (m^2)	Tenant (m^2)	Floor Level	AC	Ventilaiton
A	Sapporo	N43.068	E141.347	25289	247	10F /16F	AHU(CAV)+FCU	AHU+HEX
B	Sendai	N38.260	E140.878	6800	142	7F /8F	PAC	OHU
C	Tokyo	N35.690	E139.700	93997	209	22F /35F	AHU(VAV)	AHU(VAV)
D	Sapporo	N43.068	E141.347	1373	325	2F /3F	PAC	HEX
E	Kumamoto	N32.788	E130.744	973	156	3F /3F	PAC	Exhaust Fan
F	Kanazawa	N36.580	E136.645	806	235	1F /1F	PAC	Exhaust Fan

Estimation Method of Ventilation Volume

The ventilation volume was estimated from the CO_2 concentration measurement results and the occupants' CO_2 exhalation volume. The exhaled CO_2 emissions were calculated using Formula 1, proposed by Tajima et al. (2016). The activity level was assumed to be Met=1.1. Although the metabolic rate is expected to increase during conversation, it was assumed to remain constant in this study due to the complexity of accurately measuring and accounting for this variable. This assumption presents a potential area for future research and refinement of the estimation method. The ventilation volume was estimated using the Seidel formula (formula 2), a widely accepted method for estimating ventilation volume in indoor spaces. This formula considers the average concentration during working hours when the fluctuation of CO_2 concentration is slight and the number of occupants, providing a reliable estimate of the ventilation volume. Although natural ventilation with the windows open was not possible in A, B, and C, it was possible in D, E, and F by opening the windows. In F, there was a period during the detailed measurement when the window was open for ventilation. The CO_2 concentration was logged at one-minute intervals using a T&D TR-76Ui installed in 3 to 7 places, depending on the indoor floor area.

$$P_{CO} = 1.601 \times 10^{-4}(60.63 \times A_D \times Met \times C_a \times C_g) \quad (1)$$

$$Q = P_{CO2}/(p_{ave} - p_{out}) \quad (2)$$

Where P_{CO2}: exhaled CO_2 emissions (m^3/h), AD: body surface area (m^2), C_a: age coefficient (ratio of basal metabolic rate to basal metabolic rate by age), C_g: gender coefficient (1.00 for men, 0.73 for women), pave: spatial average indoor CO_2 concentration (-), pout: outdoor CO_2 concentration (-)

Equivalent Continuous A-Weighted Sound Pressure Level Measurement

Equivalent continuous A-weighted sound level (ESPL) was measured at the center of each office room between 10:00 and 15:00 using a Rion NL-42 (JIS C 1509-1 Class 2, A-weighting 25-138 dB, sampling frequency 48 kHz). The time-averaged ESPL ($L(A)_{eq}$) per minute was used. We also conducted a questionnaire survey regarding the duration of conversations in the office sound environment.

RESULTS

Estimation of Ventilation Volume

The estimated ventilation volume per person of each building is shown in Table 2. The estimated ventilation volume per

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person for each building ranged from 40.7 to 141.7 m^3/h, which meets Japan's recommended ventilation rate per person for COVID-19 measures of 30 m^3/h/person.

Table 2 Estimated ventilation volume (EVV) for office spaces A to F

	room CO_2 (ppm, ave.)	Outdoor CO_2 (ppm, ave.)	Calicurated total CO_2 emission (m^3/h)	Estimated Ventilation Volume (EVV), (m^3/h)	EVV per Person (m^3/h/p)
A	647.3	433.7	0.322	1507.7	100.5
B	939.7	441.4	0.203	407.4	40.7
C	745.5	437.6	1.318	4281.5	69.1
D	782.1	433	0.858	2458.7	63
E	691.2	430.7	0.257	986.2	75.9
F	580.1	430.3	0.361	2409.2	141.7

Measurement Results of Equivalent Continuous A-Weighted Sound Pressure Level

In a measurement of an open-plan office conducted by Yadav et al., the average equivalent sound pressure level was 53.6 dB(A). It was reported that the presence of carpeting had an effect of -2.7 dB(A) (Manuj Yadav, 2021). Figure 1 shows the results of the average equivalent sound pressure levels measured in all the offices that were carpeted. The six offices' average equivalent sound pressure levels ranged from 46.6 dB(A) to 52.3 dB(A). Although there were differences in the amount of conversation depending on the type of industry, the results were similar to those of overseas cases.

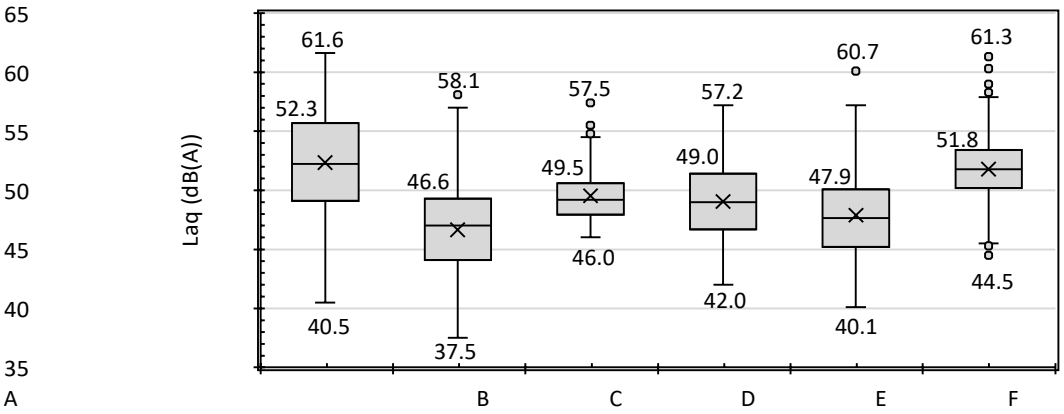

Figure 1 The results of the average equivalent sound pressure levels of measured offices （LAeq, for 5 hours）

Figure 2 shows the results of the amount of time spent talking with colleagues. It was challenging to grasp the length of time spent talking accurately; respondents were asked to rate their responses on a 5-point scale, and the median value (if over 3 hours, that is 3 hours) was used as the average length of time spent talking. The calculated average length of time spent talking (in minutes) is shown at the top of the figure.

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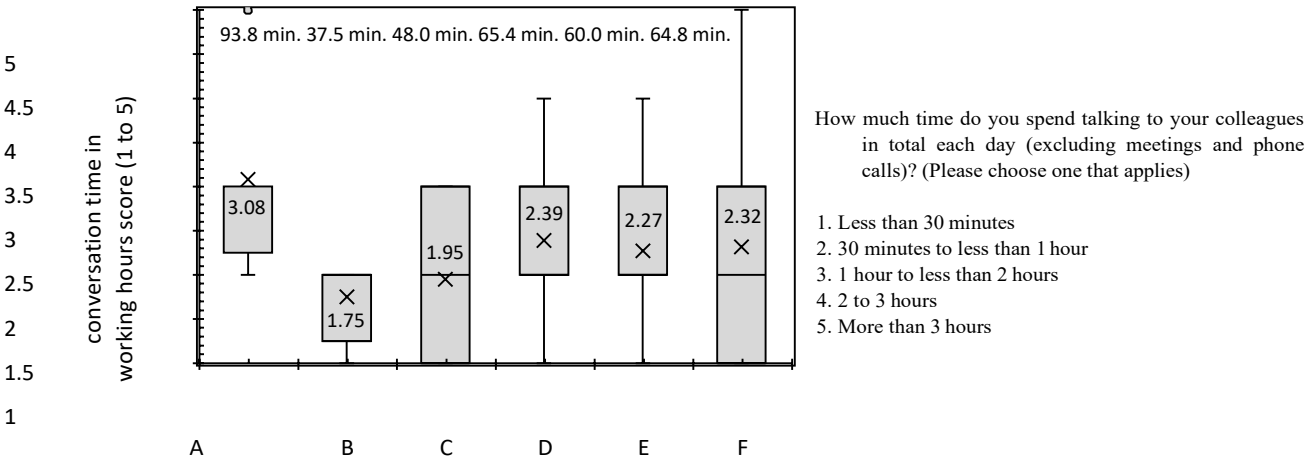

Figure 2 The time spent talking with colleagues in each office

Multiple Regression Equation for Estimating Ventilation Volume Using Average Equivalent Sound Pressure Level and Conversation Time

A multiple regression analysis was performed using the estimated ventilation volume Qestimated, calculated from the average exhaled CO_2 emissions (m^3/h) and the indoor and outdoor CO_2 concentrations (average values), as the objective variable, and the average equivalent sound level LAeq (dB(A)) and the inverse of the estimated conversation time Tc(h) as the explanatory variables, and the results shown in Table 3 and formula (3) were obtained. The adjusted R2 value was 0.778. Looking at the significance of the partial regression coefficient, the inverse of the estimated conversation time Tc(h) was slightly low at p=0.162, but this is likely due to the accuracy of the estimation of the conversation time. The ventilation volume estimation error was up to 29.9%.

$$Q_{\text{estimated}} = 12.40698 \cdot LA_{\text{eq}} + \frac{41.93901}{T_c} - 576.802 \qquad (3)$$

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Table 3: Results of multiple regression analysis

Multiple correlation R	0.931177
Multiple determination coefficient R2	0.86709
Adjusted R2	0.778483
Standard Error	16.542
Samples	6
p-value (F)	0.048455

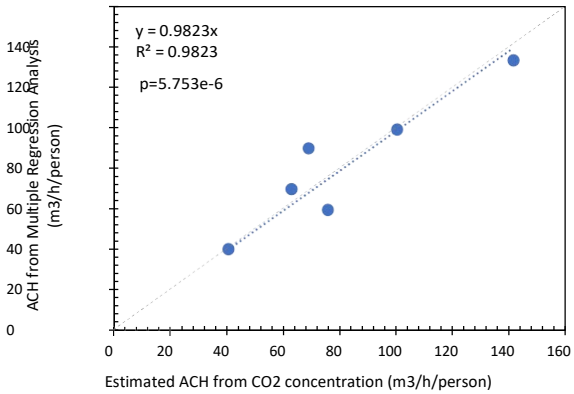

Figure 3 Accuracy of multiple regression analysis

Subjective Evaluation of Indoor Air Quality

A questionnaire survey (n=121) was conducted regarding perceived air quality and ventilation rate estimation. The contents of the two questions are shown in Table 4. The results were cross-tabulated, and a chi-square test of independence was performed, confirming a statistical correlation between perceived air quality and ventilation rate estimation (Table 5).

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Table 4 Q1 Perceived Air Quality Evaluation and Q2 Perceived Ventilation Volume Estimation

Q1: Are you concerned about the air pollution in the space you are currently in?

1. Very concerned
2. Concerned
3. A bit concerned
4. Not very concerned
5. Not concerned

Q2: How do you feel about the amount of ventilation in the space you are currently in?

1. Very poor
2. Poor
3. A little poor
4. Adequate
5. A little good
6. Good
7. Very good

Table 5 Q1 and Q2 Cross-Tabulation Results and Independence Test

		Q2 How do you feel about ventilation volume in your current space?						
		very poor	poor	a little poor	adequate	a little good	good	very good
Q1 Are you concerned about the air quality in your space?	very concerned	2 [**]	1	0	1	0	0	0
	concerned	2 [**]	4 [**]	3	0 [//]	0	0	0
	a bit concerned	0	4	14 [**]	7 [/]	1	0	0
	not really concerned	0	4	16	22	2	0	0
	not concerned	1	2	4 [//]	31 [**]	0	0	0

Chi-square test (test of independence): p<0.001

Residual analysis: Significantly high: p<0.05 [*], p<0.01[**] , Significantly low: p<0.05[/]: p<0.01[//]

Figure 4 shows the scores of perceived air quality, and Figure 5 shows the scatter plot of perceived air quality ratings and estimated ventilation volume per person. These results suggest that ventilation volume can be determined based on the perception of indoor air quality.

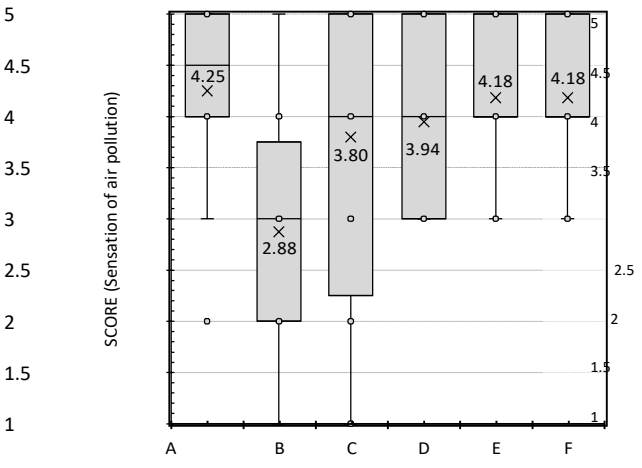

Figure 4 Scoring of Perceived Indoor Air Quality Averaged Perceived IAQ Score

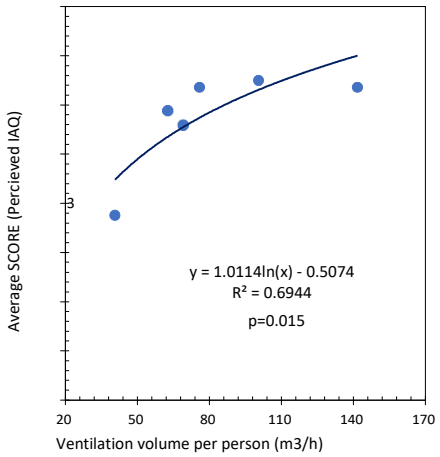

Figure 5 Estimated Ventilation Volume and the

Improvement of the Multiple Regression Equation for Estimated Ventilation Volume Considering the Subjective Evaluation of Perceived Indoor Air Quality

As shown in Figure 5 in the previous section, a significant correlation is observed between perceived air quality and estimated ventilation volume. Equation (4) is an improved equation that adds the perceived indoor air quality score Z as an explanatory variable to equation (3) and incorporates the approximation equation in Figure 5. With this improvement, the

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adjusted R2 value improved to 0.786, and the maximum error improved to 24.1%, but the p-value increased to 0.125. This is likely because the sample size of each variable became smaller when the explanatory variable was added.

$$Q_{\text{estimated}} *= 8.514951 \cdot LA_{\text{eq}} + \frac{44.09685}{\mathrm{T_c}} + 0.374164 \cdot e^{\frac{Z+0.5074}{1.0114}} - 417.347 \qquad (4)$$

Table 6: Results of Improved Multiple Regression Analysis

Multiple correlation R	0.956366
Multiple determination coefficient R2	0.914637
Adjusted R2	0.786592
Standard Error	16.2364
Samples	6
p-value (F)	0.125272

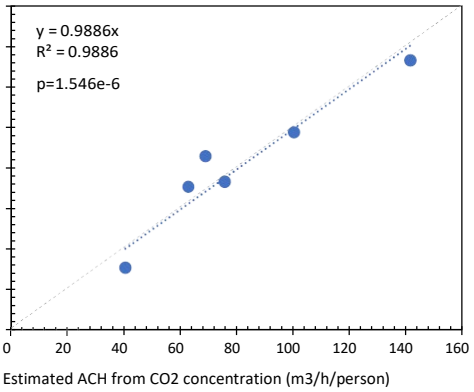

Figure 6 Accuracy of Improved Multiple Regression Analysis

CONCLUSION

A simple method using equivalent sound pressure level measurements and subjective evaluation results is investigated to understand and estimate ventilation performance in office spaces. Within the scope of this study, we found that in six measured open-plan office spaces, ventilation volume could be estimated with a maximum error of 29.9% by using the average equivalent sound pressure level and the inverse of the estimated conversation time (corrected R^2 value: 0.778). We also found a significant correlation between perceived air quality and estimated ventilation volume. By adding this relationship as an explanatory variable, the estimated ventilation volume by multiple regression analysis improved to an adjusted R^2 value of 0.786 and a maximum error of 24.1%.

ACKNOWLEDGMENTS

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