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Quantitative evaluation of nicotine and particulate matter exposure for passive- and non-smokers via a nicotine passive sampler and a particulate matter sensor

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Abstract

Passive smoking poses a major hazard to the health of non-smokers. Cigarette combustion emits environmental tobacco smoke (ETS) that contains various pollutants, including volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons, and particulate matter with particles < 2.5 μm in aerodynamic diameter ($PM_{2.5}$). Therefore, to assess the risk of passive smoking, it is necessary to determine the exposure levels to ETS compounds caused by passive smoking. However, it is difficult to assess exposure to ETS compounds by excluding the effects of other sources of pollution. In this study, we assessed the individual exposure levels to ETS compounds using a nicotine passive sampler and $PM_{2.5}$ sensor in 258 non-smokers. Median nicotine and $PM_{2.5}$ concentrations were 0.065 and 7.5 μg m^{-3}, respectively. The median nicotine concentration was nearly identical to that found in non-smoking areas (0.05 μg m^{-3}). The median $PM_{2.5}$ concentrations were below the standard value for indoor $PM_{2.5}$ concentrations (12 μg m^{-3}). These results indicated that the effect of passive smoking was rather modest. Nicotine concentrations in individuals exposed to passive smoking indoors were significantly higher than in those not exposed to passive smoking. Nicotine exposure from domestic passive smoking was twice that from non-domestic passive smoking. There was no significant difference in $PM_{2.5}$ exposure between passive smoking in domestic and non-domestic settings. Moreover, it was suggested that passive smoking was equivalent to the act of smoking 2.4×10^{-3} cigarettes per day.

Keywords Passive smoking · Passive sampler · Particulate matter sensor · LC-MS/MS · Personal exposure

Introduction

Passive smoking is a health concern for non-smokers. The emissions resulting from tobacco combustion are referred to as environmental tobacco smoke (ETS). The exposure of non-smokers to ETS has been observed in numerous countries (WHO 2007). In fact, a survey conducted across 132 countries revealed that 30–87% and 53–98% of youth were exposed to ETS at home and in public places, respectively (Group 2006).

The prevalence of smoking among individuals has shown a consistent decline over the past three decades. Specifically, the proportion of male smokers has decreased from 60% in 1992 to 27.1% in 2019, whereas the corresponding figures for female smokers have decreased from 13 to 7.6% during the same period. Additionally, the implementation of the Health Promotion Act in 2020 aimed to restrict smoking in public places in accordance with WHO recommendations. Consequently, the risk of smoking among passive smokers is expected to decrease accordingly; however, there have been no quantitative studies on the amount of passive smoke. Because outdoor smoking can increase as

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indoor smoking areas decrease, the investigation of passive smoking outdoors is important.

ETS contains various contaminants, which include volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and particulate matter with an aerodynamic diameter < 2.5 μm ($PM_{2.5}$). Indeed, passive smoking contributes an additional 14–50 μg d^{-1} to the average daily intake of benzene for individuals (Nazaroff and Singer 2004), constituting 20% of personal exposure. ETS compound emissions from smoking have been reported as follows: VOCs, 14 (*m*-cresol)–2,390 (isoprene) μg cig^{-1}(Singer et al. 2003), nicotine, 1,660 μg cig^{-1} (Singer et al. 2003); PAHs, 16.1 (dibenz[a, h]anthracene)–2,526 (naphthalene) μg cig^{-1} (Lu and Zhu 2007); and PM, 15.6 mg cig^{-1} (Bi et al. 2005). Although numerous studies have reported ETS exposure, observing individual ETS exposure is difficult to quantify because of the simultaneous pollution of the atmosphere by other sources. For example, cooking (Masuda et al. 2020), burning (Bootdee et al. 2016; Dambruoso et al. 2014; Gustafson et al. 2008), road traffic (Harrison et al. 2021), and vehicle exhaust gases (Li et al. 2018) are potential sources of VOCs, PAHs, and PM. Therefore, a method for estimating ETS concentrations that excludes contributions from other pollution sources is required to accurately assess the risk of passive smoking.

Table 1 Information regarding subjects

Gender	Age	Number of people
Male	20–29	10
	30–39	11
	40–49	12
	50–59	13
	60–79	14
Female	20–29	12
	30–39	14
	40–49	15
	50–59	13
	60–79	18
Occupations		
Office staff		65
Engineer		39
Housekeeper		36
Unemployed		30
Service		21
Management		18
Sales		17
Transport		9
Manufacturing		6
Student		6
Transportation		2
Construction		2
Security		2
Others		5

Nicotine is a tobacco-specific ETS compound. Moreover, the nicotine concentration in ETS is 3–18 times that of other tobacco-specific compounds, such as myosmine and 3-ethenylpyridine (Singer et al. 2003). Therefore, nicotine serves as an ideal ETS marker, considering the relatively low ETS concentration associated with passive smoking. The assessment of personal nicotine exposure can facilitate the estimation of ETS exposure. $PM_{2.5}$ is also present at high concentrations in ETS, and smoking status can be confirmed via real-time $PM_{2.5}$ monitoring.

In this study, we aimed to determine the levels of nicotine and $PM_{2.5}$ exposure among passive smokers and non-smokers in Japan. A nicotine passive sampler and PM sensor were used to determine the personal exposure to nicotine and $PM_{2.5}$ for 258 subjects from October to December 2022. The subjects specified the time and location they were exposed to passive smoking. The assessment of passive smoking was conducted using self-report measures. Personal nicotine and $PM_{2.5}$ exposure levels were analyzed in relation to the environmental conditions in which they were exposed to passive smoking. Finally, we estimated the extent to which passive smoking could be converted into active smoking.

Materials and methods

Chemicals

(−)-Nicotine was obtained from FUJIFILM Wako Pure Chemical Corporation (Osaka, Japan). Nicotine-d_3 was obtained from Cambridge Isotope Laboratories Inc. (Tewksbury, MA, USA) and used as an internal standard. Sodium hydrogen sulfate monohydrate (Kanto Chemical Co. Inc., Tokyo, Japan) was used as an adsorbent for the passive sampler. Sodium hydrate (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan), ultrapure water (Millipore Sigma, Burlington, MA, USA), methanol (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan), and acetonitrile (FUJIFILM Wako Pure Chemical Corporation, Osaka, Japan) were used as eluents for cleaning and extraction in liquid chromatography-mass spectrometry (LC-MS/MS).

Passive smoking survey

An internet-based questionnaire was sent to 5,390 individuals, and 258 potential subjects were selected. The subjects were non-smokers who were exposed to passive smoking. Passive smoking was determined based on self-reports. In addition, we ensured that there were no biases regarding sex, location, and occupation (Table 1). Passive nicotine samplers and PM sensors were distributed to the subjects. The subjects wore the nicotine passive samplers and PM

sensors for 24 h and then returned them to us. The subjects specified the time and location they were exposed to passive smoking while wearing the samplers during the 24-h period via self-report measures. The survey was conducted between October and December 2022.

Nicotine passive sampler

A nicotine passive sampler, which we specifically developed to monitor atmospheric particulate nicotine with high sensitivity, was used in this study (Noro et al. 2023). The size of the sampler, including the clip, was 36 × 70 × 30 mm, and its weight was 30 g. The sampler comprised a sodium hydrogen sulfate-impregnated filter and a perforated cover. This sampler could measure the nicotine concentration while minimizing the influence of the wind. Sampling rates of the sampler were $(1.17 \pm 0.05) \times 10^{-6}$ m^3 min^{-1} for both gaseous and particulate nicotine (Noro et al. 2023). After sampling, nicotine was extracted from the filters in the samplers using glass tubes containing 5 mL of a nicotine-d_3 solution (1.00 μg L^{-1}) and ultrasonic irradiation for 10 min. The extracts were centrifuged, and the supernatants were stored in LC vials for LC-MS/MS analysis.

LC-MS/MS apparatus

Nicotine concentrations were determined using an UltiMate 3000 liquid chromatograph (Thermo Fisher Scientific, Inc., Waltham, MA, USA) interfaced with a TSQ Endura triple quadrupole mass spectrometer in the ESI mode. Liquid chromatographic separation was conducted using a cation exchange column (ZORBAX 300-SCX; 2.1 mm × 150 mm, 5 μm) obtained from Agilent Technologies Inc. (Santa Clara, CA, USA), which allowed for a large-volume injection (100 μL) into the column. LC-MS/MS conditions have been described previously (Noro et al. 2023).

PM sensor

$PM_{2.5}$ concentrations were measured using "PM2.5 Monitor Pro," which was acquired from Yaguchi Electric Corp. (Ishinomaki, Miyagi, Japan). This apparatus was originally developed by Ishigaki et al. (Ishigaki et al. 2017) and is not commercially available. The sensor consisted of a laser light-emitting diode, a photodiode sensor, a fan, an amplifier, and a universal serial bus encoder. The size of the sampler was 80 × 40 × 30 mm, and its weight was 67 g. The battery and data logger were built-in, and the data acquisition cycle was six times per minute.

Quality assurance and quality control

Blank samples were extracted using a sodium hydrogen sulfate solution (5 g L^{-1}) containing nicotine-d_3 (1.00 μg L^{-1}), as opposed to using ultrapure water containing nicotine-d_3. They were treated in the same manner as the samples. The nicotine calibration curve was linear over the entire range of standard concentrations (0.01. 0.03, 0.10, 0.30, 1.00, 2.00, and 10.00 μg L^{-1}; coefficient of determination > 0.99). Peaks were identified by comparing the retention times of the samples and the standard when the signal-to-noise ratio exceeded 3 and quantified when the quantification-to-confirmation ion ratio remained within 15% of the theoretical value.

Results and discussion

Nicotine and $PM_{2.5}$ concentrations

Personal nicotine and $PM_{2.5}$ exposure concentrations were obtained for 258 and 194 samples, respectively. The number of $PM_{2.5}$ samples collected was less than 258 because some monitors stopped working during the sampling process.

Personal nicotine exposure concentrations were below the detection limit in 28 of the 258 samples (11%). The ability to observe passive smoking in 89% of the subjects indicated that this sampler was useful for effectively conducting surveys on passive smoke exposure. In contrast, the $PM_{2.5}$ readings on the monitor consistently remained above 0. The measurement range of the monitor extended up to 999 μg m^{-3}. Although there were a few instances where the recorded values exceeded this upper limit, these data points were included in the analysis because of the relatively small number of instances.

The personal exposure distribution was almost log-normal (Fig. 1), which was consistent with previous reports (Wallace 1986). The mean, standard deviation, maximum value, and minimum value of nicotine concentrations were 0.228, 0.600, 6.16, and 0.01 μg m^{-3}, respectively. Its median value was 0.065 μg m^{-3}. No significant difference in nicotine levels was observed among age, sex, and occupation, indicating that any potential bias among the subjects was negligible (Figs. 2 and 3). The atmospheric nicotine concentrations were comparable to those observed in residential and restaurant settings (0.06–37 μg m^{-3}) (Noro et al. 2023). The observed nicotine concentration of 64% in this study was higher than that in non-smoking areas (0.05 μg m^{-3}), implying that passive smoking increased ETS inhalation for non-smoking individuals (IARC 2004).

The mean, standard deviation, maximum value, and minimum value of $PM_{2.5}$ concentration were 11.1, 14.3, 136,

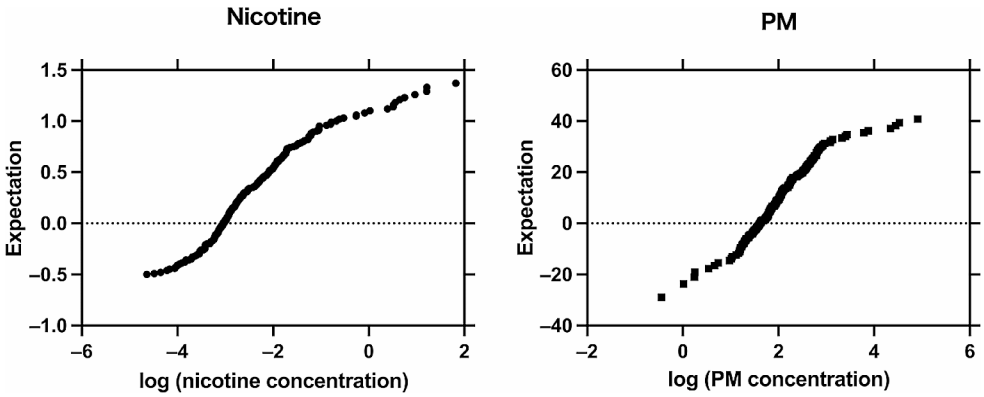

Fig. 1 Log-normal distribution of nicotine (left panel) and $PM_{2.5}$ (right panel) concentrations

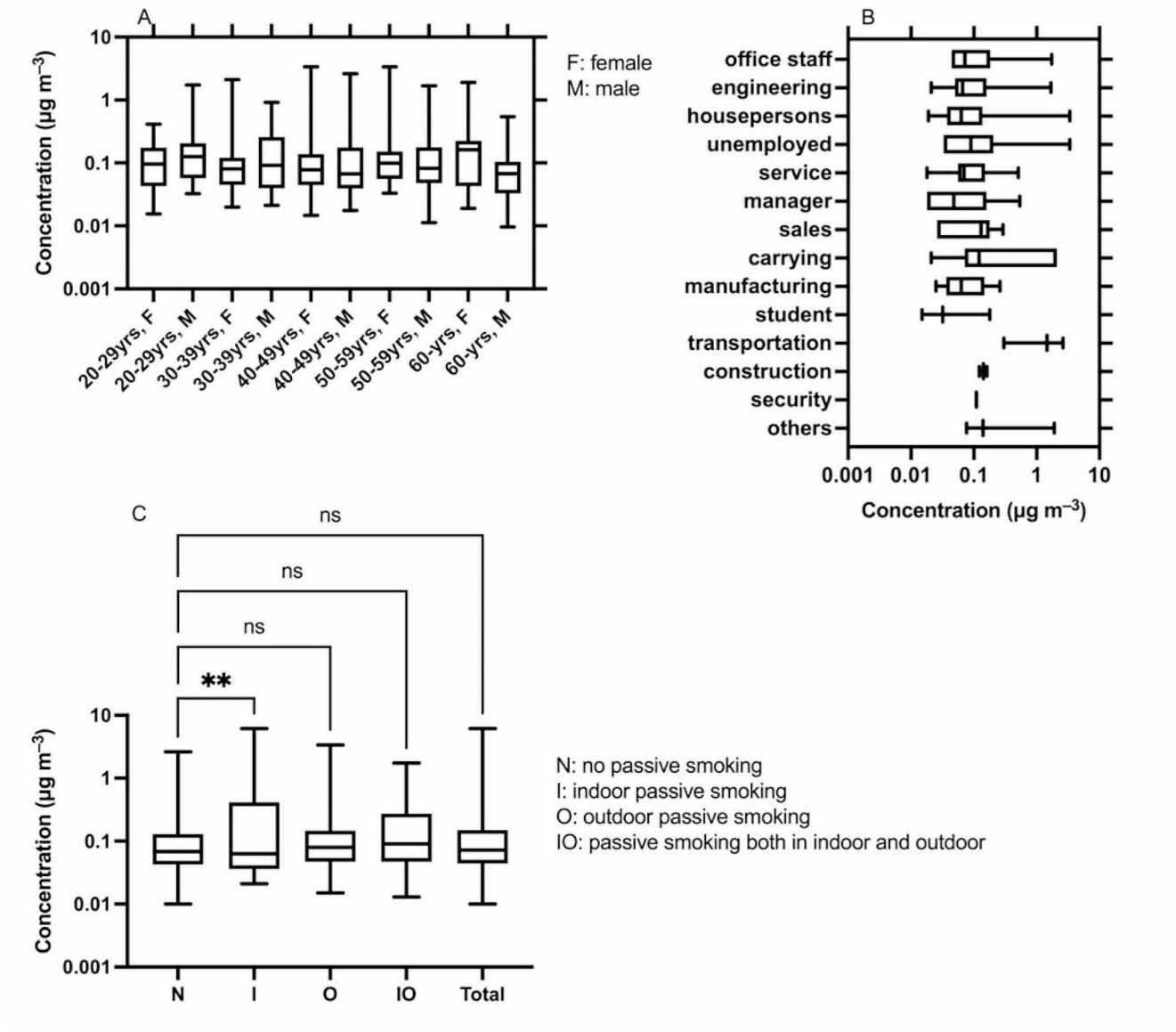

Fig. 2 Nicotine concentrations: (**A**) age and gender, (**B**) occupations, and (**C**) conditions of passive smoking. **: $p < 0.005$, ns: not significant

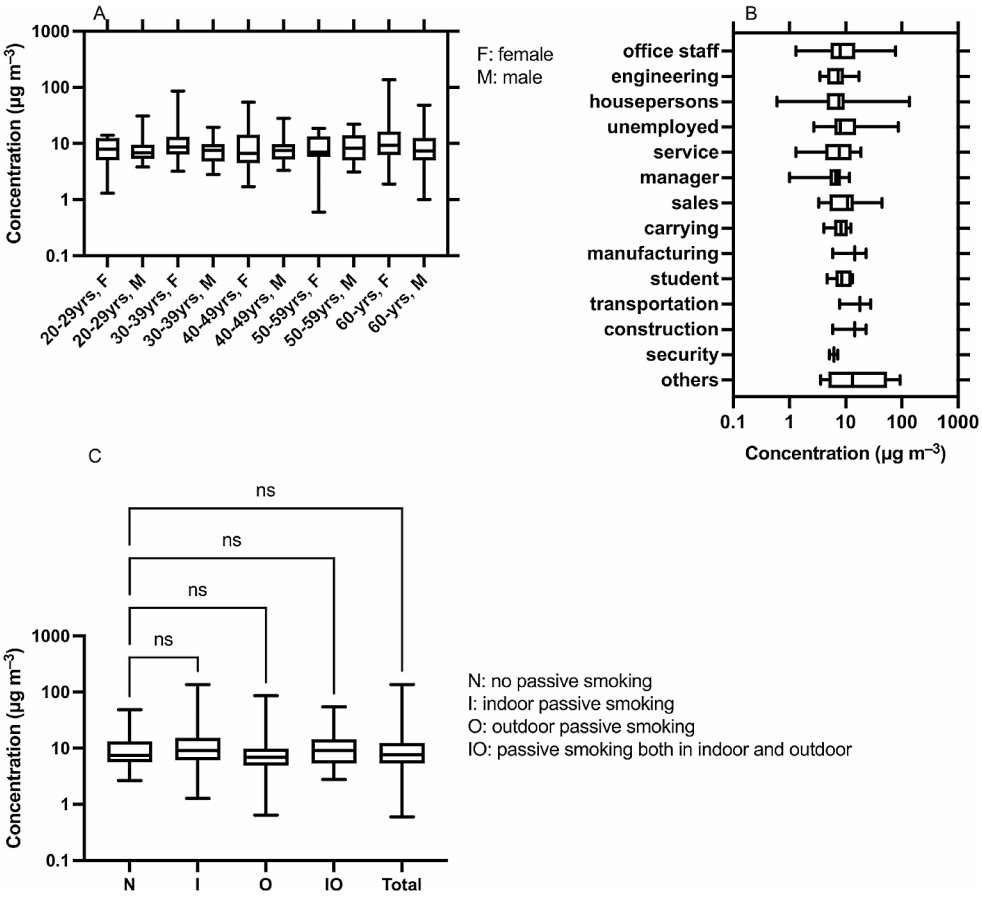

Fig. 3 Particulate matter concentrations: (**A**) age and gender, (**B**) occupations, and (**C**) conditions of passive smoking. ns: not significant

and 0.64 μg m^{-3}, respectively. Its median value was 7.5 μg m^{-3}. No significant differences in $PM_{2.5}$ concentrations were observed among age, sex, and occupation, indicating that any potential bias among the subjects was negligible (Figs. 2 and 3).

Based on the administered questionnaire, the subjects were categorized into four groups: individuals who were not exposed to passive smoke during the measurement period (N), individuals who were exposed to passive smoke indoors (I), individuals who were exposed to passive smoke outdoors (O), and individuals who were exposed to passive smoke both outdoors and indoors (IO). Nicotine concentrations in Group I were significantly higher than those in Group N (Fig. 2), but there was no significant difference between $PM_{2.5}$ concentrations in Groups I and N (Fig. 3). The results suggest that indoor exposure to passive smoking significantly increases ETS inhalation, whereas $PM_{2.5}$ is not affected by indoor passive smoking. To investigate indoor exposure in more detail, we investigated whether exposure occurred at home. There were no significant differences in nicotine and $PM_{2.5}$ concentrations between Group N and Groups O and IO (Figs. 2 and 3).

Domestic passive smoking

A total of 23 participants reported that their cohabiting partner was a smoker and that smoking occurred within their shared residence at the time of the survey. A comparison was made between the nicotine or $PM_{2.5}$ personal exposure concentrations with and without passive smoking at home (domestic versus non-domestic, respectively) (Fig. 4). Nicotine non-domestic passive smoking had a median value of 0.068 μg m^{-3}, whereas that of domestic passive smoking was 0.136 μg m^{-3}, which was twice that of nicotine non-domestic passive smoking. There was a significant difference in personal nicotine exposure levels between subjects who were exposed to secondhand smoke at home and those who were not. In contrast, there was no significant difference in $PM_{2.5}$ personal exposure concentrations between subjects exposed to domestic passive smoking and those exposed to non-domestic passive smoking. The median value of $PM_{2.5}$ non-domestic passive smoking was 7.1 μg m^{-3}, whereas that of domestic passive smoking was 8.3 μg m^{-3}, which was only 1.2 times higher than that of non-domestic passive smoking. Secondhand tobacco smoke simultaneously contains large amounts of nicotine and $PM_{2.5}$. The reason why $PM_{2.5}$ concentrations did not increase significantly as a

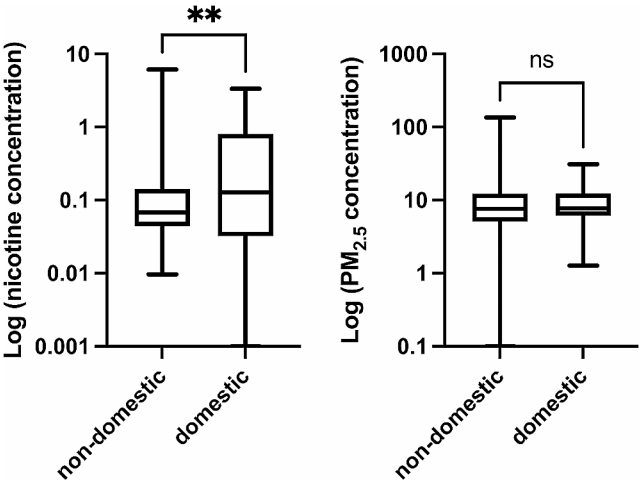

Fig. 4 Nicotine (left panel) and $PM_{2.5}$ (right panel) concentrations for individuals exposed to domestic and non-domestic passive smoking. **: $p < 0.005$, ns: not significant

result of smoking at home is thought to be because smokers have grown more considerate of non-smokers, such as by smoking near ventilation fans or balconies. The significantly higher personal nicotine exposure levels in homes may be because of exposure to residual nicotine on the surfaces of indoor materials, such as walls. High concentrations of nicotine are occasionally detected in rooms that were previously used for smoking because of the gradual vaporization of nicotine onto indoor materials.

Environmental tobacco smoke (ETS) inhalation

The nicotine intake of non-smokers was calculated as follows:

$$DI_n = C_n V \quad (1)$$

where DI_n (μg d^{-1}) represents the daily nicotine intake and V (m^3 d^{-1}) denotes the inhalation rate. V was assumed to be 17.3 m^3 d^{-1} in this study (USEPA 2011). In addition, the nicotine emission from smoking was 1,660 μg cig^{-1} (Singer et al. 2003). The mean DI_n value for non-smokers exposed to indoor passive smoking was 3.9 μg; therefore, passive smoking was equivalent to smoking 2.4×10^{-3} cigarettes per day.

Comparison between the $PM_{2.5}$ concentrations of passive smoking and non-smoking indoors in domestic settings

Not only was there no significant difference observed between the domestic and non-domestic $PM_{2.5}$ exposure concentrations, but both median $PM_{2.5}$ concentrations in those exposed to domestic (8.3 μg m^{-3}) and non-domestic passive smoking (7.1 μg m^{-3}) were lower than the standard value of indoor $PM_{2.5}$ concentration (12 μg m^{-3}) (USEPA 2023).

Conclusion

The nicotine passive sampler and PM monitor used in this study enabled quantitative measurement of the amount of passive smoke at very low concentrations. The results of a passive smoking survey of a total of 258 people revealed that median nicotine and $PM_{2.5}$ concentrations were 0.065 and 7.5 μg m^{-3}, respectively. In Japan, the Health Promotion Act was enforced in April 2020. Consequently, smoking is substantially restricted in public places and also prohibited in universities. Moreover, indoor and outdoor smoking is regulated. The low levels of passive smoke in this study are thought to be the result of the effectiveness of various regulations. This consciousness is also expanding within households, and one possible explanation is that smokers have become more considerate of non-smokers by smoking near ventilation fans or on balconies. Consequently, the nicotine exposure from domestic passive smoking was only twice that from non-domestic passive smoking. Furthermore, no significant difference was observed between the levels of $PM_{2.5}$ exposure from passive smoking in domestic and non-domestic settings. Furthermore, it was suggested that passive smoking was equivalent to the act of smoking 2.4×10^{-3} cigarettes per day.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Saria Hoshino, Kazushi Noro, Miyu Moriya and Ayana, Komatsu. The first draft of the manuscript was written by Saria Hoshino and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analysed during the current study are not publicly available due to privacy policy but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate This survey was approved by the Ethics Committee of the University of Shizuoka (code: 2–41). Informed consent to participate in the study were obtained from all participants.

Consent for publication Consent to publish was obtained from all par-

ticipants.

Competing interests Dr. Amagai received the scholarship funding from Japan Tobacco Inc.

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