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Risk assessment and estimation of controlling safe distance for exposure to particulate matter from outdoor secondhand tobacco smoke

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Exposure to secondhand smoke (SHS), and its intake through inhalation, is a major reason for premature death. Therefore, it is essential to determine safe distances from the smoking source to control passive exposure to tobacco smoke by carrying out appropriate risk assessments. In this study, we investigated the emission and diffusion of particulate matter (PM_{10} and $PM_{2.5}$), along with black carbon, from smoking different kinds of cigarettes, including conventional cigarettes, heating e-cigarettes, and liquid e-cigarettes, using computational fluid dynamics (CFD) analysis. The results were used to evaluate the risk of passive exposure to PM_{10} and $PM_{2.5}$ at different distances from the smoker for the general population and 6–10-year-old children. Results of the risk analysis were compared by considering the accumulated mortality ratio caused by cancer, and circulatory and respiratory systems disorders as the baseline risk for these two population groups. Results show that normalized emitted aerosol from vaping liquid e-cigarettes is higher than when other types of cigarettes are used. We also detected the emission of black carbon, which has a statistically significant correlation with the emission of particulate matter. Our risk assessment analysis suggests a safe distance of 10 m from smokers for the general population as well as a greater distance for children.

Keywords CFD analysis · Health risk assessment · Particulate matter emission · Safe distance for tobacco smoke exposure · Secondhand smoke exposure

Smoking has broad and serious environmental effects, which may not only affect the smoker. Passive exposure to environmental tobacco smoke (ETS) through inhalation of tobacco smoke, either from burning tobacco or exhalation of a smoker, is known as exposure to secondhand smoke (SHS). SHS is known as the reason for nearly 1% of global mortality (Torres et al. 2018; Yang et al. 2022a).

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Smoking can also emit a high amount of particulates including PM_{10} and $PM_{2.5}$. Studies conducted on the level of particulate matter in the smoke of different brands of cigarettes indicate a notably high emission of particulates with an aerodynamic diameter of less than 1 µm ($PM_{1.0}$) (Kant et al. 2016; Braun et al. 2019a, b). To control and prevent SHS exposure, it is essential to understand the dynamic aspects of emitted particles from tobacco smoke and the vapor of vaping products in the air. In this regard, using computational fluid dynamics (CFD) tools is common. Studies conducted by Al-Sarraf et al. (2015) and Wang et al. (2019) are valuable examples of using CFD for modeling the diffusion of cigarette smoke in a specified environment.

Nevertheless, such studies are conducted for indoor smoking cases and knowledge on modeling diffusion of emitted particulate matter from outdoor smoking or vaporing remains limited. Kaufman et al. (2011) measured a real-time exposure to particulate matter smaller than 2.5 µm in aerodynamic diameter ($PM_{2.5}$) at the entrance of public office buildings up to approximately 9 m away from the source of smoking. Results show that smoking can significantly increase the level of $PM_{2.5}$, up to 496 µg/m^3, compared to the background concentration. Hwang and Lee (2014) used a "smoking doll" as a cigarette smoke emitter and measured the changes in the level of ambient $PM_{2.5}$ at four different distances (1, 3, 6, and 9 m) from the smoking source. Although the smoking process was not conducted by a real smoker, results indicated that smoking cigarettes could affect the air quality at 9 m away from the source of the tobacco smoke. Although these conducted surveys are very valuable in supporting smoke-free policies, significant studies conducted by real smokers smoking different types of cigarettes, along with assessing exposure and risk to SHS, are left behind.

In the Republic of Korea, indoor smoking in public places is forbidden under the National Health Promotion Act, and smoking outdoors is only allowed in designated smoking areas at a distance of no less than 10 m from the entrance of medical institutions, schools, kindergartens, daycare centers, and residual buildings (Ministry of Health and Welfare 2012). However, exposure to the emitted particulate matter through SHS can also depend on the smoker's smoking behavior. Yang et al. (2021) reported that Korean smokers inhale an average amount of 1500 ml of smoke per cigarette, which is twice higher as that of Americans and Japanese. Considering an increase in the use of heated tobacco products and liquid e-cigarettes, studies on particulate matter emission through these products using real smokers as subjects as well as reviewing the definition of safe distance from a smoker to prevent SHS are necessary.

Accordingly, this study primarily aims to estimate safe distance smoking to avoid exposure to aerosol emitted by outdoor smoking based on diffusion of particulate matter and risk assessment. In particular, for three types of tobacco products including conventional cigarettes, heating e-cigarettes, and liquid e-cigarettes, we pursue (1) the investigation of the emission amount and outdoor diffusion of aerosols by measuring particulate matter air levels, (2) analysis of the worst case of outdoor diffusion of emitted particulate matter under a steady state using CFD modeling, and (3) use of data obtained from the CFD model to assess the risk of exposure to particulate matter emitted from outdoor smoking and estimating safe distances for the general population and children.

Subject recruitment

Subject recruitment was aimed at regular male smokers aged 20–40 years old. The nationwide recruitment was executed by Macromill Embrain Co. (Seoul, Rep. of Korea) using the self-reporting habit survey design by Yang et al. (2022b). The survey includes self-estimation of total smoking time and smoke inhalation depth.

The survey was distributed among a nationwide pool of 1,330,000 smokers through email, short messages, and phone calls. Among them, 300 people who met the gender and age criteria, and who reported smoking more than 2 min for each smoking event and inhaling the smoke down to their lungs, were selected. Among the 300 people, 100 who smoke only one type of product among conventional cigarettes, heating e-cigarettes, and liquid e-cigarettes were selected. Those who described themselves as a consumer of smoking pipes, cigars, handmade cigarettes, or chewing tobacco; receiver of nicotine replacement therapy, or diagnosed with any mental disorders or liver, kidney, and smoking-related diseases were excluded. Finally, for every three types of cigarette consumption, 10 people (totaling 30 smokers) were invited to participate in the "aerosol emission investigation." Each subject was assigned a unique identification code. All subjects were asked to bring their cigarettes, including vaping apparatus and e-juice, and proceed to smoke and vape in their usual manner.

All subjects were compensated and were asked to sign a letter of consent that included a comprehensive explanation of the objectives of the research, data processing, publications, and privacy protection policies. The Institutional Review Board (IRB) of Severance Hospital of the Yonsei University Health System approved the study design (approval number: 4–2021-1269).

Aerosol emission investigation

Experiment procedure

To investigate the amount of aerosol emitted in one event of smoking different types of cigarettes (conventional cigarette, heating e-cigarette, and liquid e-cigarette), an 18.4-m^3 spherical cap-shaped chamber was designed and constructed on the rooftop of the Yonsei Medical Research Center for indoor smoking (Fig. 1). During each smoking experiment, all openings of the chamber along with the natural ventilation system were tightly closed. Under this condition, the ventilation ratio of the structure was measured to be approximately 0.0027 per min following the ASTM E741 standard (ASTM 2017) and considering the reduction of CO_2 over time using the Testo-400 universal indoor air quality instrument (Testo Korea Ltd., Seoul, Rep. of Korea).

In each experiment, the smoker was asked to sit on a chair and smoke (or vape) the cigarettes in his usual manner. The smoker's seat was fixed to have a distance of 2 m away from the measurement apparatus, including one set of Optical Particle Counter (OPC) aerosol spectrometer model GRIMM11-D, made by DURAG Group's GRIMM Aerosol Technik Co. (Ainring, Germany), and one set of AETHLABS microAeth® model MA300 (San Francisco, CA, USA). The GRIMM11-D apparatus underwent regular annual maintenance and calibration service provided directly by DURAG Group's GRIMM Aerosol Technik Co. Flow and optical calibration for the microAeth® instrument was done directly by AETHLABS.

The GRIMM11-D apparatus, which can determine the air levels of particulates in a size range of 0.265 to 34 µm, was used to measure total suspended particulates (TSP), PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ with 6-s time resolution and 1.2 l/min airflows. The apparatus has a self-heating feature that can reduce the effect of the relative humidity of the air on the measurement of particulates (Masic et al. 2020; Wu et al. 2022).

The emission of black carbon (BC) was measured using the microAeth® instrument at 880-nm wavelength with 1-s time resolution. The measurement resolution was 0.001 µg-BC/m^3 under a 150 ml/min flow rate. The limit of detection was 30 ng-BC/m^3.

Background air quality was measured for 10 min before each experiment. After that, the smoker started to smoke. Smokers of conventional cigarettes and heating e-cigarettes were asked to smoke one cigarette per event. The smokers of liquid e-cigarettes were asked to smoke no longer than their usual smoking time per event. After smoking, the smoker was asked to stay for 10 min to record the steady-state condition of the indoor air quality. After each smoking event, the structure was ventilated using a commercial-grade air circulator to reduce the indoor air quality indicators down to their background concentration.

For the smokers of liquid e-cigarettes, the weight of their e-cigarette cartridges was measured before and after each smoking event. The difference between these amounts was considered as the mass of vapored e-juice. The background air quality measurement time, smoking time, and steady-state air quality measurement time were recorded and controlled by an operator. For each smoker, the experiment was triplicated at 20–30-min intervals.

Raw data analysis

Raw data were used to calculate the emission amount of pollutants from different types of cigarettes following Eq. 1, which is derived from a model suggested by the U.S. Department of Health and Human Services (Repace et al. 1998) and presented in the RIVM report 320104004/2005 of the National Institute for Public Health and the Environment (Delmaar et al. 2006). In this equation, C_{TWA} is the time-weighted average of the concentration of the pollutant in the air (µg/m^3), C_t is the concentration of the pollutant in the air at the moment t (µg/m^3), $C_{Background}$ is the background concentration of the pollutant in the air (µg/m^3), Δt is measurement interval (min), C_{cig} is the emission amount of pollutant

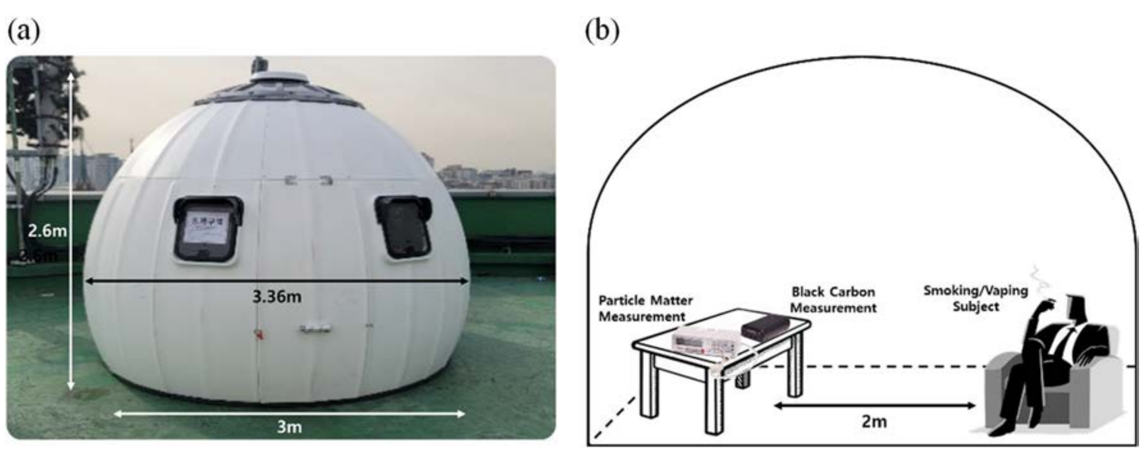

Fig. 1 **a** View of the structure constructed for aerosol emission investigation, **b** a schematic view of the experiment settings

from cigarette smoke or vape (µg/cig), V is the volume of the experiment venue (18.4 m^3), n is the ventilation ratio of the experiment venue (0.0027 per min), t_r is the smoking time (min), and t_e is the total experiment time from the moment that smoking or vaping begins until the beginning of ventilation.

$$C_{TWA} = \frac{\sum_{t=0}^{t=t_e} (C_t - C_{Background}) \times \Delta t}{t_e} = \frac{C_{Cig}}{V \times n \times t_r} \times (1 - e^{-nt_r}) \times \left(e^{-n(t_e - t_r)}\right) \quad (1)$$

Accordingly, for conventional cigarettes and heating e-cigarettes, the C_{cig} was calculated using Eq. 2.

$$C_{cig} = \frac{C_{TWA} \times V \times n \times t_r}{(1 - e^{-nt_r}) \times \left(e^{-n(t_e - t_r)}\right)} \quad (2)$$

For liquid e-cigarettes, the variable C_{cig} was corrected and normalized based on the amount of vaped e-juice following Eq. 3. In this equation, $m_{e\text{-juice}}$ is the mass of consumed e-juice at each vaping event (g).

$$C_{cig} = \frac{C_{TWA} \times V \times n \times t_r}{m_{e-juice} \times (1 - e^{-nt_r}) \times \left(e^{-n(t_e - t_r)}\right)} \quad (3)$$

Following the instructions provided in the RIVM report 090013003/2014 of the National Institute for Public Health and the Environment, we considered the 75^{th} percentile value of C_{cig} for developing CFD and risk assessment procedures (Te Biesebeek et al. 2014).

Outdoor aerosol diffusion investigation

To investigate the diffusion of aerosol in one event of smoking or vaping different types of cigarettes, an outdoor smoking and vaping experiment was designed to be run at the amphitheater of Yonsei University, which is located far from nearby urban streets with restricted vehicular traffic. Considering the results of the aerosol emission investigation, three participants, who through their smoking or vaping process highest emission of pollutants recorded, were invited per each cigarette type to participate in the aerosol diffusion investigation.

Figure 2 presents the setting used in this experiment. Smoking or vaping subjects were located on a certain spot beside a wall to limit the effect of natural wind. Measurement desks were installed at < 1-, 3-, 5-, and 10-m distances from the subject. The height of the measurement desks was adjusted to approximate the level of the subjects' faces. At all measurement spots, the air level of total suspended particles (TSP), PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ was measured.

At a 3-m distance from the subject, the air level of black carbon (BC) was measured. The measurement instrument was the same as the ones utilized in the aerosol emission investigation. Before the experiment begins, the background air level of all pollutants was measured for 10 min, and the measurement process continued up to 3–5 min after the last smoker finished smoking. The experiment was conducted under light air with an average wind speed of 0.9 m/s. The average values of air temperature and humidity were 2.7℃ and 38.1% respectively. A commercial-grade fan was placed 1 m behind the subject to produce wind at a speed of 1.8 m/s. The experiment was executed with one, two, and three smokers with and without wind.

Worst case analysis for outdoor particulate matter diffusion using CFD

In this research, analyses were performed using Star-CCM+, a commercial software developed by Siemens. Star-CCM+ is suitable for analyzing physical problems based on the finite volume method (Sugahara et al. 2017; Kim et al. 2020). The analysis assumed incompressible turbulent flows and used the Reynolds-averaged Navier–Stokes (RANS) Turbulence model (Jeanjean et al. 2015; Hong et al. 2018; Mohammadi and Calautit 2021). The Boussinesq model was used to simulate the buoyancy effect of outdoor conditions. A realizable K-epsilon model was used as the turbulence model.

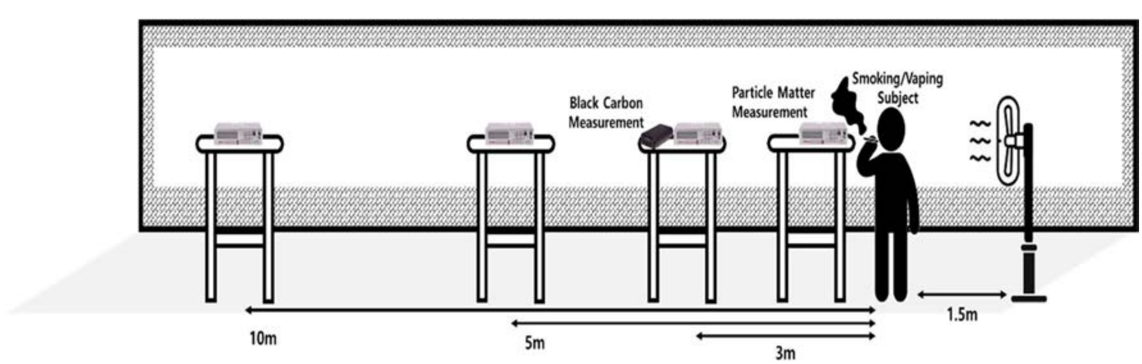

Fig. 2 Experiment setup for aerosol diffusion investigation

A domain of 100 m*200 m*50 m was created to model an outdoor environment, while human models were made for the simulation of one and three cigarette smokers with a height of 175 cm. Unstructured mesh, specifically Polyhydral Mesher, was used with a mesh number of 2,500,000. An outer environment mesh measuring above 20 m in height was formed loosely, while a dense network was formed for people and the surrounding environment below 20 m in height. Cigarette smoke was set to be released by the human model's exhalation with a flow rate of 8.04 m/s and a temperature of 45 °C, as mentioned in prior studies such as the one conducted by Kuga et al. (2018). The Eulerian multiphase model (passive scalar) was used to analyze the cigarette smoke's PM (particulate matter), which flows in the same manner as the air. The wind speed was set to 1.8 m/s, considering the average wind speed distribution from the ground (where the wind speed is 0 m/s) to the height of 10 m (where the wind speed is approximately 2.2 m/s) in Seoul. There were no surrounding obstacles in this model. The applied CFD model and boundary conditions are presented in Fig. 3 and Table 1, respectively.

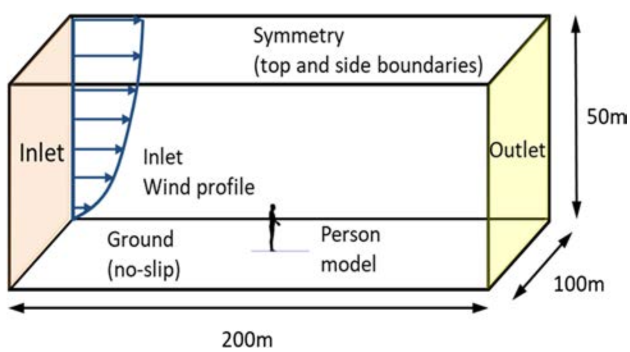

Fig. 3 Applied CFD model and conditions

Risk assessment of exposure to emitted particulate matter at different distances from the smoker

Nationwide subjects of SHS exposure

Similar to the study conducted by Yang et al. (2022a), datasets of the Seventh Korea National Health and Nutrition Examination Survey (KNHANES VII) were used for selecting nationwide subjects of SHS exposure in South Korea. The survey was conducted for three years (2016–2018) by the Korea Disease Control and Prevention Agency (2020) for approximately 24,300 subjects, and the results are open-accessed. All datasets included results of self-reporting smoking status along with urinal cotinine and creatinine for subjects aged 6 and above. Urinal cotinine has been considered a biomarker of exposure to tobacco smoke, and its levels have been corrected by diving into the urinary concentration of creatinine.

First, we excluded subjects who reported being smokers or ex-smokers, along with those who did not have valid data regarding age and body weight. Then among all remaining non-smoker subjects, those who reported themselves as SHS exposure subjects were selected ($n=2999$). Benowitz et al. (2016) suggested a lower cut-point of 0.25 µg/l for significant SHS exposure, while Kim (2016) suggested a cutoff of 100 µg/g-creatinine for urinary cotinine to distinguish smokers and non-smokers. Therefore, we narrowed the subject selection to those whose urinary cotinine is within the mentioned range ($n=2220$). These subjects, whose SHS exposure condition could be confirmed by both self-report survey and their urinary level of cotinine, accounted for 74% of the total SHS exposure group. This value has been considered as the exposure frequency ratio (EF_{Ratio}), which will be used for exposure concentration and risk assessment.

Table 1 Boundary conditions of the developed CFD model

Parameter	Boundary conditions	Unit	Value (unit)
Outdoor wind velocity†	Velocity inlet (magnitude)	m/s	1.8
Outdoor temperature	Wall (temperature)	°C	22
Heat from person	Wall (Heat flux)	W/m^2	60
Exhale velocity	Velocity inlet (magnitude)	m/s	8.04
Exhale smoke temperature	Velocity inlet (temperature)	°C	45
Emission rate of PM_{10} (conventional cigarettes)‡	Velocity inlet (emission source)	µg/s	94.21
Emission rate of PM_{10} (heating e-cigarettes)‡	Velocity inlet (emission source)	µg/s	14.83
Emission Rate of PM_{10} (liquid e-cigarettes)‡	Velocity inlet (emission source)	µg/s	1311.70
Emission Rate of $PM_{2.5}$ (conventional cigarettes)‡	Velocity inlet (emission source)	µg/s	94.83
Emission Rate of $PM_{2.5}$ (heating e-cigarettes)‡	Velocity inlet (emission source)	µg/s	15.06
Emission Rate of $PM_{2.5}$ (liquid e-cigarettes)‡	Velocity inlet (emission source)	µg/s	1278.86

† Average value of the wind speed profile in Seoul, considering the 0 m/s on the ground up to 2.2 m/s at 10-m height

‡Values are based on the aerosol emission investigation results (75th percentile)

Since the major objective of this study is to investigate outdoor SHS exposure, we excluded those who are living with at least one smoker in their family along with subjects aged below 19 with smoking experience. After this process, the total number of nationwide subjects with SHS exposure was 1129. Among them, 18 subjects were children with ages ranging from 6 to 10 years old, and 966 subjects were adults with an age range of 19 years old and above. For these subjects, we calculated the exposure of equivalent smoked cigarettes per day as performed by Yang et al. (2022a). Table 2 summarizes the results of calculated equivalent CPDs for nationwide subjects of SHS exposure.

Exposure concentration and risk assessment

The inhalation exposure concentration was calculated using Eq. 4 (Yang et al. 2022a; Gilardi et al. 2023). In this equation, $C_{\text{PM-d}}$ is the exposure concentration of PM_{10} or $PM_{2.5}$ at the distance of d from the smoker (μg/m^3). $C_{\text{Cig.PM-d}}$ is the emitted concentration of pollutants from one cigarette, which is calculated using the CFD model and adjusted as multiplied by the ratio between the measured pollutants at < 1-m away from the smoker in the outdoor aerosol diffusion investigation and the one estimated by the CFD model (μg/m^3-cig). The EF_{Ratio} is the exposure frequency ratio, which has a value of 0.74 as explained earlier.

$$C_{PM-d} = C_{Cig.PM-d} \times CPD \times EF_{Ratio} \quad (4)$$

Accordingly, the risk of exposure to PM_{10} and $PM_{2.5}$ at different distances from the smoker is estimated by Eq. 5, where UR is the unit risk for mortality because of short-term exposure to each pollutant.

$$Risk = C_{PM-d} \times UR \quad (5)$$

Some studies were conducted to estimate the UR for mortality because of short-term exposure to PM_{10} and $PM_{2.5}$ in South Korea. Considering the study location, duration, and procedure, we used the URs suggested by Bae (2014), which are 0.0004 per μg/m^3 and 0.0009 per μg/m^3 for PM_{10} and $PM_{2.5}$, respectively, through a study duration of 5 years (2006–2010) in Seoul. Details are presented in Table 3.

Safe distance determination

To determine the safe distance from a smoker to control the risk of exposure to PM_{10} and $PM_{2.5}$ emitted from different types of cigarettes, defining a baseline risk is required. As presented in Table 4, we derived the latest nationwide ratio of mortality caused by cancer, circulatory, and respiratory systems disorders from the Korean Statistical Information Service (KOSIS), which was related to data collection executed in 2020 (Korean Statistical Information Service (KOSIS) 2022). The sum of these risks for each age range is considered the baseline risk. The safe distance from the smoker is considered to be where the calculated risk of exposure to PM_{10} and $PM_{2.5}$ is below the baseline risk.

Data analysis

Where applicable, the nonparametric method of the Mann–Whitney U test or Kruskal–Wallis H test was used to analyze the significance of differences in parameters. Spearman's correlation coefficient (ρ) was calculated to analyze the associations between parameters. The significance level was considered to be $\alpha = 0.05$. All statistical analyses were performed using IBM® SPSS® Statistics version 25 (IBM Company, Armonk, NY, USA). In the boxplots created using this software, the outliers are identified as the data

Table 2 Results of calculated equivalent CPDs for nationwide subjects of SHS exposure (Yang et al. 2022a)

Type of cigarette	Nicotine Composition (mg/cig)	Equivalent CPD: Mean ± SD (min–max)		
		All subjects (n = 1129)	Children (n = 18)	Adults (n = 966)
Conventional cigarettes	0.5	0.03 ± 0.14 (0.0009–2.13)	0.005 ± 0.005 (0.0009–0.02)	0.03 ± 0.15 (0.0013–2.13)
Heating e-cigarettes	0.3	0.05 ± 0.22 (0.001–3.34)	0.008 ± 0.007 (0.001–0.03)	0.05 ± 0.24 (0.002–3.34)
Liquid e-cigarettes	1.9	0.007 ± 0.03 (0.0002–0.53)	0.001 ± 0.001 (0.0002–0.005)	0.008 ± 0.04 (0.0003–0.53)

Table 3 Unit risk for mortality because of short-term exposure to PM_{10} and $PM_{2.5}$ in South Korea

Pollutant	Age range	Relative risk (per 10 μg/m^3)	95% confidence interval (per 10 μg/m^3)	Unit risk (per μg/m^3)	Reference
PM_{10}	All ages	1.004	1.002 – 1.006	0.0004	(Bae 2014)
$PM_{2.5}$		1.009	1.006 – 1.013	0.0009	

Table 4 Korean nationwide mortality ratio caused by cancer, circulatory, and respiratory systems disorders, and the related baseline risk

Age range	Mortality Ratio				Remarks
	Cancer	Circulatory system disorder	Respiratory system disorder	Baseline risk	
6–10 years old	$1.30*10^{-5}$	$7.00*10^{-6}$	$1.00*10^{-6}$	$2*10^{-5}$	
20–59 years old	$4.63*10^{-4}$	$2.06*10^{-4}$	$3.99*10^{-5}$	$7*10^{-4}$	Applied to the general subjects

with values between 1.5 and 3 times the interquartile ranges, which are indicated by a circle and an asterisk, respectively.

Results of aerosol emission investigation

Table 5 presents the results of the emitted amount of pollutants per cigarette through Eqs. 2 and 3, along with the characteristics of smokers who participated in the aerosol emission investigation. The average age of all participants was 35.9 ± 8.7 years old. On average, people of younger age vaped liquid e-cigarettes, while participants with higher average age smoked conventional cigarettes. Nicotine and tar compositions for conventional cigarettes were considered to be equal to their nominal nicotine and tar yield, which is written on the label of the cigarette box. For heating e-cigarettes, however, the nicotine and tar composition was not written on the box of any brands of the cigarette. In this regard, we used the results of direct nicotine composition measurement for each product, which was presented by the Ministry of Food and Drug Safety (2018).

For liquid e-cigarettes, the nicotine concentration in e-juice (in mg/ml) was derived from the labeled product information. This was then normalized with the unit of mg/cig by considering the average amount of consumed e-juice and its density. The density of each e-juice differs based on its composition. Results of a study presented by Soulet et al. (2019) suggest that the density of commercial e-juices is lower than 1.26 g/ml. Accordingly, we considered the average density of e-juices to be approximately 1 g/ml. Under these circumstances, the nicotine composition of liquid e-cigarettes was estimated to be approximately 5 times higher than that of conventional cigarettes or heating e-cigarettes.

Figure 4 presents the average measured air level of pollutants when smoking and vaping different types of cigarettes. For each pollutant, the measured level in the air was significantly different among the type of cigarettes ($p < 0.001$). For all types of cigarettes, $PM_{1.0}$ had the major components of particulate matter (64–94%).

Our results show that the highest average level of PM_{10} and $PM_{2.5}$ in air has been recorded for liquid e-cigarette vaping events (PM_{10} = 2558 μg/m^3 and $PM_{2.5}$ = 2437 μg/m^3) followed by conventional cigarette (PM_{10} = 708 μg/m^3 and $PM_{2.5}$ = 692 μg/m^3) and heating e-cigarette (PM_{10} = 180 μg/m^3 and $PM_{2.5}$ = 167 μg/m^3) smoking events. The average amount of black carbon in the air was the highest during conventional cigarette smoking (6.99 μg/m^3), followed by liquid e-cigarettes (3.88 μg/m^3). These results are consistent with the findings of Savdie et al. (2020).

Association analysis of the results also shows a positive, strong, and statistically significant correlation between the emission of black carbon with TSP ($\rho = 0.740$, $p < 0.001$), PM_{10} ($\rho = 0.744$, $p < 0.001$), $PM_{2.5}$ ($\rho = 0.748$, $p < 0.001$), and $PM_{1.0}$ ($\rho = 0.764$, $p < 0.001$).

Following Eq. 3, for liquid e-cigarettes, the emission amount was adjusted to the amount of vapored e-juice, with the equivalent unit of μg/g e-juice. Results of the 75th percentile for the amount of emission have been used for developing the outdoor particulate matter diffusion analysis using CFD.

Results of outdoor aerosol diffusion investigation

Figure 5 presents the ratio of air level for diffused particulate matter emitted from smoking or vaping by three people under wind condition at different distances from the smoking or vaping source compared to the air level measured at < 1 m from the smoking or vaping source. Results yield an approximate diffusion ratio range of 0.2–10% at 10 m away from the smokers. Similar results were observed using other measurement conditions.

Figure S1 presents the changes in particle number concentration for $PM_{1.0}$ with time and distance from the source of smoking or vaping. Similar trends were observed for the results of both particle number and mass concentrations related to PM_{10} and $PM_{2.5}$. Results indicate that up to a distance of 10 m away from the source of smoking, for all types of smoking or vaping products, particulate matter concentration increases. This is regardless of wind conditions and the number of smokers, and the increase is attributed to the aerosols emitted from smoking and vaping.

Table 5 Smoking characteristics and pollutants emission during smoking or vaping different types of cigarettes

Type of cigarette	Smoking characteristics Mean ± SD (min–max)	Pollutant	Amount of emission (µg/cig)					
			n	Mean ± SD	p50th	p75th	p95th	Range (min–max)
Conventional cigarette	Smokers' age (years) [*n* = 10] 40.9 ± 7.3 (28 – 49)	Total suspended particulates	30	2388 ± 2134	2003	2992	7890	126 – 9039
	Nicotine composition (mg/cig) [*n* = 10] 0.39 ± 0.23 (0.1 – 0.7)	PM_{10}	30	2332 ± 2046	2015	2988	7483	88 – 8153
	Smoking time (min) [*n* = 30] 3.73 ± 0.87 (2.00 – 5.00)	$PM_{2.5}$	30	2407 ± 2043	2131	3126	7498	149 – 8176
		$PM_{1.0}$	30	2355 ± 1981	2070	3100	7315	162 – 7869
		Black carbon	9	10.3 ± 8.80	7.60	11.41	32.3	3.79 – 32.3
Heating e-cigarette	Smokers' age (years) [*n* = 10] 37.2 ± 7.7 (27 – 49)	Total suspended particulates	30	12,163 ± 2879	12,035	14,906	15,881	4891 – 16,476
	Nicotine composition (mg/cig) [*n* = 10] 0.34 ± 0.18 (0.1 – 0.5)	PM_{10}	30	12,170 ± 2731	12,127	14,601	15,579	4949 – 15,756
	Smoking time (min) [*n* = 30] 2.67 ± 0.76 (2.00 – 5.00)	$PM_{2.5}$	30	12,228 ± 2708	12,220	14,573	15,651	4948 – 15,677
		$PM_{1.0}$	30	12,044 ± 2636	12,025	14,415	15,380	4892 – 15,461
		Black carbon	27	85.8 ± 23.9	79.7	98.8	129.0	48.9 – 140.2
Liquid e-cigarette	Smokers' age (years) [*n* = 10] 29.6 ± 7.4 (22 – 46)	Total suspended particulates	30	176,927 ± 92,487	163,465	211,840	369,469	45,132 – 383,101
	Nicotine concentration (mg/ml) [*n* = 10] 9.80 ± 0.10 (9.50 – 9.90)	PM_{10}	30	177,538 ± 92,542	163,310	212,239	369,927	47,542 – 383,041
	Vapored e-juice (g/cig) [*n* = 30] 0.19 ± 0.11 (0.01 – 0.41)	$PM_{2.5}$	30	172,706 ± 84,075	163,264	209,110	345,256	46,297 – 354,860
	Nicotine composition (mg/cig) [*n* = 10] 1.90 ± 0.02 (1.84 – 1.92)	$PM_{1.0}$	30	139,328 ± 51,806	141,625	172,845	217,808	36,679 – 246,536
	Vaping time (min) [*n* = 30] 3.73 ± 2.43 (2.00 – 12.00)	Black carbon	15	312 ± 244	199	523	865	23.9 – 865

In particular, in the case of 3 people vaping e-liquid cigarettes at the same time, the maximum particle number concentration for $PM_{1.0}$ at a 10-m distance from smokers was $1.3^{*}10^{9}$ particles/m^3. This number is comparable with the results of measuring the average concentration of $PM_{1.0}$ on the roadsides of Daegu Metropolitan City, which is in the range of 1.4–7.2$^{*}10^{9}$ particles/m^3 (Cho et al. 2019).

Results of the black carbon measurement at a distance of 3 m from the smoker are presented in Fig. 6. Results indicate a statistically significant increase in the level of black carbon in the air during and after smoking compared to the background level ($p < 0.05$). The highest emission of black carbon was during vaping liquid e-cigarettes by three consumers.

Results of the worst case analysis of outdoor particulate matter diffusion using CFD

Based on the results of the aerosol emission investigation, the 75th percentiles of the emission rate of PM_{10} and $PM_{2.5}$ particles are calculated and considered as boundary conditions of the CFD model (Table 1). As presented in Figures S2 to S5, the CFD simulation was conducted for one and three smokers using the amount of emitted PM_{10} and $PM_{2.5}$ from smoking or vaping each type of cigarette. As presented in Fig. 7, analysis was subsequently performed on the distance needed for the level of cigarette-generated particulate matter, when there

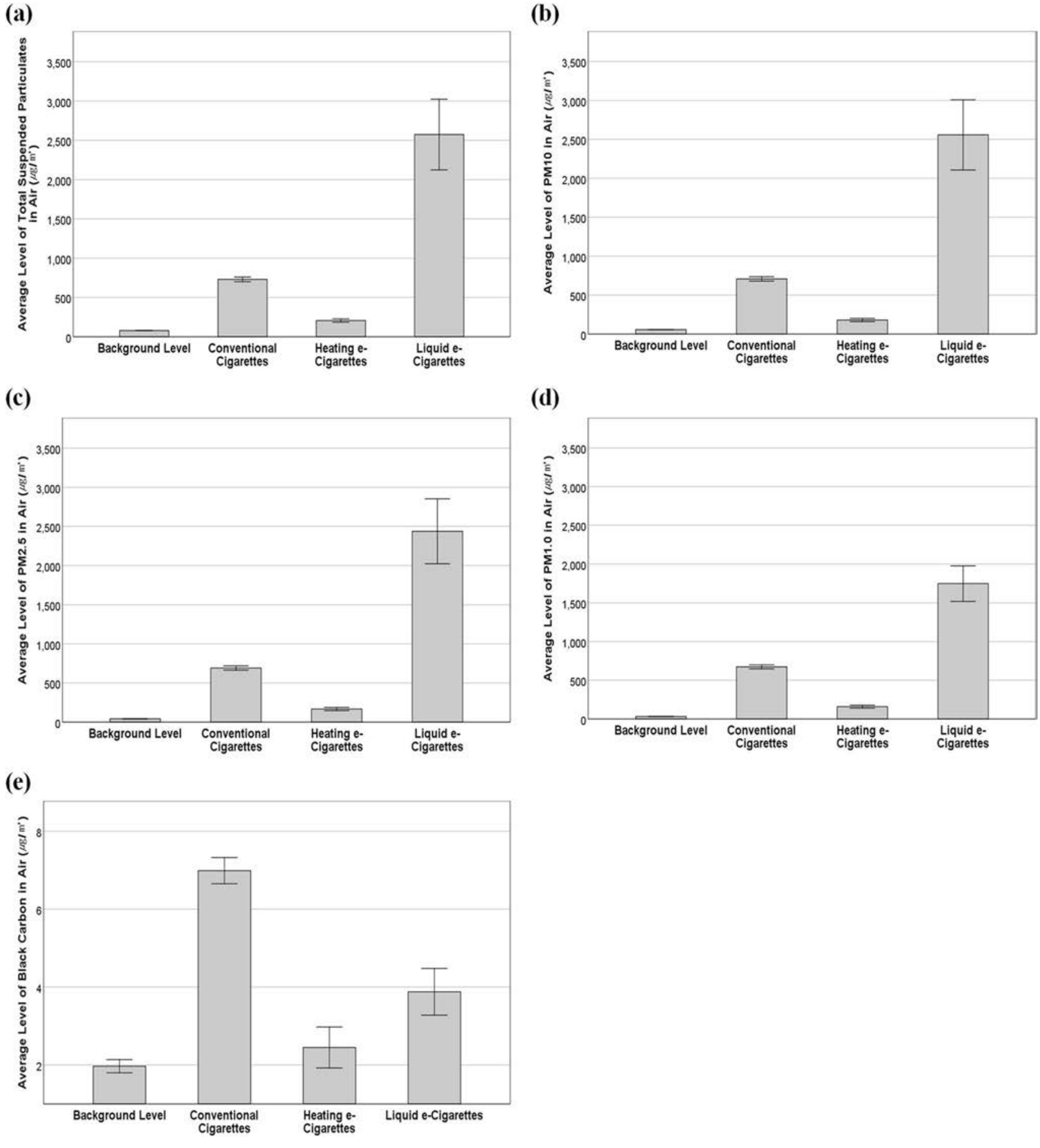

Fig. 4 Average of measured level of pollutants in the air during smoking or vaping different types of cigarettes: **a** total suspended particles, **b** PM_{10}, **c** $PM_{2.5}$, **d** $PM_{1.0}$, and **e** black carbon. Error bars indicate the standard error

are one and three smokers, to follow the World Health Organization (WHO) air quality guideline (AQG) level of 45 µg/m^3 PM_{10} and 15 µg/m^3 $PM_{2.5}$ for the 24-h averaging time (World Health Organization 2021). The average ratio between the measured levels of both PM_{10} and $PM_{2.5}$ measured at < 1-m away from the smoker in the outdoor aerosol diffusion investigation and the one simulated by the CFD model was 10%.

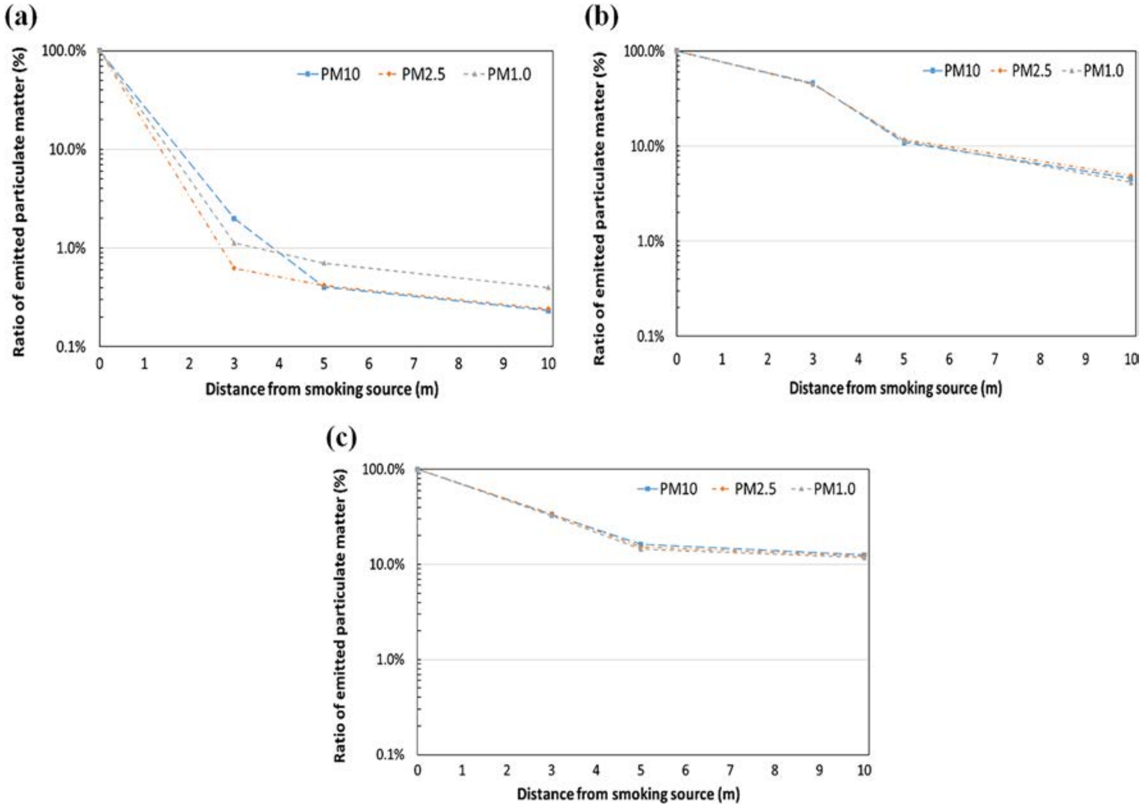

Fig. 5 Results of diffusion ratio of particulate matter emitted from **a** conventional cigarette, **b** heating e-cigarette, and **c** liquid e-cigarettes consumed by 3 smokers under mild wind condition

Results of risk assessment of exposure to emitted particulate matter at different distances from the smoker

Figures 8 and 9 present the results of risk assessment for passive exposure to emitted PM_{10} and $PM_{2.5}$ from smoking and vaping different types of cigarettes for both general subjects and children (6–10 years old). The safe distance for controlling passive exposure to smoke or vapor has been defined where the calculated risk is below the baseline risks, which are 7×10^{-4} and 2×10^{-5} for the general population and children, respectively.

Results indicate that the risks for passive exposure to both PM_{10} and $PM_{2.5}$ exceed the baseline risk, regardless of the number of smokers or type of cigarettes. Accordingly, from the public health point of view, no cigarette is considered safe or safer than other cigarettes.

For conventional cigarettes with one or three smokers, risk assessment results for PM_{10} and $PM_{2.5}$ indicate that the safe distance of 10 m from smokers, as considered in the National Health Promotion Act, is reasonable for the general population. For children, this distance is increased up to 30 m based on risk assessment results for PM_{10}. The risk of exposure to $PM_{2.5}$ yields an estimated safe distance to be above 100 m.

Regarding passive exposure to PM_{10} and $PM_{2.5}$ through heating e-cigarettes to be smoked by one or three smokers, results suggest maintaining the current legalized safe distance of 10 m from smokers for both the general population and children.

In the case of vaping liquid e-cigarettes by one and three smokers, although results of risk exposure to PM_{10} suggest a safe distance of 10 m from smokers for the general population, risk analysis for $PM_{2.5}$ suggests a safe distance of 70 m when three people are vaping liquid e-cigarette. For children, the estimated risk of exposure to both particulate matter when three smokers are vaping liquid e-cigarettes suggests a distance of over 100 m.

In this study, we measured the emission of particulate matter and black carbon from different types of cigarettes, including conventional cigarettes, heating e-cigarettes, and liquid e-cigarettes. In the case of liquid e-cigarettes, the emission of pollutants was normalized to the amount of vaped e-juice in each event.

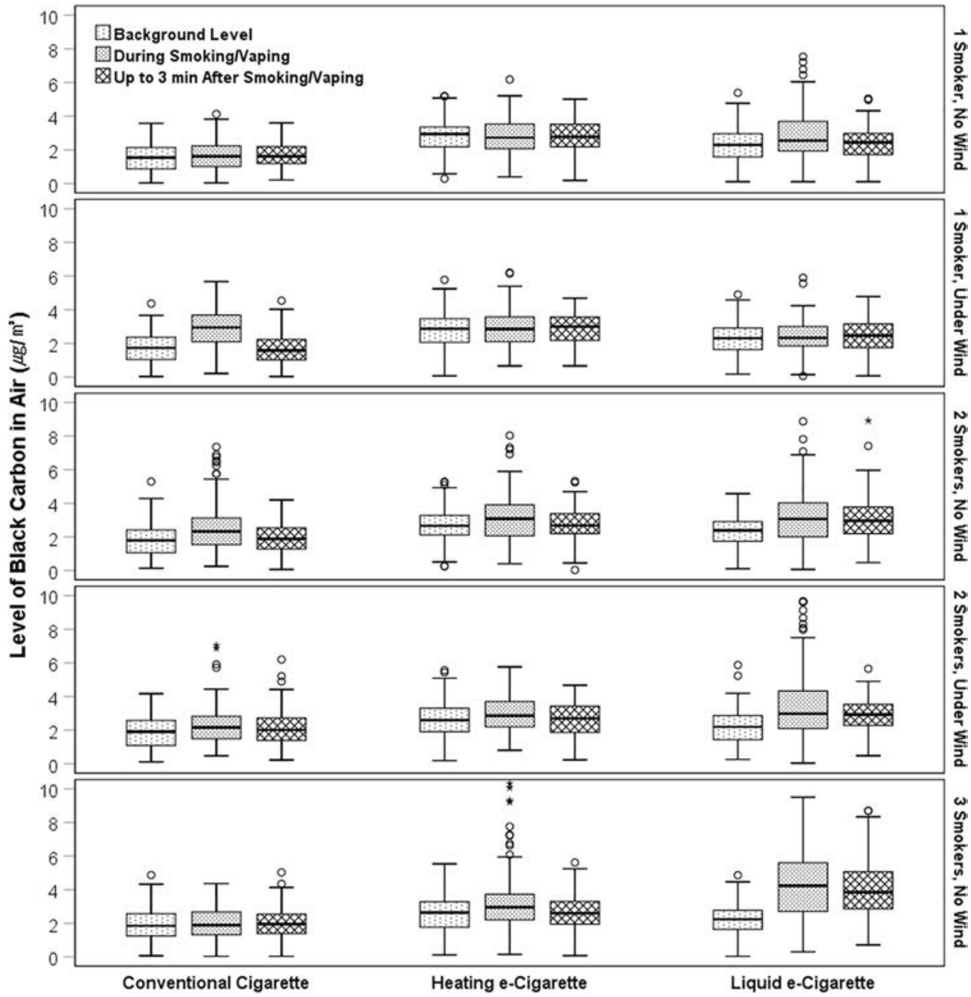

Fig. 6 Results of black carbon emission from smoking different types of cigarettes at a 3-m distance from smokers

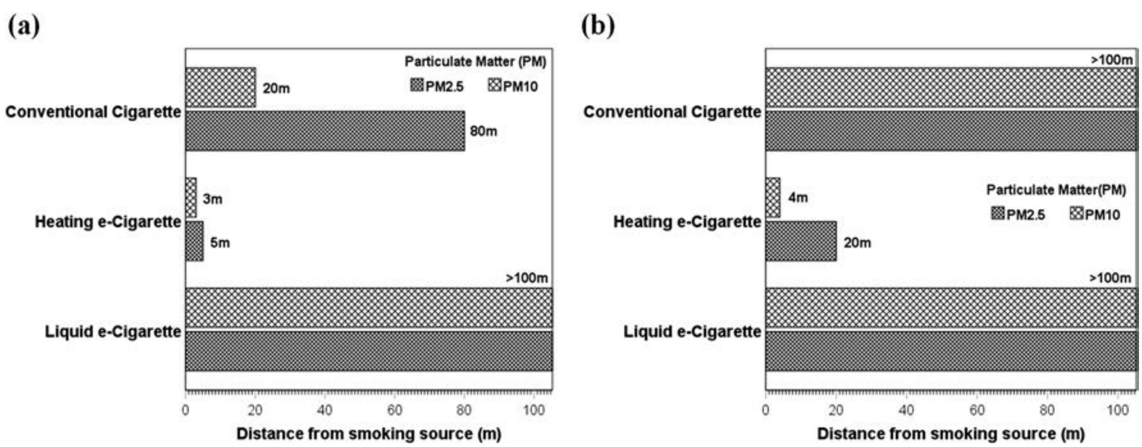

Fig. 7 Results of CFD analysis of the required distance for the diffusion of emitted particulate matter from smoking different types of cigarette by **a** one smoker and **b** three smokers to be below WHO AQG levels

Our results indicate that emissions from vaping liquid e-cigarettes are the highest compared to other types of cigarettes. The apparatus that we used for measuring the emission of particulate matter first measures the particle number concentration of each pollutant and then converts it to mass concentration. Our results are in agreement with

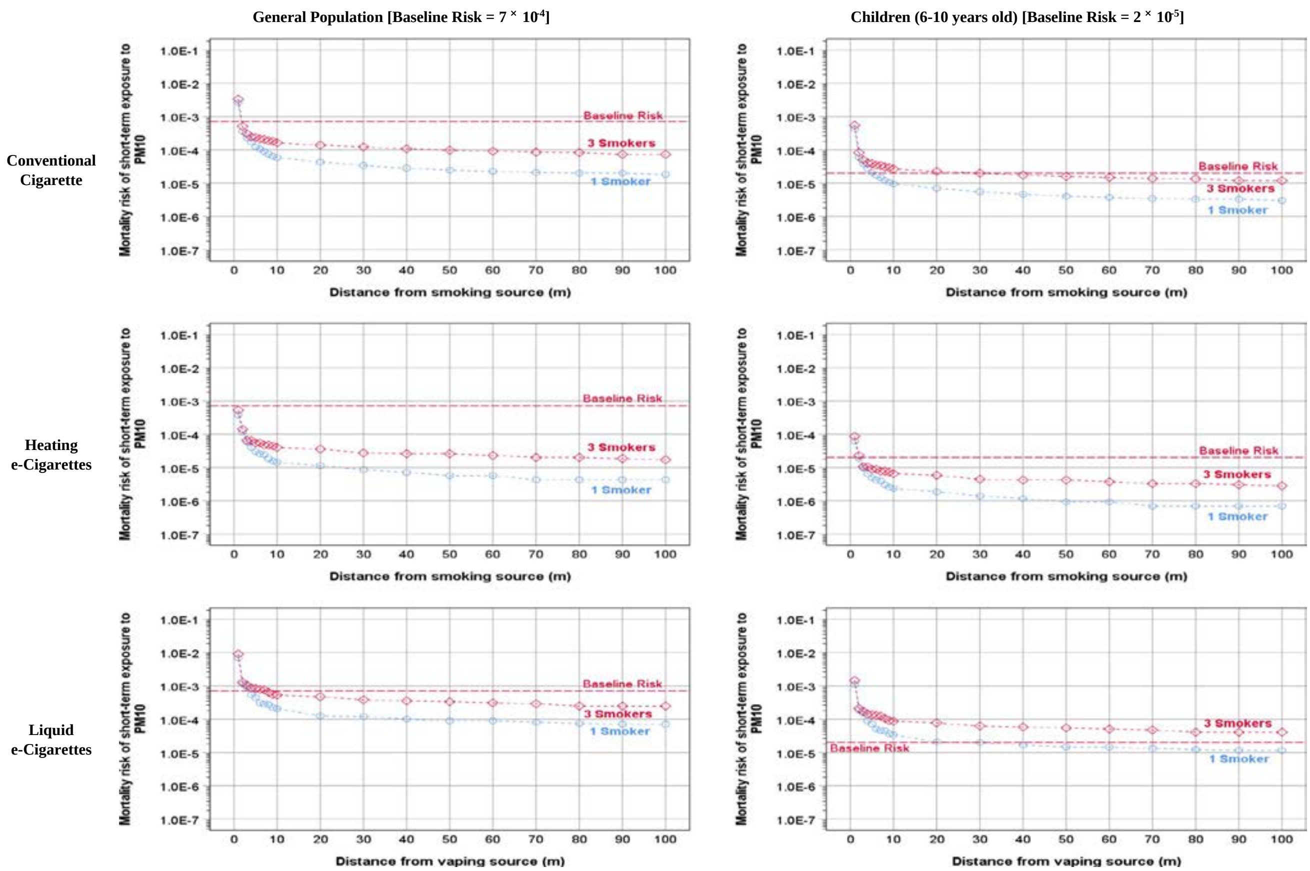

Fig. 8 Risk assessment of exposure to emitted PM_{10} from smoking different cigarettes and determination of safe distance

the ones reported in the literature using a similar measurement method including one conducted by Fuoco et al. (2014). Studies conducted under different environmental conditions, along with using a different measurement apparatus for measuring the emitted particulate matter from vaping liquid e-cigarettes and smoking conventional cigarettes, reported higher $PM_{2.5}$ emissions from conventional cigarettes (Czogala et al. 2014; Fernández et al. 2015). Despite general differences in measurement environment and apparatus, comparing our results with these studies may suggest that emitted particulate matter from liquid e-cigarettes can have a notably lower weight than what is emitted from smoking conventional cigarettes, with substantial physical and chemical differences, as discussed by Lampos et al. (2019).

The diffusion of emitted particulate matter with time and distance from the smoker for different types of cigarette (Figure S1) also shows that for both types of e-cigarettes, the pollution levels are lower when the experiment was executed under wind condition. Nevertheless, in the case of conventional cigarettes, it seems that wind has the role of pushing the smoke ahead rather than diluting it. In other words, more intense wind may be applied to make similar dissection patterns with e-cigarettes for the conventional ones. Consequently, these results also may indicate the notable differences in the types and the weight of particles emitted from different types of cigarettes, which deserves to be investigated in further detailed studies.

Measurement of black carbon and its positive and statistically strong correlation with the emission of other particulate matter, once again, provided evidence against the false and baseless commonsense that liquid e-cigarette emissions are only water vapor or glycerin and propylene glycol (Fernández et al. 2015). Although some studies, including those conducted by researchers who are affiliated with tobacco companies, suggested a high composition of water vapor in liquid e-cigarette emissions by measuring direct exhale samples, measuring the composition of water vapor in the machine-generated mainstream of liquid e-cigarettes is usually below 10%, and approximately similar to the water content of the e-juice (Long 2014; Kim et al. 2015; Fernández et al. 2015; Cunningham et al. 2020).

Another important note is that we observed a relatively lower emission of black carbon from heating e-cigarettes compared to liquid e-cigarettes. This observation can be

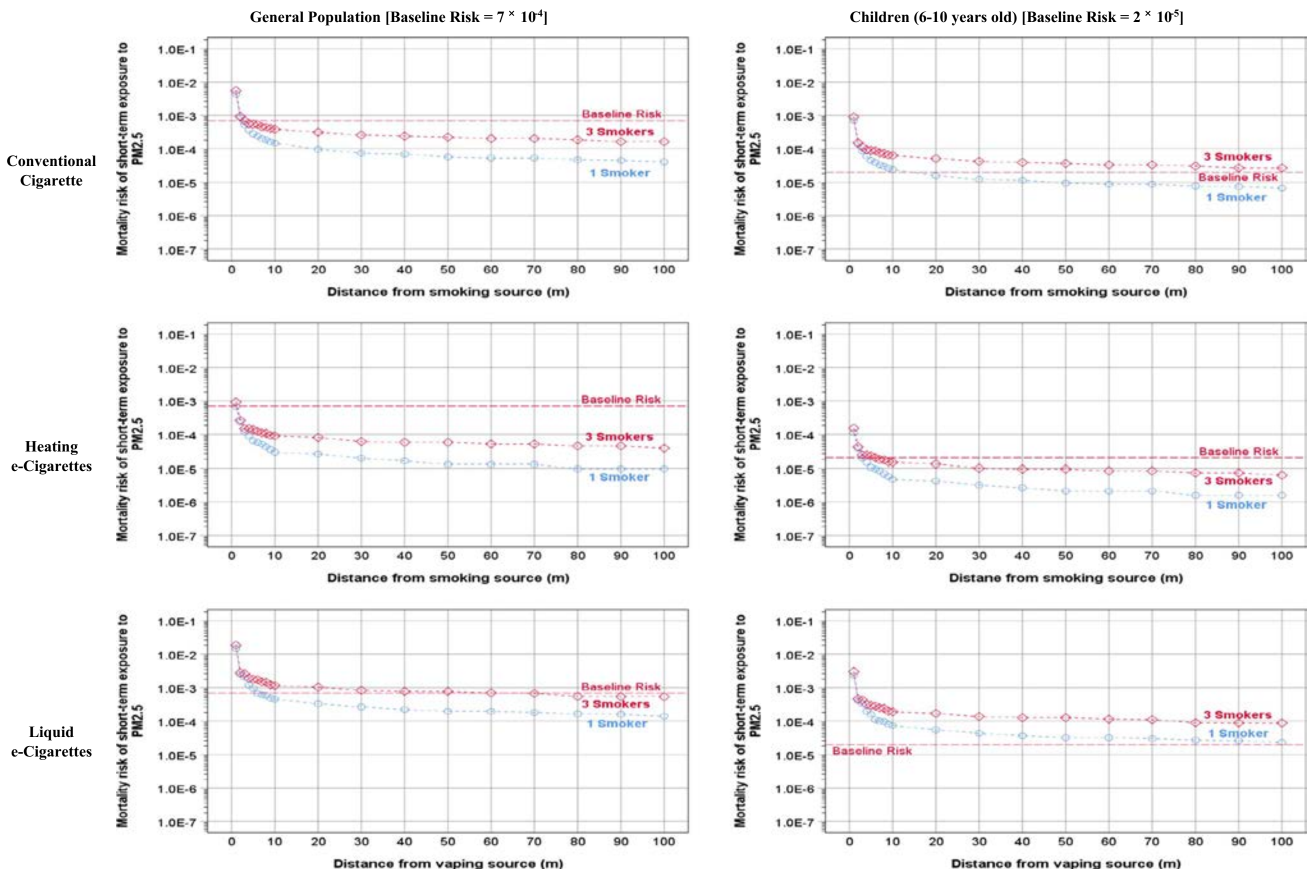

Fig. 9 Risk assessment of exposure to emitted $PM_{2.5}$ from smoking different cigarettes and determination of safe distance

explained by considering the way that heating e-cigarettes are being smoked. In this study, all subjects who smoked heating e-cigarettes used devices that limit the smoking time up to an average of 3 min and puff counts up to an average of 14 times, whatever the smoker reaches first. Therefore, the smoking time is relatively shorter than other cigarettes. In contrast, there is no smoking time or puff limits for vaping liquid e-cigarettes and we also did not limit our subjects to study their ad libitum and natural way of smoking.

In this study, the aerosol diffusion investigation yielded the effect of smoking and vaping on real-time air quality even at 10 m away from the source of smoking or vaping for all types of cigarettes. The CFD model was developed to predict the diffusion of PM_{10} and $PM_{2.5}$ under a steady-state condition for worst cases, and results were used for the evaluation of the risk of death due to short-term exposure to PM_{10} and $PM_{2.5}$ particles. Focusing on the CFD model results for dispersion of $PM_{2.5}$, there was a sharp decrease in concentration at a distance of 2 to 3 m from the smoker as presented in Figure S4. Specifically, in the case of heating e-cigarettes, the maximum distance of the $PM_{2.5}$ diffusion was up to 5 m. The dispersion range for conventional cigarettes is projected to be over 80 m.

As presented in Figures S2 to S5, the CFD simulation results also indicated that the air with emitted PM_{10} from smoking can decrease to a level below the WHO air quality guideline (45 μg/m^3 for the 24-h averaging time) compared to $PM_{2.5}$. However, this can vary based on the smoker's respiratory and exhale characteristics, which may make the emitted particulate matter disperse to even longer distances. In the case of liquid e-cigarettes, the projected emission amount is so enormous that the diffusion could not reduce it to a level below the WHO air quality guideline (45 μg/m^3 and 15 μg/m^3 for the 24-h average time of exposure to PM10 and PM2.5, respectively) at a distance below 100 m from the smoker.

Our results should be considered with several limitations, mostly caused by insufficient funds. First of all, the scale of the study, including the number of participants, was not designed to indicate the general smoking or vaping conditions in the Republic of Korea. Subjects had closed smoking habits, while the smoking habit may influence the emission and diffusion of pollutants from smoking and vaping activities (Fuoco et al. 2014; Yang et al. 2020, 2021). Accordingly, more detailed and large-scale investigations are required to understand the influence of gender, age, and smoking habits on the emission and diffusion of aerosols from smoking and vaping activities.

Studies by Kant et al. (2016) or Braun et al. (2019b) may suggest that the composition of conventional cigarettes can have a notable effect on the emission of particulate matter during smoking. This is while the results reported by Fuoco et al. (2014) showed that the particle number concentration of the aerosol emitted from different brands of liquid e-cigarettes was not significantly different. Furthermore, according to Yang et al. (2022a), the compositions of popular conventional cigarettes are not significantly different in Korea. Hence, further experimentation on particulate matter emission should be conducted by considering different types of cigarettes with a broader range of compositions.

The outdoor aerosol diffusion was investigated during winter, without intention or effort to control or investigate the impact of meteorological factors such as temperature or air pressure on the diffusion of emitted particulate matter from smoking or vaping. Although several studies were conducted on the correlations between $PM_{2.5}$ concentration and meteorological conditions, these limited studies focused on the effect of meteorological conditions on the diffusion of emitted particulate matter from smoking or vaping (Yang et al. 2017; Chen et al. 2020). Accordingly, more in-depth studies are required to fill such knowledge gaps. Nevertheless, this may not have a major effect on the measurement accuracy because the GRIMM11-D apparatus has a self-heating effect that can reduce the noises, which may be attributed to some meteorological parameters such as humidity (Masic et al. 2020; Wu et al. 2022).

It should be noted that the CFD analysis also does not consider any real, external factors that change with time, such as wind characteristics and speed. Thus, it is suggested that the predictions here may be considered an overestimation of reality to analyze the exposure risk under the worst scenario. Results of risk assessment suggest a greater distance from the source of smoking for children than the current nationwide legalized value of 10 m. In further studies, such models should be developed in a way to be closer to real-time smoking and vaping conditions.

In this study, we investigated the emission amount and outdoor diffusion of aerosols, including particulate matter from different types of cigarettes including conventional cigarettes, heating e-cigarettes, and liquid e-cigarettes. The normalized emission amounts were used to analyze the worst case of outdoor diffusion for the emitted particulate matter by developing a CFD model. Utilizing the results of these investigations, we assessed the risk of exposure to PM_{10} and $PM_{2.5}$ emitted from outdoor smoking and estimated safe distances for the general population and children.

In this study, we did not aim to compare the risks associated with different types of cigarettes. Our risk assessment results indicate that no type of cigarette should be recommended for smoking. Our results support the nationwide legalized safe distance of 10 m from the source of smoking for the general population. When it comes to spaces where children are involved, an enforced safe distance of 30 to 100 m should be considered. Nevertheless, more in-depth investigations are required for providing convincing scientific pieces of evidence for determining the national or international scaled safe distance from smokers to control the risk of exposure to SHS.

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Author contributions JY: conceptualization, methodology, validation, formal analysis, investigation, resources, writing–review and editing; SH: methodology, formal analysis, investigation, visualization, writing–original draft preparation; TK: conceptualization, writing–review and editing; JP: formal analysis, investigation, visualization; MP: formal analysis, investigation, visualization; WH: investigation; DP: formal analysis, writing–original draft preparation; YL: conceptualization, supervision, writing–review and editing.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article. Publicly available datasets of the Korea National Health and Nutrition Examination Survey (KNHANES) were analyzed in this study. These data can be found here: https://knhanes.kdca.go.kr/knhanes/main.do (accessed on 22 October 2021).

Declarations

Ethics approval The Institutional Review Board (IRB) of Severance Hospital of the Yonsei University Health System approved the study design (approval number: 4-2021-1269).

Consent to participate and publish All subjects were compensated and were asked to sign a letter of consent that included a comprehensive explanation of the objectives and procedure of the research, data processing, publications, and privacy protection policies.

Competing interests The authors declare no competing interests.

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