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Exposure to particulate matter ($PM_{2.5}$) and prevalence of diabetes mellitus in Indonesia

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ABSTRACT

Background: Recently emerging evidence suggests an association between particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) exposure and diabetes risk. However, evidence from Asia is limited. Here, we evaluated the association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus in one of the most populated countries in Asia, Indonesia.

Methods: We used the 2013 Indonesia Basic Health Research, which surveyed households in 487 regencies/municipalities in all 33 provinces in Indonesia (n = 647,947). We assigned individual exposure to $PM_{2.5}$ using QGIS software. Multilevel logistic regression with a random intercept based on village and cubic spline analysis were used to assess the association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus. We also assessed the lower exposure at which $PM_{2.5}$ has potential adverse effects.

Results: We included 647,947 subjects with a mean age of 41.9 years in our study. Exposure to $PM_{2.5}$ levels was associated with a 10-unit increase in $PM_{2.5}$ (fully adjusted odds ratio: 1.09; 95% confidence interval: 1.05–1.14). The findings were consistent for quartile increases in $PM_{2.5}$ levels and the cubic spline function. Even when we restricted to those exposed to $PM_{2.5}$ concentrations of less than 10.0 $\mu g/m^3$ in accordance with the recommended guidelines for annual exposure to $PM_{2.5}$ made by the World Health Organization, the association remained elevated, especially among subjects living in the urban areas. Hence, we were unable to establish a safe threshold for $PM_{2.5}$ and the risk of diabetes.

Conclusions: Our findings suggest a positive association between $PM_{2.5}$ exposure and prevalence of diabetes mellitus, which is possibly below the current recommended guidelines. Further studies are needed to ascertain the causal association of this finding.

1. Introduction

Particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) is reported to be associated with increased risk of cardiorespiratory disease and lung cancer (Cohen et al., 2017). Furthermore, studies have suggested a possible association between $PM_{2.5}$ exposure and diabetes risk (Pearson et al., 2010; Wang et al., 2014; Weinmayr et al., 2015). Indeed, a systematic review and meta-analysis including 10 studies (5 cross-sectional and 5 prospective) suggests an increase in the risk for type 2 diabetes with exposure to $PM_{2.5}$ (Balti et al., 2014). The prospective studies showed an overall significant effect on diabetes occurrence and $PM_{2.5}$ whilst the elevated risk was only apparent in two cross-sectional studies. Based on the accumulated evidence, globally in 2016, diabetes-related mortality and disability-adjusted life years due to $PM_{2.5}$

Abbreviations: BHR, basic health research; CI, confidence interval; GWR, geographically weighed regression; OR, odds ratio; $PM_{2.5}$, particulate matter ≤2.5 µm; QGIS, quantum geographic information system

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exposure has been estimated to reach 206,105 and 8.2 million, respectively (Bowe et al., 2018).

The number of people with diabetes is projected to rise from 171 million in 2000 to 366 million in 2030 (Wild et al., 2004), and more than half of the world's population with diabetes lives in Asia (Nanditha et al., 2016). However, there are limited studies in Asia assessing the association between $PM_{2.5}$ exposure and diabetes. Therefore, we evaluated the association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus in Indonesia, one of the top ten countries of diabetes prevalence in Asia (Ramachandran et al., 2010).

2. Methods

2.1. Study population

We included participants from the Indonesian Basic Health Research (BHR). The BHR is a nationally representative cross-sectional health survey that started in 2007 and continues periodically. The survey collects community-based information through interviews to evaluate changes in the health status of the population. For the present study, we used the latest 2013 Indonesia BHR, which surveyed households in 497 regencies/municipalities in all 33 provinces across Indonesia. The survey selected households using probability sampling proportional to the number of households in each municipality to maintain regional representation (Ministry of Health and National Institute of Health Research and Development, 2013). This sampling procedure selected 300,000 households from 12,000 census blocks across Indonesia, and the 2013 Indonesian BHR received the questionnaire from 294,959 households (response rate: 98.3%) and 1,027,763 household members (response rate: 93.0%). The present study included 648,202 subjects aged 18 years and above. Ethical clearance for the 2013 BHR was approved by the Ethical Commission for Health Research (Komisi Etik Penelitian Kesehatan/KEPK), the National Institute of Health Research and Development (NIHRD) for Indonesia (LB.02.01/5.2/KE.006/2013).

2.2. $PM_{2.5}$ exposure

We used the annual mean global geographically weighed regression (GWR)-adjusted $PM_{2.5}$ estimates at 0.01° × 0.01° (approximately 1 km × 1 km) for 2013 as the main exposure indicator. We obtained ground-level ($PM_{2.5}$) estimates from the Atmospheric Composition Analysis Group at Dalhousie University, Canada as previously described elsewhere (Lavigne et al., 2017; Yorifuji et al., 2019). The group estimates $PM_{2.5}$ concentrations using the combination of aerosol optical depth, and the GEOS-Chem chemical transport model, which are then calibrated to global-based observations of $PM_{2.5}$ by a geographically weighted regression (van Donkelaar et al., 2016). After obtaining estimates of annual concentrations of $PM_{2.5}$ in Indonesia, we used QGIS 2.18 to calculate annual $PM_{2.5}$ concentrations in each *kelurahan*/village, the smallest administrative level in Indonesia (i.e., smaller than a regency/municipality). We excluded 5 of the identified 10,775 *kelurahan*/villages because levels of $PM_{2.5}$ were missing in the modelled dataset. This left 10,770 *kelurahan*/villages (n = 647,947) for the analysis. We then assigned the *kelurahan*/village-level $PM_{2.5}$ estimates to the participants living in the corresponding *kelurahan*/villages.

2.3. Diabetes mellitus status

We obtained diabetes mellitus status of the participants through interviews in the 2013 BHR survey. In the survey, the participants were queried using the following question to ascertain their status: "Have you ever been diagnosed with diabetes mellitus by a doctor?" Although we do not know the type of diabetes of the participants (i.e., type 1, juvenile diabetes, or type 2, adults-onset), around 85% to 95% of diabetes cases worldwide relate to type 2 diabetes (NCD Risk Factor Collaboration (NCD-RisC), 2016).

2.4. Statistical analysis

After performing a descriptive analysis, to evaluate the association between $PM_{2.5}$ levels in 2013 and the prevalence of diabetes mellitus, we performed the multilevel logistic regression with a random intercept based on village to account for the non-independence of participants within the same village. We estimated the odds ratios (OR) with 95% confidence intervals (CIs) both (1) per 10.0-μg/m^3 increase of $PM_{2.5}$ and (2) for quartile levels of $PM_{2.5}$, using the lowest quartile as a reference. In the analysis, we adjusted for the following individual-level potential confounders: age (continuous: years), sex (dichotomous), education (categorical: university graduate, diploma, high school, junior high school, primary school, did not finish primary school, and no school), body mass index (continuous: kg/m^2), type of residence (dichotomous: urban/rural), smoking in the past month (categorical: everyday, sometimes, no but previously smoked every day, no but previously smoked sometimes, and never), daily exposure to second-hand smoke (dichotomous: yes/no), physical activity (categorical: high and moderate, high, moderate, and low), vegetable intake (dichotomous: yes/no), fruit intake (dichotomous: yes/no), and hypertension status (dichotomous: yes/no). These individual-level potential confounders were obtained from the survey and information on urban and rural classification was available from the primary sampling unit (PSU) list for the 2013 BHR. We also adjusted for the following area-level potential confounder: gross-domestic regional product per-capita (thousand rupiahs) at the province-level (continuous) because some areas did not have the information below the provincial level from 2008 through 2013. The province in Indonesia is a higher administrative level than the regency/municipality or *kelurahan*/village, and this area-level potential confounder was entered into the model as a continuous variable. We selected these potential confounders based on the previous studies (Balti et al., 2014; Hansen et al., 2016; Liang et al., 2019; Qiu et al., 2018). We also stratified the participants by urban and rural areas and repeated the analysis; we did not adjust for the type of residence during this stratification.

To evaluate the shape of the association between $PM_{2.5}$ and the prevalence of diabetes mellitus, we performed a restricted cubic spline analysis with four knots for $PM_{2.5}$ (Harrell, 2001). Furthermore, to evaluate the lower exposure level at which $PM_{2.5}$ has potential adverse effects, we restricted the participants to those exposed to $PM_{2.5}$ concentrations below 25.0 μg/m^3, below 20.0 μg/m^3, below 15.0 μg/m^3, and below 10.0 μg/m^3, and repeated the analyses. We tested potential effect modification by performing a subgroup stratified analysis by age, sex, body mass index, residency, and hypertension. We assessed differences in the effect estimates by adding an interaction term between the covariates and the exposure using the fully adjusted model. We categorized continuous variables such as age and body mass index to have almost equal number of participants in each strata.

In the sensitivity analysis, we first used the average $PM_{2.5}$ concentrations from 2008 to 2012 instead of the concentration in 2013 to determine whether there were any significant changes to the main result. Second, we restricted the participants older than 45 or 55 years old to include those with type 2 diabetes rather than type 1 diabetes (Brook et al., 2013). Third, because there is evidence suggesting the important role of geographical variables linked to diabetes, we further adjusted for latitude, longitude (both at the village level) and population density (people per km^2) at the province-level (Woolcott et al., 2014). These area-level potential confounders were entered into the model as continuous variables.

All of the analyses used STATA 13.1 (StataCorp LLC, College Station, TX). We did not seek additional ethical clearances for this study because we received anonymized data.

3. Results

A total of 647,947 subjects with a mean age of 41.9 years were

Table 1
Sociodemographic characteristics of subjects: total and by diabetes status.

		Diabetes	
	Total (n = 647,947)	Yes (n = 12,220)	No (n = 635,727)
Age, years (mean ± SD)	41.9 ± 15.0	54.2 ± 11.1	41.7 ± 15.0
Sex, n (%)			
Men	314,045 (48.5)	5243 (42.9)	308,802 (48.6)
Women	333,902 (51.5)	6977 (57.1)	326,925 (51.4)
Education, n (%)			
University	27,832 (4.3)	900 (7.4)	26,932 (4.2)
University diploma 1, 2, 3	21,316 (3.3)	607 (5)	20,709 (3.3)
High school	166,239 (25.7)	2869 (23.5)	163,370 (25.7)
Junior high school	111,262 (17.2)	1757 (14.4)	109,505 (17.2)
Primary school	191,139 (29.5)	3682 (30.1)	187,457 (29.5)
Did not finish primary school	84,757 (13.1)	1679 (13.7)	83,078 (13.1)
No school	45,402 (7.0)	726 (5.9)	44,676 (7)
Body mass index, kg/m^2 (mean ± SD)	23.0 ± 4.2	24.6 ± 4.5	23.0 ± 4.1
Residency			
Urban	299,216 (46.2)	7788 (63.7)	291,428 (45.8)
Rural	348,731 (53.8)	4432 (36.3)	344,299 (54.2)
Smoking in the past month, n (%)			
Yes, everyday	181,403 (28)	2149 (17.6)	179,254 (28.2)
Yes, sometimes	33,678 (5.2)	528 (4.3)	33,150 (5.2)
No, but previously every day	16,902 (2.6)	841 (6.9)	16,061 (2.5)
No, but previously sometimes	13,915 (2.2)	499 (4.1)	13,416 (2.1)
Never	402,049 (62.1)	8203 (67.1)	393,846 (62)
Daily exposure to second-hand smoke, n (%)			
Yes	181,475 (84.4)	2195 (82)	179,280 (84.4)
No	33,606 (15.6)	482 (18)	33,124 (15.6)
Physical activity			
High and Moderate	224,906 (34.7)	2373 (19.4)	222,533 (35)
High	39,734 (6.1)	331 (2.7)	39,403 (6.2)
Moderate	334,665 (51.7)	7659 (62.7)	327,006 (51.4)
Low	48,642 (7.5)	1857 (15.2)	46,785 (7.4)
Vegetable intake			
Yes	639,520 (98.7)	12,029 (98.4)	627,491 (98.7)
No	8427 (1.3)	191 (1.6)	8236 (1.3)
Fruit intake			
Yes	558,689 (86.2)	10,952 (89.6)	547,737 (86.2)
No	89,258 (13.8)	1268 (10.4)	87,990 (13.8)
Hypertension			
Yes	67,675 (10.4)	4563 (37.3)	63,112 (9.9)
No	580,272 (89.6)	7657 (62.7)	572,615 (90.1)
Province-level GRDP per capita, thousand rupiahs (mean ± SD)	56,056.2 ± 61,875.2	62,448.5 ± 69,574.1	55,865.4 ± 61,620.7
$PM_{2.5}$ concentration, μg/m^3 (mean ± SD)			
Urban	10.2 ± 6.4	10.9 ± 6.7	10.2 ± 6.4
Rural	6.6 ± 4.7	6.9 ± 4.7	6.6 ± 4.7

SD: standard deviation, GDP: gross-domestic regional product

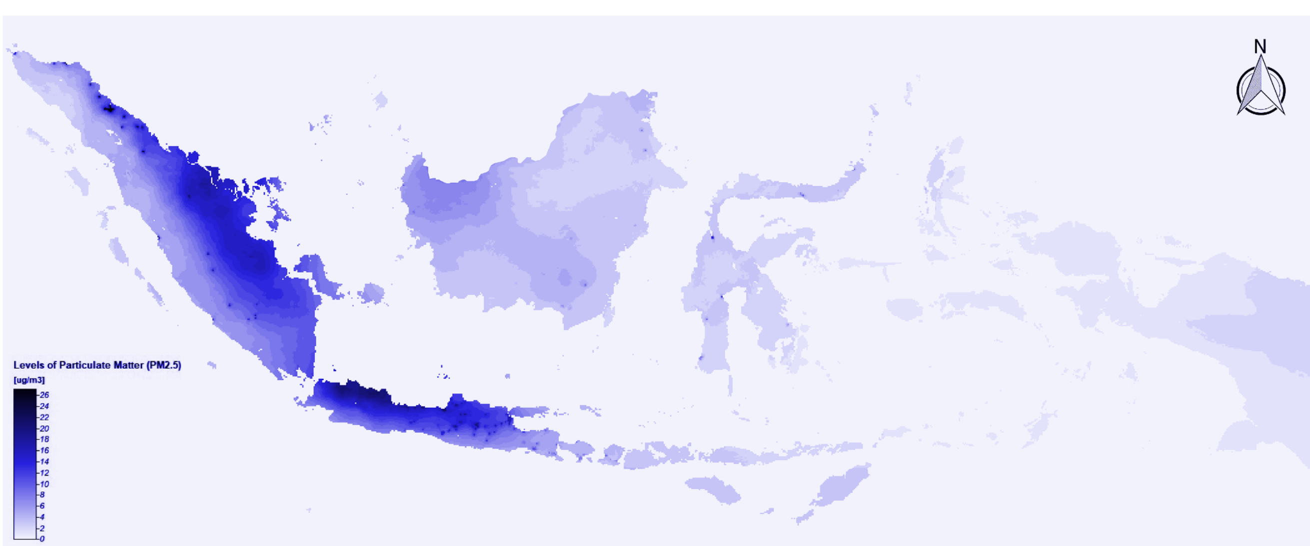

Fig. 1. Distribution of particulate matter ($PM_{2.5}$) levels in 2013 in Indonesia.

Table 2
Odds Ratios and 95% Confidence Intervals for the Association between Particulate Matter ($PM_{2.5}$) Exposure in 2013 and the Prevalence of Diabetes Mellitus in Indonesia: Total and by Type of Residence.

			OR (95% Confidence Interval)		
	Case/N	Prevalence	Crude	Adjusted[a]	Fully-adjusted[b]
Total					
Per 10 μg/m³ increase	12,220/647,947	1.89	1.41 (1.35–1.46)	1.11 (1.07–1.15)	1.09 (1.05–1.14)
Quartiles:					
Q1 (≤3.0 μg/m³)	3064/189,349	1.62	1 (ref.)	1 (ref.)	1 (ref.)
Q2 (4.0–7.0 μg/m³)	2504/151,125	1.66	1.03 (0.96–1.11)	0.91 (0.85–0.97)	0.91 (0.85–0.97)
Q3 (8.0–12.0 μg/m³)	2708/146,850	1.84	1.16 (1.09–1.25)	0.98 (0.92–1.04)	0.98 (0.92–1.04)
Q4 (13.0–31.0 μg/m³)	3944/160,623	2.46	1.56 (1.47–1.67)	1.10 (1.03–1.17)	1.08 (1.02–1.15)
Urban					
Per 10 μg/m³ increase	7788/299,216	2.60	1.17 (1.12–1.23)	1.17 (1.12–1.23)	1.14 (1.09–1.19)
Quartiles:					
Q1 (≤3.0 μg/m³)	1422/58,424	2.43	1 (ref.)	1 (ref.)	1 (ref.)
Q2 (4.0–7.0 μg/m³)	1470/62,740	2.34	0.96 (0.87–1.05)	0.95 (0.87–1.04)	0.95 (0.87–1.04)
Q3 (8.0–12.0 μg/m³)	1611/66,548	2.42	0.98 (0.90–1.08)	0.97 (0.89–1.06)	0.98 (0.89–1.07)
Q4 (13.0–31.0 μg/m³)	3285/111,504	2.95	1.20 (1.11–1.31)	1.17 (1.08–1.26)	1.15 (1.06–1.24)
Rural					
Per 10 μg/m³ increase	4432/348,731	1.27	1.14 (1.05–1.23)	1.14 (1.05–1.23)	1.04 (0.97–1.12)
Quartiles:					
Q1 (≤3.0 μg/m³)	1642/130,925	1.25	1 (ref.)	1 (ref.)	1 (ref.)
Q2 (4.0–7.0 μg/m³)	1034/88,385	1.17	0.94 (0.85–1.03)	0.88 (0.80–0.97)	0.89 (0.81–0.97)
Q3 (8.0–12.0 μg/m³)	1097/80,302	1.37	1.10 (1.00–1.21)	1.00 (0.91–1.10)	0.99 (0.91–1.09)
Q4 (13.0–21.0 μg/m³)	659/49,119	1.34	1.09 (0.97–1.22)	1.00 (0.89–1.11)	0.99 (0.89–1.10)

[a] Adjusted for age, sex, education, body mass index, type of residence, smoking, daily exposure to second-hand smoke, physical activity, vegetable intake, fruit intake, and hypertension status.
[b] Included covariates in [a] and further adjusted for gross-domestic regional product per-capita.

included in this study, with the prevalence of diabetes mellitus being 1.89% (N = 12,220) (Table 1). The annual mean for $PM_{2.5}$ in 2013 was 8.3 μg/m³ (Map in Fig. 1).

We present the association between exposure to $PM_{2.5}$ concentrations and diabetes mellitus in Table 2. There was a positive association between $PM_{2.5}$ levels and prevalence of diabetes (fully adjusted OR = 1.09, 95%CI: 1.05–1.14, for a 10 μg/m³ increase in $PM_{2.5}$ level). This was consistent with the findings for quartiles of $PM_{2.5}$. When the first quartile was used as reference (≤3.0 μg/m³), the prevalence of diabetes mellitus increased with increasing quartiles, with the highest being in the fourth quartile (13.0–31.0 μg/m³) (fully adjusted OR = 1.08; 95%CI: 1.02–1.15). When we stratified by type of residence, we found that the effect estimates for the association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus were higher for subjects living in urban areas compared with the rural areas. Further assessment using a spline function showed similar results. The association between $PM_{2.5}$ and diabetes mellitus nearly levelled at low concentrations and then steadily increased at around 8.0-μg/m³; that is, the prevalence of diabetes mellitus increased with increasing $PM_{2.5}$ concentrations (Fig. 2).

We show the results from when we restricted the subjects to various $PM_{2.5}$ concentrations (Table 3). Even when we restricted subjects to those exposed to $PM_{2.5}$ concentrations of less than 10.0-μg/m³, the association between $PM_{2.5}$ and the prevalence of diabetes mellitus remained elevated, in particular among subjects living in urban areas. We found no significant effect modification for the relationship between $PM_{2.5}$ and the prevalence of diabetes mellitus, except for age (Table 4). The effect estimates for the association between $PM_{2.5}$ and the prevalence of diabetes mellitus were significantly higher in those aged above and 42 years (fully adjusted OR = 1.11; 95%CI: 1.07–1.16) compared to those aged less than 42 years (fully adjusted OR = 0.95; 95%CI: 0.86–1.05).

We found comparable results from the sensitivity analyses. We found no substantial changes to the main result when we used exposure information from 2008 to 2012, in those aged above 45 years, and with different models (Supplementary Tables 1, 2, and 3).

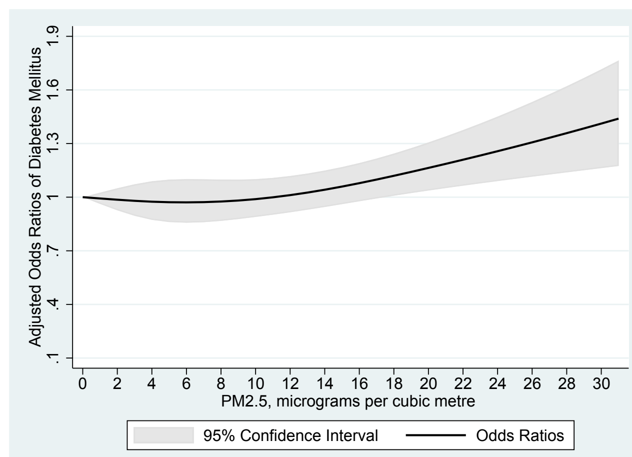

Fig. 2. Restricted cubic spline regression of the association between exposure to particulate matter ($PM_{2.5}$) and the prevalence of diabetes mellitus.

4. Discussion

In this study, after we assessed the association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus, we found that exposure to $PM_{2.5}$ was associated with diabetes mellitus. This was confirmed by the analysis per 10.0-μg/m³ increase of $PM_{2.5}$, quartiles of $PM_{2.5}$, and the restricted cubic spline analysis. Furthermore, although not significant, an association remained among the urban subjects when subjects were restricted to concentrations of $PM_{2.5}$ of less than 10 μg/m³, which was lower than the current guidelines for annual exposure to $PM_{2.5}$ (World Health Organization, 2018).

As reported in previous studies (Eze et al., 2015; Kim et al., 2015; Pearson et al., 2010), our study demonstrated the positive association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus. Long-term exposure to $PM_{2.5}$ increases the incidence of diabetes and mortality associated with diabetes (Bowe et al., 2018; Brook et al., 2013; Hansen et al., 2016; He et al., 2017; Liang et al., 2019). Studies

Table 3
Odds Ratios and 95% Confidence Intervals for the Association between $PM_{2.5}$ Exposure and the Prevalence of Diabetes Mellitus in Varying Concentrations of $PM_{2.5}$: Total and by Type of Residence.

$PM_{2.5}$ levels for 2013 (per 10 μg/m³ increase)	Case/N	Prevalence	OR (95% Confidence Intervals)		
			Crude	Adjusted[a]	Fully-adjusted[b]
Total					
All	12,220/647,947	1.89	1.41 (1.35–1.46)	1.11 (1.07–1.15)	1.09 (1.05–1.14)
< 25.0 μg/m³	12,032/642,357	1.87	1.41 (1.35–1.47)	1.11 (1.06–1.15)	1.09 (1.04–1.13)
< 20.0 μg/m³	11,205/616,879	1.82	1.33 (1.27–1.40)	1.07 (1.02–1.12)	1.07 (1.02–1.12)
< 15.0 μg/m³	9525/544,520	1.75	1.30 (1.21–1.38)	1.06 (1.00–1.13)	1.06 (1.00–1.12)
< 10.0 μg/m³	6479/391,148	1.66	1.30 (1.13–1.49)	0.96 (0.84–1.09)	0.95 (0.84–1.08)
Urban					
All	7788/299,216	2.60	1.17 (1.12–1.23)	1.14 (1.09–1.19)	1.12 (1.07–1.17)
< 25.0 μg/m³	7600/293,626	2.59	1.17 (1.11–1.23)	1.14 (1.09–1.20)	1.12 (1.07–1.18)
< 20.0 μg/m³	6824/270,631	2.52	1.11 (1.05–1.18)	1.11 (1.05–1.17)	1.11 (1.05–1.17)
< 15.0 μg/m³	5393/219,119	2.46	1.08 (0.99–1.18)	1.07 (0.99–1.16)	1.07 (0.99–1.16)
< 10.0 μg/m³	3456/143,450	2.41	1.09 (0.90–1.31)	1.06 (0.89–1.26)	1.06 (0.89–1.26)
Rural					
All	4432/348,731	1.27	1.14 (1.05–1.23)	1.04 (0.97–1.12)	1.03 (0.96–1.11)
< 25.0 μg/m³	4432/348,731	1.27	1.14 (1.05–1.23)	1.04 (0.97–1.12)	1.03 (0.96–1.11)
< 20.0 μg/m³	4381/346,248	1.27	1.11 (1.02–1.20)	1.02 (0.94–1.10)	1.01 (0.93–1.09)
< 15.0 μg/m³	4132/325,401	1.27	1.18 (1.07–1.30)	1.06 (0.96–1.16)	1.05 (0.96–1.15)
< 10.0 μg/m³	3023/247,698	1.22	1.05 (0.86–1.27)	0.88 (0.73–1.05)	0.87 (0.72–1.05)

PM: particulate matter, OR: odds ratio.
[a] Adjusted for age, sex, education, body mass index, type of residence, smoking, daily exposure to second-hand smoke, physical activity, vegetable intake, fruit intake, and hypertension status.
[b] Included covariates in [a] and further adjusted for gross-domestic regional product per-capita.

assessing the prevalence of diabetes have also suggested the association between $PM_{2.5}$ exposure and diabetes (Orioli et al., 2018; Pearson et al., 2010; Yang et al., 2018). Two studies with an ecological design suggest that $PM_{2.5}$ exposure resulted in an increased prevalence of $PM_{2.5}$ in the United States and Italy (Orioli et al., 2018; Pearson et al., 2010). Although studies on diabetes and air pollution are limited in Asia, a study by Yang et al. (2018) of 11,504 Chinese older adult people aged 50 years and above showed a positive association between $PM_{2.5}$ exposure and the prevalence of diabetes (adjusted OR = 1.27; 95%CI: 1.12–1.43) (Yang et al., 2018). Our findings are in line with these previous studies.

When we compared urban and the rural areas, the association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus was stronger in the urban areas (Table 2). The reason behind this finding could be affected by the undiagnosed or less likelihood of reported diabetes due to limited access to health care facilities and low education level among the rural subjects in the BHR survey. However, this finding had previously been reported by Weinmayr et al. (2015), pointing out the possible effect of PM-related traffic exposure to the occurrence of type 2 diabetes in highly urbanized areas in Germany. The association between PM exposure and type 2 diabetes has been reported elsewhere (Balti et al., 2014; Qiu et al., 2018; Weinmayr et al., 2015). Indeed, a systematic review and meta-analysis including ten cross-sectional and prospective studies reported that exposure to $PM_{2.5}$ was significantly associated with an increased risk of type 2 diabetes (Balti et al., 2014).

When we assessed the lower exposure level at which $PM_{2.5}$ has potential adverse effects (Table 3), although not significant, effect estimates were still elevated among the urban subjects. This indicated that exposure to air pollution (i.e. $PM_{2.5}$) was still detrimental to health even below the World Health Organization's recommended guidelines (Table 3). This corroborates with findings from previous studies that showed elevated effect estimates below the recommended guidelines for air quality (Orioli et al., 2018; Pearson et al., 2010). Hence, in this study, we were unable to establish a safe threshold for $PM_{2.5}$ and the risk of diabetes. In addition, we observed a stronger effect estimate for the association between $PM_{2.5}$ exposure and prevalence of diabetes mellitus in subjects aged 42 years and above compared to subjects younger than 42 years (Table 4). This supports the findings of previous studies showing that $PM_{2.5}$ is a significant risk factor for type 2 diabetes as compared to type 1 diabetes which tends to occur in children and young adults (Liu et al., 2013; Meo et al., 2015; Rao et al., 2015; Weinmayr et al., 2015).

There are some strengths to our study. First, we used a large population-based nationally representative survey (BHR), which had been validated beforehand. The quality of data collected in the 2013 BHR was assured in terms of methodology, validity of the variables, data

Table 4
Effect modification of the association between prevalence of diabetes mellitus and exposure to $PM_{2.5}$ levels in Indonesia.

Characteristics	Subgroups	Case/N	Prevalence	OR (95%Confidence Intervals)	*p*-interaction
Age	< 42	1392/336,982	0.41	0.95 (0.86–1.05)	0.001
	≥ 42	10,828/310,965	3.48	1.11 (1.07–1.16)	
Sex	Men	5243/314,045	1.67	1.12 (1.06–1.18)	0.196
	Women	6977/333,902	2.09	1.08 (1.03–1.13)	
Body Mass Index	< 23	4654/360,933	1.29	1.09 (1.02–1.15)	0.259
	≥ 23	7566/287,014	2.64	1.10 (1.05–1.15)	
Residency	Urban	7788/299,216	2.60	1.12 (1.07–1.17)	0.067
	Rural	4432/348,731	1.27	1.03 (0.96–1.11)	
Hypertension	Yes	4563/67,675	6.74	1.06 (1.00–1.12)	0.103
	No	7657/580,272	1.32	1.11 (1.06–1.17)	

Adjusted for age, sex, education, body mass index, type of residence, smoking, daily exposure to second-hand smoke, physical activity, vegetable intake, fruit intake, hypertension status, and gross-domestic regional product per-capita.

management, and data processing (Ministry of Health and National Institute of Health Research and Development, 2013). Second, subjects in the 2013 BHR included the entire household, where households were randomly selected. Third, the response rates for the survey were above 90.0% (98.3% for the households and 93.0% for the subjects within households). Fourth, in this study, we were able to examine the association with a relatively wide range of the $PM_{2.5}$ exposure. This has been a limitation in other studies, which were mainly conducted in developed countries where the observations of diabetes mellitus and air pollution were condensed in low concentrations (Orioli et al., 2018; Pearson et al., 2010). For example, in our study, concentrations of $PM_{2.5}$ reached 31.0-μg/m3, higher than that reported by Pearson et al., 2010 that assessed diabetes prevalence and exposure to $PM_{2.5}$ in the United States that reached 17.7-μg/m^3.

Conversely, there are several limitations to our study. First, the outcome was based on self-reported data, which can introduce misclassification of the outcome. For example, we found a lower prevalence of diabetes mellitus in Indonesia (1.89%) to that reported by the International Diabetes Federation in 2017 as 6.7% (International Diabetes Federation, 2017) which may arise from the undiagnosed or less likelihood of reported diabetes in the BHR survey. However, this misclassification would be nondifferential, moving the estimate towards the null (Rothman, 2012). Second, the measurement for exposure was at the village level and not the individual level and that a limitation may arise from the modelled data used for the exposure. Third, the BHR had no information on indoor air pollution concentrations, which may have a possibility to confound the association. However, we found positive associations between $PM_{2.5}$ exposure and the prevalence of diabetes even in urban areas where concentrations of indoor air pollution are relatively low mainly attributed to the use of solid/biomass fuel (Mestl et al., 2007; Suryadhi et al., 2019).

Our findings support the emerging evidence that suggests an association between $PM_{2.5}$ and diabetes even at levels below the World Health Organization recommended Guidelines. However, other studies (i.e., cohort and case-control) are warranted to confirm the association. If that association is causal, certain measures should be taken to consider the burden of diabetes, especially in countries with high air pollution. For example, in Indonesia, with a prevalence of diabetes mellitus that is projected to increase to 14.1 million people by 2035 (Guariguata et al., 2014), this would not only pose a burden to the healthcare system (Soewondo et al., 2013) but also the quality of life of people with diabetes.

5. Conclusion

In this study, we assessed the association between $PM_{2.5}$ exposure and diabetes mellitus in Indonesia. Our findings suggest a positive association between $PM_{2.5}$ exposure and the prevalence of diabetes mellitus that is possibly below the current recommended guidelines. Future studies are needed to ascertain the causal association of this finding. If a causal association is established, this should become a main interest point for the public health sector and policy makers, especially for those in places with high air pollution.

Ethical statement

We received anonymous data that had previously received ethical clearance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.105603.

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