Effects of Particulate Air Pollution on the Respiratory Health of Subjects Who Live in Three Areas in Kanpur, India

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ABSTRACT. In this study, the authors assessed the relationship between daily changes in respiratory health and particulate levels with diameters of (a) less than 10 μm (PM_{10}) and (b) less than 2.5 μm ($PM_{2.5}$) in Kanpur, India. The subjects ($N = 91$) were recruited from 3 areas in Kanpur: (1) Indian Institute of Technology (Kanpur), which was a relatively clean area; (b) Vikas Nagar, a typical commercial area; and (c) finally, the residential area of Juhilal Colony. All subjects resided near to air quality monitoring sites. Air quality and peak expiratory flow rate samplings were conducted for 39 d. Once during the sampling period, lung-function tests (i.e., forced expiratory volume in 1 s, forced vital capacity) were performed on each subject. Subjects who resided at the clean site performed at predicted (i.e., acceptable) values more often than did subjects who lived at the remaining 2 sites. Subjects who lived at all 3 sites demonstrated a substantial average deficit in baseline forced vital capacity and forced expiratory volume in 1 s values. The authors used a statistical model to estimate that an increase of 100 μg/m³ of the pollutant PM_{10} could reduce the mean peak expiratory flow rate of an individual by approximately 3.2 l/min.

<Key words: $FEV_{1.0}$, FVC, health effects, India, PEFR, PM_{10}, $PM_{2.5}$>

AMBIENT LEVELS OF POLLUTANTS are increasing in most of the metropolitan cities in India because urbanization and industrialization continue to increase. Although emission norms have been stipulated and industrial emissions are being controlled, there is a rise in the concentration of particulate matter (PM [specifically particulate matter with aerodynamic diameters of 50 μm or less]) in urban areas. Biswas and Pandey[1] reviewed air quality trends of the major metropolitan areas in India, and they observed that the levels of criteria pollutants (e.g., sulfur dioxide [SO_2], nitrogen oxides [nitrogen dioxide {NO_2} + nitric oxides {NO} = nitrogen oxide {NO_x}]) were well within the national ambient air quality standards. They also found, however, that the concentration of ambient PM was increasing. Among many of India's cities, PM levels are approximately 4–5 times those in U.S. cities.[2] Such high PM levels may severely affect the public health of India's citizens.

A 16-yr-long survey conducted by Dockery et al.[3] revealed a strong correlation between ambient concentration of PM and increased mortality and hospitalizations for respiratory diseases. In several epidemiological studies,[4,5] investigators linked the presence of particulate matter with aerodynamic diameters less than or equal to 10 μm (PM_{10})—and especially particulate matter with aerodynamic diameters of less than or equal to 2.5 μm ($PM_{2.5}$)—with significant health problems, including the following: premature mortality, chronic respiratory disease, emergency-room visits and hospital admissions, aggravated asthma, acute respiratory symptoms, and an overall decrease in lung function. $PM_{2.5}$ is of specific concern because it contains a high proportion of toxic metals and acids and, aerodynamically, it can penetrate deeper into the respiratory tract.[6] In most of the epidemiological studies on PM,[3,7] investigators have focused on PM and PM_{10}, but they typically issue the caveat that $PM_{2.5}$ is a better indicator of PM-related mortality than are the other 2 "indicators."

For example, Wichmann et al.[8] reported that the concentrations of both ultrafine ($PM_{<0.1}$) and fine particles ($PM_{0.1–2.5}$) were associated with increased daily mortality. Lippmann et al.[9] reported that of 5 particulate size fractions studied (i.e., PM_{40}, $PM_{10–40}$, PM_{10}, $PM_{2.5-10}$, and $PM_{2.5}$), only $PM_{10–40}$ was *not* associated with increased morbidity and mortality. In Mexico City, Castillejos et al.[10] found that health effects were associated with the coarse fraction (i.e., $PM_{2.5–10}$ particles in the aerodynamic diameter range of 10–2.5 μm) as well, but in a study by Schwartz,[5] conducted in the United States and in Canada, investigators reported that effects of fine particles are predominant. The results of the studies would appear to indicate that particulate matter, especially fine particles (i.e., $PM_{0.1}$–$PM_{2.5}$) are better indicators of health effects than are PM_{10} or total suspended particulate matter (TSPM).

Major concerns for human health from exposure to PM_{10} include effects on breathing, respiratory symptoms, decrease in pulmonary function, damage to lung tissue, cancer, and premature death. Vedal et al.[11] reported that a drop in temperature was associated with increased upper and lower respiratory illnesses but *not* with increased wheeze or with a decrease in peak expiratory flow rate (PEFR). An association between elevated PM_{10} levels and hospital admissions for pneumonia, bronchitis, and asthma was observed by Pope[4]; long-term particulate exposure was associated with an increase in risk of respiratory illness in children.[12] Statistically significant relationships were observed between TSPM levels and forced vital capacity (FVC) and forced expiratory volume in 1 s ($FEV_{1.0}$).[13] A decrease in lung function and an increase in respiratory symptoms were observed as particulate pollution levels increased.[14]

In a series of studies, Ostro[15] reported that observed associations existed between daily changes in particulate pollution levels and daily mortality. Associations between mortality risk and air pollution were strongest for respirable particles and sulfates.[16] PEFR and respiratory symptoms were associated (a) strongly with PM_{10} levels, and (b) marginally with ozone levels.[17] The coarse fraction of PM_{10} reportedly causes significant health problems—especially to individuals exposed to high concentrations of this pollutant in their work environments.[18] In a study in six U.S. cities, investigators found an association between fine particulate matter ($PM_{2.5}$)—primarily from combustion sources—and daily mortality.[5] Laden et al.[19] have clearly established that combustion particles in the fine fraction from mobile and coal combustion sources are associated with increased mortality.

Our review of the literature indicates that although air pollution health-effect studies have been conducted in developed countries, there is a need to examine the effects of PM in developing countries. This determination is especially important for developing countries (e.g., India), where exposure to fine particulate matter is increasing rapidly. The literature lacks cohort-based acute-exposure studies on the productive age group (i.e., 20–55 yr of age) in these countries, and in the aforesaid countries this age group very often represents more than 70% of the total population.

Materials and Method

The City of Kanpur (latitude 26°26′ N, longitude 88°22′ E) is among the most polluted cities in India, and the PM concentration in ambient air continues to increase.[20,21] Kanpur, therefore, is an ideal choice for the conduct of studies on the health effects of $PM_{2.5}$ and PM_{10} (Fig. 1). Lung function parameters (PEFR, $FEV_{1.0}$, and FVC) were examined vis-à-vis ambient air levels of PM_{10} and $PM_{2.5}$ for subjects located in 3 different sections of Kanpur (Fig. 2): (1) Indian Institute of Technology Kanpur (IITK), which is relatively clean; (2) Vikas Nagar,

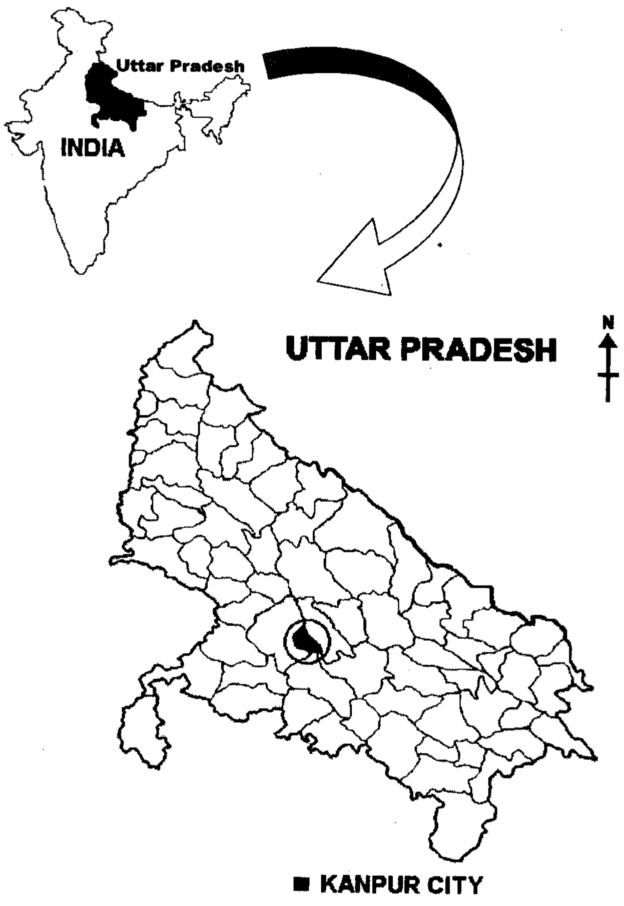

Fig. 1. Location of Kanpur City in India.

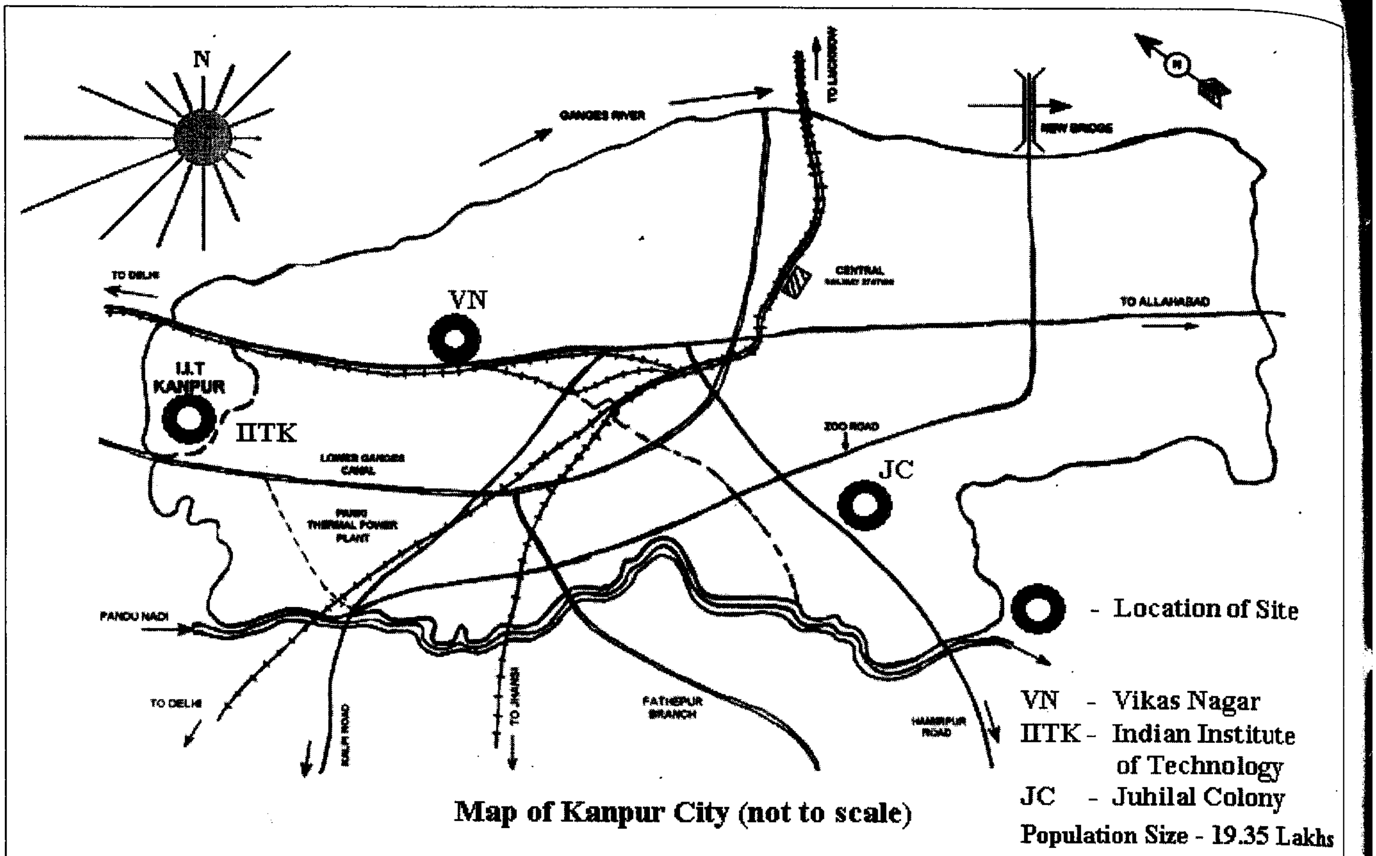

Fig. 2. Map depicting location of selected sites in Kanpur City and Wind Rose Diagram (June–August 2002).

an industrial area; and (3) Juhilal Colony, a residential area.

Study sites. IITK is an educational institution that includes a residential campus and no commercial or industrial activities. The campus is approximately 15 km north of the city (upwind) and enjoys minimum emissions. Campus vehicular traffic is mainly 2-wheelers and cars. There are very few heavy-duty vehicles. During most of the year, the campus receives no air pollution from Kanpur City. This site can ideally be identified as a control site. Sharma et al.[21] indicated it to be a clean site compared to other locations in the city (mean PM_{10} levels: 61 $\mu g/m^3$ at IITK, and other four locations in Kanpur City: 260–400 $\mu g/m^3$).

Vikas Nagar (VN) is a commercial and residential area on National Highway No. 91. It experiences heavy traffic: heavy-duty diesel vehicles and 2-stroke and diesel-driven 3 wheelers (Vikram Tempo) occupy the area throughout most days. Numerous commercial activities and other local sources of pollution (e.g., restaurants, garages, roadside vendors) are found in and around the area. Some of the roads proximal to the sampling site are not paved properly, and resuspension of soil most likely affected air quality at the time of this study. Previous air-monitoring data of the Central Pollution Control Board (CPCB) in Kanpur indicate that PM_{10} levels in this area were very high during the study and were typically representative of an urban commercial site.

Juhilal Colony (JC), although not "purely" a residential area, had no major roads or traffic in its immediate vicinity. Markets and considerable traffic exist within an approximate 1-km radius, all of which made this site a typical residential area within an urban area.

Subjects. We selected subjects on the basis of the results of a preliminary questionnaire specifically designed for this study. A database was generated from the survey results that included occupation (indicating income), height, weight, age, sex, food habits, type of residential facility, and distances of office and residence from the air quality monitoring site. We tried to ensure that all participants had similar socioeconomic indicators and that they were distributed evenly with respect to age (i.e., 20–55 yr). Although it was impossible for us to select participants with all the same socioeconomic indicators at all 3 aforementioned sites, we attempted to exclude the extremely rich (monthly income more than Rs 45,000, or approximately $1,023) or the extremely poor (monthly income less than Rs 5,000, or approximately $114). Tobacco smokers at all 3 locations were excluded from this study.

In total, 91 subjects participated in this study, and more than 90% of them worked or resided within 2 km of an air quality sampling site. This approach ensured that air quality levels represented exposure to PM for the participants. At IITK, the participants who were selected were mainly students and laboratory staff of the Department of Civil Engineering, and every participant in this category resided on campus. The CPCB Kanpur Zonal office was located near the VN site; therefore, we determined that a cohort from the aforementioned office staff would be representative of the population (i.e., exposure would exceed 8 hr). In addition, 2 families who lived in VN and who were located less than 200 m from the air quality monitoring site were also selected for study. At JC, all of the families we selected were middle income, and they worked and lived near the monitoring site.

Air sampling. Twenty-four-hour air quality sampling was performed at the selected locations for PM_{10} and $PM_{2.5}$ for 39 d during November 2002–April 2003. Specifically, the sampling was performed in 2002 at VN from November 26–29; December 2–5; December 9–11, 18–20, and 23. In 2003, the sampling was performed at JC on February 5–19 and at IITK on April 18–26. The sampling was performed during these months because higher values of pollutants were expected in winter, but sometimes sampling had to be done only on those days when uninterrupted electric power was available. High-volume samplers were used for PM_{10} (model APM 451, Envirotech, New Delhi, India; NPM-HVS sampler, Netel, India) and $PM_{2.5}$ (model APM 550, Envirotech, New Delhi, India) sampling. Additional details about particulate sampling have been published by Maloo.[20] In summary, PM_{10} air samples were analyzed for heavy metals and benzene soluble fraction (BSF). BSF indicates the organic content of particulate matter—especially the aromatic component—including polycyclic aromatic hydrocarbons (PAHs).

Pulmonary function tests. Pulmonary function tests were conducted by graduate students at the Department of Chest and Tuberculosis, GSVM Medical College, Kanpur, India. The PEFR, which was measured with a Personal-Best PEF Meter (Respironics, Murrysville, Pennsylvania), was conducted for each subject for the same 39-d period as was the air monitoring. PEFR is an indicator of asthma. The National Asthmatic Education and Prevention Program of the National Institutes of Health (NIH)[22] has classified asthmatic conditions into 3 zones: (a) green, (2) yellow, and (3) red. This classification is predicated on the percentage of observed PEFR value of predicted PEFR value. The predicted PEFR value (or acceptable value) of an individual depends on sex, age, and height.[23] The zones are defined as follows: (a) green—observed PEFR value that exceeds 80% of the predicted value (i.e., no symptoms of asthma); (b) yellow—observed PEFR value that exceeds 50% but that is less than 80% of the predicted value (i.e., beginning of asthma); and (c) red—observed PEFR value less than 50% of the predicted value (i.e., requires medical attention). In accordance with these guidelines, the asthmatic status of each subject was determined on the basis of a PEFR value.

Pulmonary function tests were achieved with a spirometer (Spirobank-G, MIR, Rome, Italy) once during the air-sampling period, approximately halfway through the sampling campaign at each site. With the limited tests (i.e., PEFR, FVC, and $FEV_{1.0}$) performed, it was impossible for the authors to state clearly whether individuals suffered from asthma or if they had respiratory problems or whether the problems resulted from dust-induced bronchitis. A complete diagnosis for the determination of disease type would require follow-up testing, which was not performed in this study.

Statistical analysis. It was not advisable to directly examine a 1-to-1 association between PEFR and PM_{10} and $PM_{2.5}$ of all individuals as a group because the absolute PEFR value of an individual depends on body responses and body parameters (e.g., height, age, sex). The authors determined that a technique to overcome confounding factors during the development of a composite assessment of health effects with respect to PEFR values vis-à-vis PM_{10} and $PM_{2.5}$ levels was to calculate mean daily deviations in PEF (i.e., ΔPEFs) and evaluate them with respect to PM_{10} and $PM_{2.5}$ levels.[14] The mean PEFR (l/min) for each participant of a given site where air quality sampling and PEFR measurements were done concurrently was calculated for 15 d at VN, 15 d at JC, and 9 d at IITK. The days of sampling were November 2002–April 2003. Individual deviations in daily performance were calculated from each participant's mean PEFR data; in other words, we calculated the deviation in PEFR performance of individual subjects (from their respective mean PEFR) for each day of sampling. Then, for each day, we averaged the calculated deviations across the participants *individually* to obtain a daily mean deviation (i.e., ΔPEF). If ΔPEF was negative, it suggested that the lungs were performing below the average capacity of the subjects. Pope and Dockery[14] used the aforementioned technique to examine ΔPEF vs. PM concentration, and they found an association between health effects and PM levels. Therefore, if ΔPEF decreases, and PM_{10} and/or $PM_{2.5}$ increase consistently, pollution levels are considered the cause of lung function deterioration.

The authors used correlational analysis to analyze mean ΔPEF (for the day) versus 4 daily PM parameters: (1) PM_{10}, (2) $PM_{2.5}$, (3) PM_{10} (1-d lag), and (4) $PM_{2.5}$ (1-d lag). Regression models were fitted to the data set with $PM_{10}/PM_{2.5}$ as the independent and ΔPEF as the dependent variable. Such models can predict ΔPEF with increasing or decreasing pollution levels. All calculations and the model fitting were performed using a Microsoft Excel spreadsheet.

Results

The number of subjects and their characteristics at the 3 study sites are summarized in Table 1. Subjects were mostly male at VN and at IITK, as the respective samples were drawn from people working in the offices in VN and students residing in a boy's hostel. At JC (a residential area), there were more female subjects, most of whom were housewives. Mean PEFR values of the subjects, by air-sampling area, appear in Figure 3. The largest percentage of subjects with normal lung performance were mostly from IITK, a relatively cleaner site, and the next largest were the subjects at VN, an urban commercial site. At JC, a small fraction (about 8%) of subjects showed lung performance below 50% of their normal value.

Means and standard deviations for PM_{10} and $PM_{2.5}$ by air sampling site are presented in Table 2. The spatial variation of PM levels shows the least particulate pollution at IITK, followed by JC and VN. Heavy metals were highest at VN, followed by JC and IITK (Table 3). Lead was of particular significance because its level in gasoline has been reduced from 0.15 to 0.013 g/l; nonetheless, it remains present in ambient air in India and still poses health risks to the occupants of that country. The spatial variation of BSF (i.e., organic pollution) was similar to that of heavy metals and particulate concentrations. Levels of BSF were lowest at IITK and very high at

Table 1.—Number and Characteristics of Subjects, by Air-Sampling Site

	Males		Females		Other characteristics					
Site	Age ≤ 35 yr (*n*)	Age > 35 yr (*n*)	Age ≤ 35 yr (*n*)	Age > 35 yr (*n*)	Average age (yr)	Range (yr)	Average weight (kg)	Range (yr)	Average height (cm)	Range (cm)
VN	16	11	5	1	34	20–58	63	40–85	165	154–182
JC	6	8	11	8	37	20–61	53	37–71	159	147–180
IITK	17	3	4	1	27	22–50	60	46–81	168	154–185

Notes: VN = Vikas Nagar, JC = Juhilal Colony, and IITK = Indian Institute of Technology Kanpur.

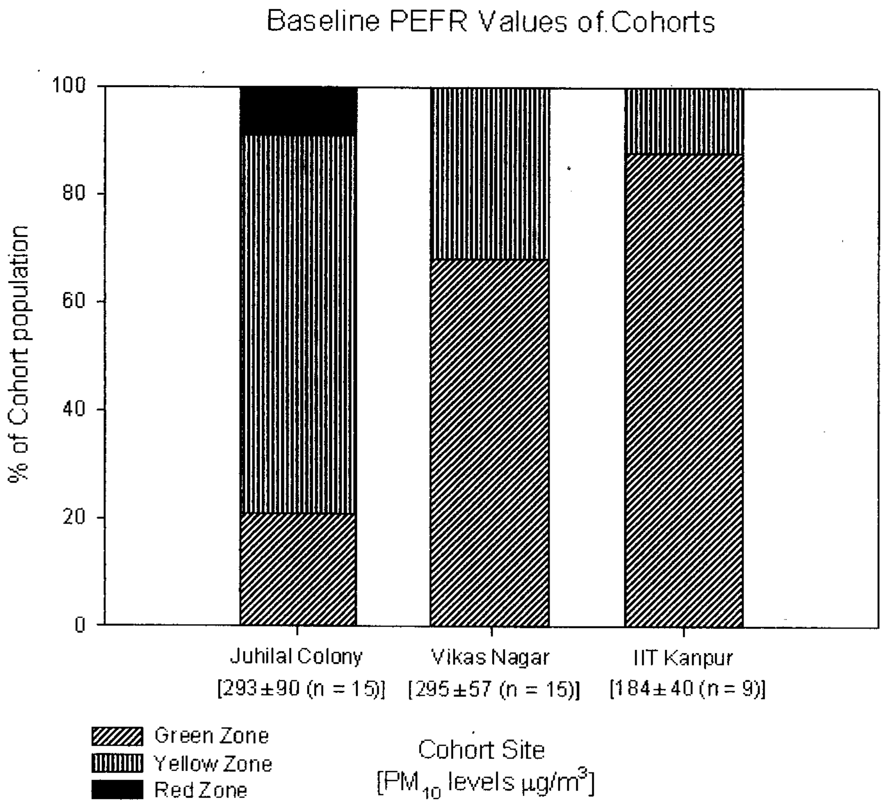

Fig. 3. Baseline lung status of study cohort.

both VN (i.e., 107 ± 62 $\mu g/m^3$) and JC (48 ± 42 $\mu g/m^3$). Such high levels indicate increased exposures to organic PM, including polycyclic aromatic hydrocarbons (PAHs).

In Table 4 are shown the correlations between mean ΔPEF of a day (no. of days of sampling = 39) and 4 indicators of PM levels (PM_{10}, $PM_{2.5}$, PM_{10} [1-d lag], and $PM_{2.5}$ [1-d lag]). The negative correlations were all statistically significant ($p < .05$) (i.e., as pollution levels increased, lung function in terms of PEFR deteriorated). The negative correlation with PM_{10} (1-d lag) and $PM_{2.5}$ (1-d lag) also suggests that PM pollution may have a sustained effect on a PEFR value because of the pollution level of the previous day.

Two models—(1) ($\Delta PEF = C_1 + a_1 PM_{10}$ [hereinafter Model I]) and (2) ($\Delta PEF = C_2 + a_2 PM_{2.5}$ [hereinafter Model II]), where C_1 and C_2 are the intercepts and a_1 and a_2 are the slopes of the fitted line to indicate ΔPEF due to unit change in PM_{10} and $PM_{2.5}$ levels in Models I and II—were fitted to the data set (Table 5, Figs. 4 and 5). The estimated regression coefficients were statistically significant. The Pearson correlation coefficients (−.52 for Model I and −.3 for Model II) between modeled and observed ΔPEF for both models were statistically significant. Although imperfect, the models served to predict the change in ΔPEF as pollution levels increased and/or decreased. We compared our results to those of Pope and Dockery[14] (Table 5), who used similar models to estimate the impact of increasing and/or decreasing PM levels. Their sample size was much larger than ours, and their asymptomatic and symptomatic samples were separated. The coefficients estimated in the current study were somewhat higher than those estimated by Pope and Dockery.[14]

Table 2.—Means and Standard Deviations for Particulate Matter with Diameters ≤ 10 μm (PM_{10}) and Particulate Matter with Diameters ≤ 2.5 μm ($PM_{2.5}$), by Air-Sampling Site

		PM_{10} ($\mu g/m^3$)		$PM_{2.5}$ ($\mu g/m^3$)	
Site	*n*	Mean	*SD*	Mean	*SD*
VN	15	295	58	158	22
JC	15	293	90	85	30
IITK	9	184	40	59	9

Notes: SD = standard deviation, VN = Vikas Nagar, JC = Juhilal Colony, and IITK = Indian Institute of Technology Kanpur.

Table 4.—Correlations between Change in Peak Expiratory Flow and 4 Indicators of Particulate Matter (PM) Levels

Parameter	ΔPEF	PM_{10}	$PM_{2.5}$	PM_{10} (1-d lag)	$PM_{2.5}$ (1-d lag)
ΔPEF	1				
PM_{10}	−.52	1			
$PM_{2.5}$	−.30	.67	1		
PM_{10} (1-d lag)	−.32	.45	.49	1	
$PM_{2.5}$ (1-d lag)	−.27	.46	.88	.67	1

Notes: All values were statistically significant (i.e., $p < .05$). ΔPEF = change in peak expiratory flow, PM_{10} = particulate matter with diameter ≤ 10 μm, $PM_{2.5}$ = particulate matter with diameter ≤ 2.5 μm, PM_{10} (1-d lag) = PM_{10} concentration of previous day, and $PM_{2.5}$ (1-d lag) = $PM_{2.5}$ concentration of previous day.

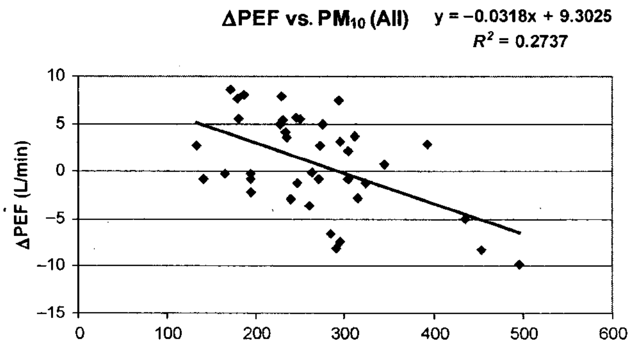

Fig. 4. Particulate matter with diameters ≤ 10 μm (PM_{10}) vs. change in peak expiratory flow (ΔPEF).

Table 3.—Means and Standard Deviations for Heavy Metal and Benzene-Soluble Fraction (BSF) Concentrations ($\mu g/m^3$) by Air-Sampling Site

	Pb		Ni		Cd		Cr		Fe		Zn		BSF	
Site	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
IITK	0.15	0.08	0.06	0.02	0.004	0.002	0.04	0.008	0.62	0.30	0.32	.12	9	4
VN	0.66	0.47	0.19	0.08	0.030	0.013	0.28	0.13	4.17	2.00	1.10	.53	107	62
JC	0.33	0.14	0.10	0.06	0.010	0.004	0.11	0.05	3.09	1.82	0.97	.57	48	42

Notes: Pb = lead, Ni = nickel, Cd = cadmium, Cr = chromium, Fe = iron, Zn = zinc, VN = Vikas Nagar, JC = Juhilal Colony, and IITK = Indian Institute of Technology Kanpur.

Table 5.— Regression Coefficients, by 3 Indicators of Particulate Matter (PM) Levels across Studies

			Pope and Dockery[14]			
	Current study		Symptomatic (n = 100)		Asymptomatic (n = 100)	
Indicators	Model I (n = 39)	Model II (n = 39)	Model I	Model II	Model I	Model II
PM_{10} (concurrent day, μg/m^3)	−0.0318 (9.025)	—	−0.0175 (0.6006)	—	−0.0110 (−3.606)	—
$PM_{2.5}$ (concurrent day, μg/m^3)	—	−0.0297 (4.0947)	—	—	—	—
PM_{10} (5-d moving average)	—	—	—	−0.0359 (2.0934)	—	−0.0254 (−2.504)

Notes: Values that appear in parentheses are the intercepts. PM_{10} = PM with diameters ≤ 10 μm, and $PM_{2.5}$ = PM with diameters ≤ 2.5 μm. In the regression analysis prepared by Pope and Dockery,[14] low temperature and time trend were included (n represents number of sampling days).

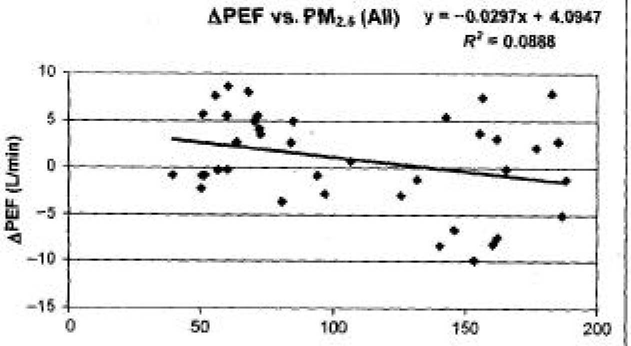

Fig. 5. Particulate matter with diameters of 2.5 μm ($PM_{2.5}$) vs. change in peak expiratory flow (ΔPEF).

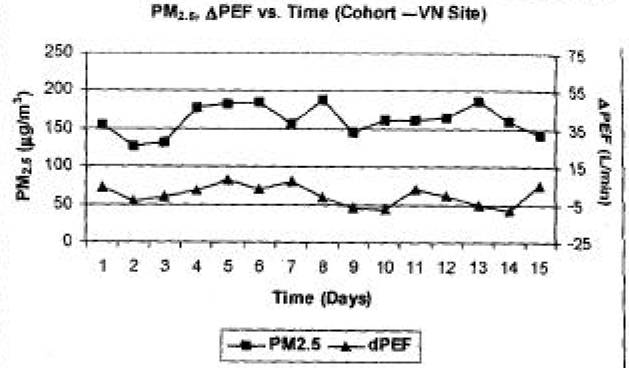

Fig. 7. Daily changes in levels of particulates with diameters of 2.5 μm ($PM_{2.5}$) and mean change in peak expiratory flow (ΔPEF) at Vikas Nagar (VN). *Notes:* PM2.5 = $PM_{2.5}$, and dPEF = ΔPEF.

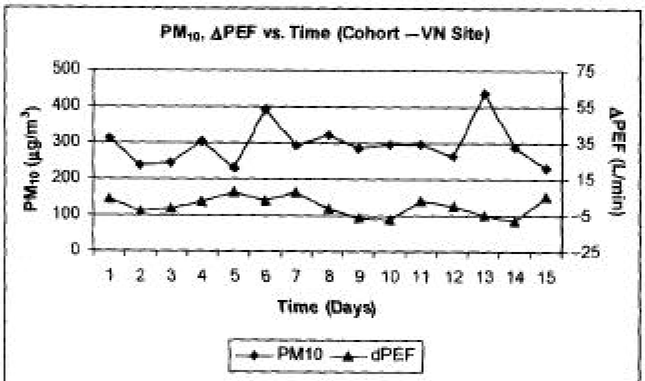

Fig. 6. Daily changes in levels of particulates with diameters ≤ 10 μm (PM_{10}) and mean change in peak expiratory flow (ΔPEF) at Vikas Nagar (VN). *Notes:* PM10 = PM_{10}, and dPEF = ΔPEF.

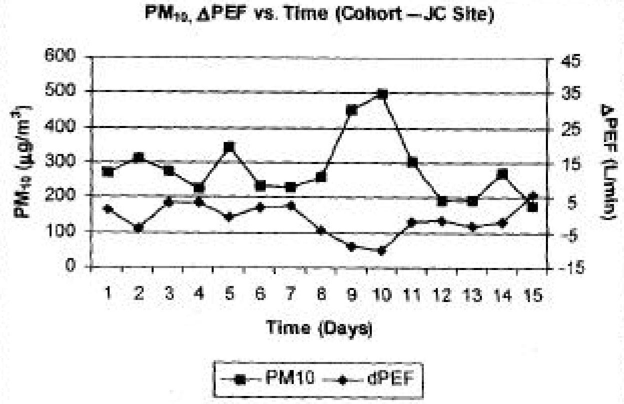

Fig. 8. Daily changes in levels of particulates with diameters of 10 μm (PM_{10}) and mean change in peak expiratory flow (ΔPEF) at Juhilal Colony (JC). *Notes:* PM10 = PM_{10}, and dPEF = ΔPEF.

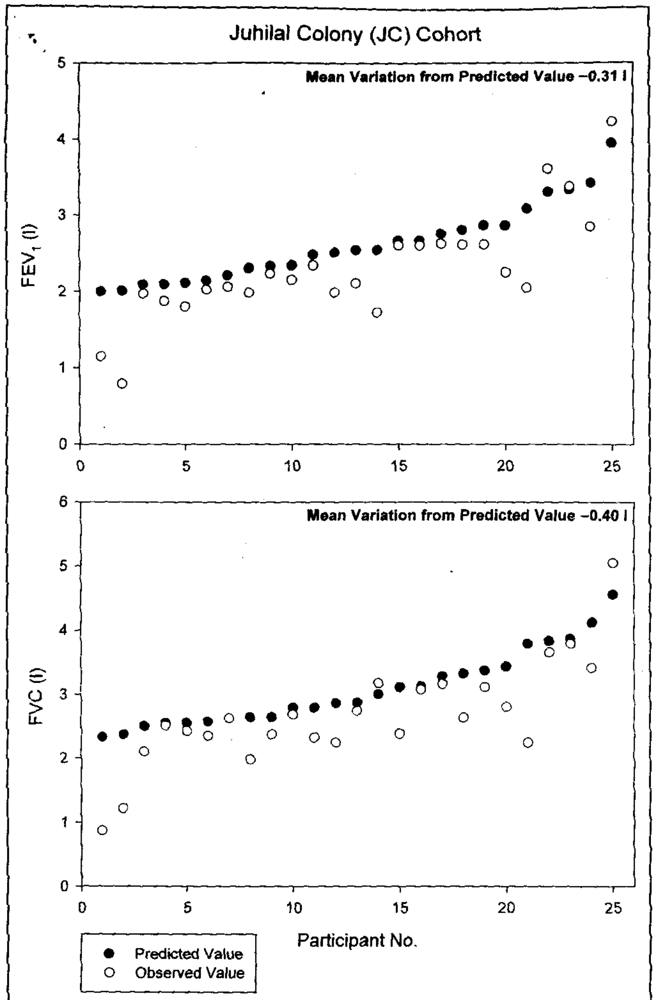

Fig. 13. Comparison of observed and predicted (reference) forced expiratory volume in 1 s ($FEV_{1.0}$) and forced vital capacity (FVC) values at Juhilal Colony (observed $FEV_{1.0}$ and FVC sorted in ascending order).

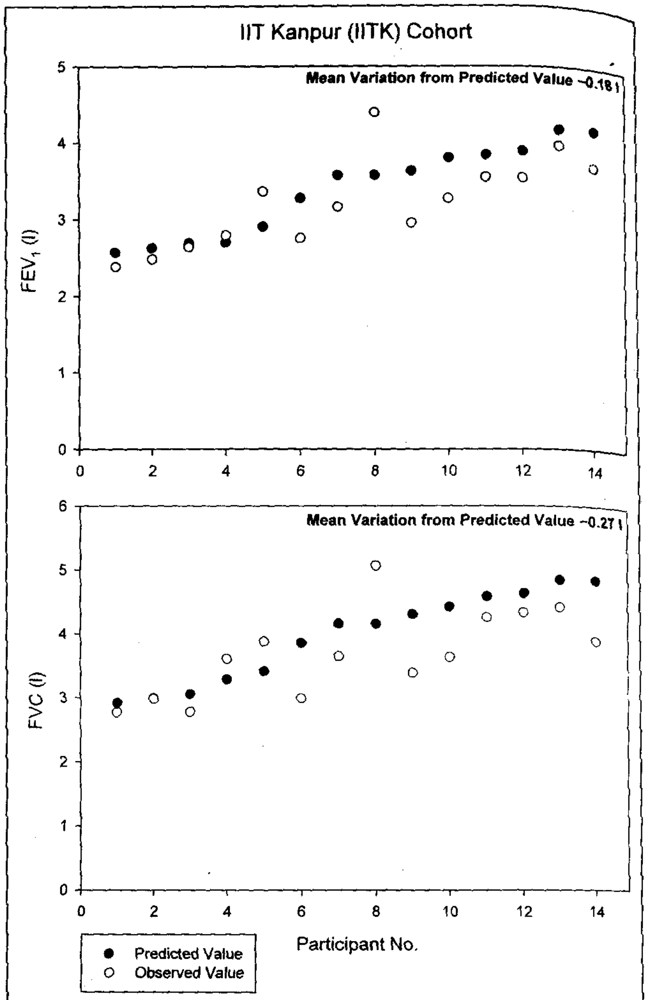

Fig. 14. Comparison of observed and predicted (reference) forced expiratory volume in 1 s ($FEV_{1.0}$) and forced vital capacity (FVC) values at the Indian Institute of Technology Kanpur (IITK) (observed $FEV_{1.0}$ and FVC sorted in ascending order).

Table 6.—Mean Variation of Forced Expiratory Volume in 1 s ($FEV_{1.0}$), Forced Vital Capacity (FVC [from Predicted Value]), and Mean Particulate Concentrations, by Air-Sampling Site

Site	$\Delta FEV_{1.0}$ (l)	ΔFVC (l)	PM_{10} ($\mu g/m^3$)	$PM_{2.5}$ ($\mu g/m^3$)	$PM_{10-2.5}$ ($\mu g/m^3$)
VN	−0.30	−0.42	295	158	137
JC	−0.31	−0.40	293	85	208
IITK	−0.18	−0.27	184	59	125

Notes: VN = Vikas Nagar, JC = Juhilal Colony, and IITK = Indian Institute of Technology Kanpur. Period during which air quality was monitored: VN (15 d; Nov.–Dec. 2002); JC (15 d; Feb. 2003); and IITK (9 d; April 2003). Spirometry: once at the end of the air quality campaign at each site for each participant. $FEV_{1.0}$ = forced expiratory volume in 1 s, FVC = forced vital capacity, and PM_{10} and $PM_{2.5}$ = particulate matter with diameters ≤ 10 μm and 2.5 μm, respectively.

$FEV_{1.0}$, FVC, and PEFR are the key lung function parameters that reflect the long-term health effect of air pollution[24] on lung performance. $FEV_{1.0}$ and FVC depend on age, height, weight, sex, and race. To avoid the complexity in analysis due to age, height, and sex, we examined the variations in $FEV_{1.0}$ and FVC with respect to predicted values of $FEV_{1.0}$ and FVC. Predicted (reference/acceptable) values accounted for age, height, weight, sex, and race. To determine unequivocally if there was a difference between predicted and observed values of $FEV_{1.0}$ and FVC, we sorted the predicted values in an ascending order (Figs. 12–14). More subject values approximated the predicted values at the IITK site than at the VN and JC sites (i.e., the more polluted sites). At IITK, the deviation (i.e., average of observed–predicted values) was much lower than at the other sites, suggesting that the population at IITK had better respiratory health ($\Delta FEV_{1.0}$: –0.30 l, –0.31 l, and –0.18 l at VN, JC, and IITK, respectively; ΔFVC: –0.42 l, –0.40 l, and –0.27 l, respectively).

The variation in $FEV_{1.0}$ and FVC values with respect to the 3 particulate indicators (i.e., PM_{10}, $PM_{2.5}$, and $PM_{10-2.5}$) is shown in Table 6. $PM_{10-2.5}$, which is a composite indicator of $PM_{2.5}$ and PM_{10}, is a better gauge of lung function than either of the other 2 indicators viewed individually (Table 6).

Discussion

In this study, we examined the effects of PM on the respiratory health of subjects in 3 distinct areas of Kanpur, India. Average PM_{10} concentrations in the study areas ranged from 184 $\mu g/m^3$ to 295 $\mu g/m^3$. Subjects from areas with higher PM_{10} levels demonstrated a somewhat greater reduction in PEFR per unit increase in PM_{10}. Such changes can trigger harmful acute respiratory effects, and in cities in which large numbers of individuals have asthma, the potential impact on public health is significant.

Our findings can be compared to those of Xiping et al.,[25] who reported changes in $FEV_{1.0}$ and FVC values in Beijing with respect to total suspended particulate matter (TSPM) levels (i.e., annual TSPM: 389 $\mu g/m^3$ [residential area], 261 $\mu g/m^3$ [suburban area], and 449 $\mu g/m^3$ [industrial area]). The aforementioned levels are similar to the pollution levels we documented in Kanpur (except at IITK). Xiping et al.[25] also reported mean reductions in $FEV_{1.0}$ and FVC for a "clean" area (coal as cooking fuel) versus a polluted area of 0.16 l and 0.34 l, respectively. One can also similarly assess the change in $FEV_{1.0}$ in polluted and unpolluted areas in Kanpur (i.e., reduction in $FEV_{1.0}$, approximately 0.12 l [VN, 0.30 l; IITK, 0.18 l]); the reduction in FVC, approximately 0.15 l (i.e., 0.42 l at VN and 0.27 at IITK). Such findings are comparable with the results published by Xiping et al.[25]

In a study by Chestnut et al.,[13] the authors suggested that a 34 $\mu g/m^3$ increase in TSP has the potential to reduce FVC by 2.25%. However, in our current study there was a much greater increase in particulate matter concentration, and PM_{10}—not TSP—was considered, the result of which was a larger reduction in FVC. Ratios of $FEV_{1.0}$ to FVC were compared at 3 locations herein. The average ratio of $FEV_{1.0}$/FVC at the 3 sites was similar (i.e., 0.8 to 0.85). The absence of a relationship between $FEV_{1.0}$/FVC ratios with particulate pollution was also reported by Chestnut et al.[13] for TSPs.

The negative correlations we found between mean ΔPEF (a measure of PEFR) and 4 indicators of PM levels (i.e., PM_{10}, $PM_{2.5}$, PM_{10} [1-d lag], and $PM_{2.5}$ [1-d lag]) indicated that as pollution levels increased, there was a deterioration or reduction in lung function (i.e., PEFR). The negative correlation with PM_{10} (1-d lag) and $PM_{2.5}$ (1-d lag) also suggested that PM pollution may have a sustained effect on PEFR values as a result of previous-day pollution levels.

Our statistical models estimated that an increase in pollution level of 100 $\mu g/m^3$ (i.e., PM_{10}) can cause a reduction in the mean PEFR by approximately 3.2 l/min. We concluded (spirometry tests [$FEV_{1.0}$ and FVC]) that more people were close to predicted (reference) values at the clean site than at the remaining 2 sites (i.e., VN and JC), both of which were highly polluted areas. In this study, we concluded that there was a substantial average deficit in baseline FVC and $FEV_{1.0}$— even at the cleaner site.

Finally, although both PM_{10} and $PM_{2.5}$ correlated with ΔPEF, PM_{10} appeared to be a better indicator of changes in PEFR values. Perhaps this conclusion can be explained by the fact that deposition of larger particles (i.e., PM_{10}) occurs in the upper portion of the respiratory system, which then activates mucus secretion and results in constriction of the airways, thus lowering the PEFR value. Given that the coarse fraction of PM is of great importance in the prediction of adverse respiratory health effects, particularly in developing cities such as Kanpur in which dusty conditions are prevalent, PM_{10} sampling cannot be preempted by $PM_{2.5}$ sampling.

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