Epidemiology and Prevention

Air Pollution and Incidence of Hypertension and Diabetes Mellitus in Black Women Living in Los Angeles

Patricia F. Coogan, ScD; Laura F. White, PhD; Michael Jerrett, PhD; Robert D. Brook, MD; Jason G. Su, PhD; Edmund Seto, PhD; Richard Burnett, PhD; Julie R. Palmer, ScD; Lynn Rosenberg, ScD

Background—Evidence suggests that longer-term exposure to air pollutants over years confers higher risks of cardiovascular morbidity and mortality than shorter-term exposure. One explanation is that the cumulative adverse effects that develop over longer durations lead to the genesis of chronic disease. Preliminary epidemiological and clinical evidence suggests that air pollution may contribute to the development of hypertension and type 2 diabetes mellitus.

Methods and Results—We used Cox proportional hazards models to assess incidence rate ratios (IRRs) and 95% confidence intervals (CIs) for incident hypertension and diabetes mellitus associated with exposure to fine particulate matter (PM$_{2.5}$) and nitrogen oxides in a cohort of black women living in Los Angeles. Pollutant levels were estimated at participants’ residential addresses with land use regression models (nitrogen oxides) and interpolation from monitoring station measurements (PM$_{2.5}$). Over follow-up from 1995 to 2005, 531 incident cases of hypertension and 183 incident cases of diabetes mellitus occurred. When pollutants were analyzed separately, the IRR for hypertension for a 10-$\mu$g/m$^3$ increase in PM$_{2.5}$ was 1.48 (95% CI, 0.95–2.31), and the IRR for the interquartile range (12.4 parts per billion) of nitrogen oxides was 1.14 (95% CI, 1.03–1.25). The corresponding IRRs for diabetes mellitus were 1.63 (95% CI, 0.78–3.44) and 1.25 (95% CI, 1.07–1.46). When both pollutants were included in the same model, the IRRs for PM$_{2.5}$ were attenuated and the IRRs for nitrogen oxides were essentially unchanged for both outcomes.

Conclusion—Our results suggest that exposure to air pollutants, especially traffic-related pollutants, may increase the risk of type 2 diabetes mellitus and possibly of hypertension. (Circulation. 2012;125:767-772.)

Key Words: air pollution ■ diabetes mellitus ■ epidemiology ■ hypertension

Hundreds of epidemiological studies have established associations between exposure to air pollutants and increased risks of acute cardiovascular events, including fatal and nonfatal heart attack and stroke.\textsuperscript{1–3} The overall evidence also suggests that longer-term exposure over years confers higher risks than does shorter-term exposure.\textsuperscript{2} One explanation is that there are cumulative adverse health effects during longer durations that lead to the genesis of chronic diseases. In particular, given the potential for air pollutants to promote inflammation, oxidative stress, and endothelial dysfunction, it has been suggested that air pollution may contribute to 2 chronic conditions that are major risk factors for acute cardiovascular events, hypertension and diabetes mellitus.\textsuperscript{2} Preliminary evidence supports the plausibility of this hypothesis. Animal\textsuperscript{4,5} and human\textsuperscript{6,7} studies have shown that air pollutant exposure is associated with another chronic condition, atherosclerosis, and both particulate matter and NO$_2$ have been shown to elevate blood pressure\textsuperscript{8–11} and to increase fasting glucose levels.\textsuperscript{12}

Clinical Perspective on p 772

Associations between air pollutants and hypertension\textsuperscript{13} and diabetes\textsuperscript{14} prevalence have been reported in cross-sectional studies. Only 2 studies have assessed diabetes incidence.\textsuperscript{15,16} In a German study, the risk of incident diabetes mellitus over 16 years of follow-up increased from 15% to 42% per interquartile range (IQR) of long-term traffic-related exposures including particulate matter and NO$_2$.\textsuperscript{15} In the Nurses’ Health Study, incident diabetes mellitus had little association with particulate matter, but living within 50 m of a major road was associated with an 11% increase in incidence.\textsuperscript{16}

Even a modest effect of air pollutants on the risks of hypertension and diabetes mellitus will have a significant

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public health impact because of their high incidence and the ubiquity of exposure. This issue is of particular importance for black women because the incidence of both hypertension and diabetes mellitus is almost twice as high in black women as in white women, and black Americans experience higher levels of air pollution than do white Americans. We assessed the risks of incident hypertension and diabetes mellitus associated with exposure to fine particulate matter with an aerodynamic diameter of ≤2.5 μm (PM$_{2.5}$) and to nitrogen oxides (NOx), a marker of traffic-related air pollution, in a cohort of black women living in Los Angeles.

**Methods**

**Study Population**

The women included in the present analyses are participants in the Black Women’s Health Study (BWHS), a prospective cohort study of black women. The BWHS was established in 1995, when ~59,000 black women 21 through 69 years of age were recruited mainly from subscribers to Essence magazine. The baseline questionnaire elicited information on demographic and lifestyle factors, reproductive history, dietary intake, and medical conditions. The cohort is followed up biennially by mailed questionnaire, and follow-up has averaged >80% of the original cohort through 7 questionnaire cycles. The study protocol was approved by the Institutional Review Board of Boston University. Participants indicate informed consent by completing the questionnaires.

The analytic cohorts for the present analyses were derived from 10 years of follow-up (1995–2005) of 4204 women who lived in Los Angeles at baseline in 1995. The hypertension cohort included 3236 women who were free of hypertension at baseline in 1995; the diabetes cohort included 3992 women who were free of diabetes mellitus at baseline. Mean follow-up time in both cohorts was 10 years.

**Case Ascertainment**

**Hypertension**

We defined an incident case of hypertension as self-report of doctor-diagnosed hypertension during follow-up through 2005 and concurrent use of antihypertensive medications. We assessed the accuracy of self-reported hypertension among 139 participants who met these criteria for whom we were able to obtain medical records or physician checklists; hypertension was confirmed in 99%, with all systolic pressures being ≥140 mm Hg and diastolic pressures being ≥90 mm Hg.

**Diabetes Mellitus**

We defined an incident case of type 2 diabetes mellitus as self-report of doctor-diagnosed diabetes mellitus at ≥30 years of age during follow-up through 2005. Among 227 participants who met the definition of diabetes mellitus and whose physicians provided data from their medical records, the diagnosis of type 2 diabetes mellitus was confirmed in 96%.

**Environmental Exposure Assessment**

**PM$_{2.5}$ Assessment**

To estimate PM$_{2.5}$ exposure, we interpolated from 23 state and local district monitoring stations in the Los Angeles basin for the year 2000 with a kriging model. We used a universal kriging algorithm that allowed the assignment of long-term mean ambient PM$_{2.5}$ concentrations to the ZIP code area of each participant’s residential address. Further details are given elsewhere. A comparison of PM$_{2.5}$ values estimated from the model with monitored concentrations for the Los Angeles region showed that >50% of the area had estimated values within 15% of monitored concentrations and 67% were within 20%.

**NOx Assessment**

We used a land use regression model to estimate mean annual NOx (parts per billion [ppb]) levels at participants’ residential addresses. Methods are described in detail elsewhere. In brief, the model was based on field measurements at 183 locations in Los Angeles. The measurements were obtained in both the summer and winter seasons for 2-week periods closest to the seasonal mean. These measurements were averaged to represent the annual mean for 2006. The measurements then were used as the dependent variable in a spatial land use regression model with traffic, land use, population, and physical geography as predictors of pollution levels. The model was highly predictive; the $R^2$ between the field measured and predicted pollutant level was 85%. Sixteen measurements were chosen at random to use as cross-validation sites, leaving 167 for the analysis. Cross-validation with the 16 sites not used in model calibration indicated excellent model performance with $R^2≈92%$.

**Noise Assessment**

Noise levels were estimated at participant addresses with the Federal Highway Administration’s Traffic Noise Model, which has been validated against field measurements in San Francisco. The model computes hourly noise levels based on traffic volumes and noise emissions rates for various classes of vehicles and then compiles the measures into a 24-hour weighted mean in units of decibels. We modeled noise as a binary measure (<70 dB, ≥70 dB) because 70 dB is the level at which annoyance from traffic noise is considerable. This level is also consistent with significant adverse effects on blood pressure and ischemic heart disease.

**Covariate Assessment**

Height and weight were obtained at baseline in 1995, and weight was updated on each follow-up questionnaire. Smoking and alcohol consumption were obtained at baseline and also updated biennially. Information on household income and family size supported by that income was obtained in 2003. Educational attainment was obtained at baseline. Residential addresses from 1995 to 2003 were linked to the 2000 US Census Data at the block group level. Using principal components analysis, we created a neighborhood socioeconomic status score that included 6 Census variables (median household income; median housing value; percent of households receiving interest, dividend, or net rental income; percent of adults ≥25 years of age who have completed college; percent of employed persons ≥16 years of age in managerial, executive, or professional occupations; and percent of families with children not headed by a single female). Regression coefficients from the factor analysis were used to weight the variables for a combined neighborhood score, with higher scores indicating higher neighborhood socioeconomic status.

**Statistical Analyses**

We used Cox proportional hazards models to estimate the incidence rate ratios (IRR) and 95% confidence intervals (CI) associated with the IQR of NOx and with a 10-μg/m$^3$ increase in PM$_{2.5}$. The IQR of NOx and 10-unit increase in PM$_{2.5}$ were chosen to capture the greatest variation in the respective distributions of the pollutants. Person-time was calculated from the start of follow-up in 1995 until the occurrence of hypertension or diabetes mellitus, loss to follow-up, moving from the study area, death, or end of follow-up, whichever happened first.

The IRRs for both hypertension and diabetes mellitus were adjusted for age, body mass index (weight in kilograms divided by height in meters squared), years of education, household income, number of people supported by the household income, smoking status, alcohol consumption, hours per week of vigorous exercise, and neighborhood socioeconomic status score. The IRRs for hypertension were additionally adjusted for neighborhood noise level (<70 dB, ≥70 dB); the IRRs for diabetes mellitus were also adjusted for family history of diabetes mellitus. Air pollutant exposures and all covariates except for education, household income, and number of people supported by the income were time varying.

We analyzed the pollutants separately and included them in models together. We tested for interaction between the 2 pollutants.
for both outcomes and for the interaction of noise with both pollutants in the hypertension analysis by including interaction terms in the models. All analyses were conducted with the statistical analysis program R version 2.9.2.

**Results**

The mean annual average of \( \text{PM}_{2.5} \) in the study area was 20.7 \( \mu \text{g/m}^3 \) (SD, 2.10 \( \mu \text{g/m}^3 \)); the 25th, 50th, and 75th percentiles were 20.3, 21.1, and 21.6 \( \mu \text{g/m}^3 \), respectively. The mean annual average of NOx was 43.3 ppb (SD, 11.0 ppb), and the 25th, 50th, and 75th percentiles were 36.9, 41.6, and 49.2 ppb. The correlation coefficient for the 2 air pollutants was 0.27 (\( P<0.0001 \)).

Table 1 shows the distribution of baseline participant characteristics in the highest and lowest quartiles of the pollutant measures. Higher levels of pollutants were associated with lower levels of education, household income, neighborhood socioeconomic status, and vigorous exercise. Higher levels were also positively associated with body mass index and smoking.

Over the 10-year follow-up period, 531 incident cases of hypertension and 183 cases of diabetes mellitus occurred among women at risk in 1995. In models that considered the pollutants separately, the IRR was 1.48 (95% CI, 0.95–2.31) for hypertension associated with a 10-unit increase in \( \text{PM}_{2.5} \) and 1.14 (95% CI, 1.03–1.25) for the IQR of NOx (12.4 ppb; Table 2). When the 2 pollutants were modeled together, the IRR for \( \text{PM}_{2.5} \) was attenuated and the IRR for NOx did not materially change (Table 2). In single-pollutant models, the IRR for \( \text{PM}_{2.5} \) was 1.63 (95% CI, 0.78–3.44) for diabetes mellitus associated with \( \text{PM}_{2.5} \) and 1.25 (95% CI, 1.07–1.46) for NOx. When the pollutants were considered together, the IRR for \( \text{PM}_{2.5} \) was much diminished, and the IRR for NOx was essentially unchanged.

There was no evidence of statistical interaction between the 2 pollutants for either outcome. In the hypertension analysis, there was no evidence of interaction of the pollutants with noise.

**Discussion**

In this population of black women in Los Angeles, exposure to NOx was associated with a statistically significant increased incidence of type 2 diabetes mellitus both before and after control for effects of \( \text{PM}_{2.5} \). NOx exposure also significantly increased the incidence of hypertension, although the association became marginally significant after control for \( \text{PM}_{2.5} \). On the other hand, \( \text{PM}_{2.5} \) was associated with nonsignificant increases in incident hypertension and diabetes mellitus before control for NOx, and the associations became weaker after control for NOx.

Two previous studies have assessed associations of incident type 2 diabetes mellitus with air pollutants. Results from the first, the German Study on the Influence of Air Pollution on Lung, Inflammation and Aging (SALIA) study, were consistent with the present results in that stronger associations were found with an indicator of traffic-related pollutants, NOx, than with particulate matter. The study, con-

<table>
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<th>Table 1. Baseline Characteristics of the Study Population in the Highest and Lowest Quartiles of Fine Particulate Matter and Nitrogen Oxides</th>
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<tr>
<td>Quartile of ( \text{PM}_{2.5} )</td>
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<tr>
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<tr>
<td>Lowest</td>
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<td>Age, y</td>
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<td>Body mass index, kg/m²</td>
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<td>Noise, dB</td>
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<tr>
<td>Highest quartile of neighborhood SES score, %</td>
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<td>College graduate, %</td>
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<td>Income &gt;$100 000 in 2003, %</td>
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<tr>
<td>Current drinker, %</td>
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<td>Current smoker, %</td>
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<td>≥3 h/d of vigorous exercise, %</td>
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\( \text{PM}_{2.5} \) indicates fine particulate matter with an aerodynamic diameter of \( \leq 2.5 \mu \text{m} \); NOx, nitrogen oxides; and SES, socioeconomic status. Values are given as mean (SD) when appropriate.

<table>
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<tr>
<th>Table 2. Incidence Rate Ratios for Hypertension and Diabetes Mellitus Associated With a 10-Unit Increase in Fine Particulate Matter and Interquartile Range Increase of Nitrogen Oxides</th>
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<tbody>
<tr>
<td>Hypertension*</td>
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<td>( \text{PM}_{2.5} )</td>
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<td>Diabetes mellitus†</td>
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<td>NOx</td>
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*531 cases/33 657 person-years.
†183 cases/25 318 person-years.
ducted in the highly polluted Ruhr district, identified 87 self-reported cases of diabetes mellitus among 1775 women 54 to 55 years of age from 1990 to 2006. Results varied according to the method used to estimate the pollutants. The highest IRR (1.42; 95% CI, 1.16–1.73) was observed for the IQR of NO2 (15 μg/m3 or ~ 30 ppb) estimated from a land use regression model, similar to the model used in the present study. The IRR per IQR of PM2.5 absorbance (soot) estimated with the land use regression model was 1.27 (95% CI, 1.09–1.48). The estimates were adjusted for age, body mass index, education, smoking, and indicators of indoor pollutant exposures. In the Ruhr district, NO2 is primarily from traffic, whereas soot reflects both traffic and industrial sources. Thus, the results suggest that traffic-related pollutants may be the exposure responsible for the increased incidence of diabetes mellitus.15

The second study of the incidence of type 2 diabetes mellitus assessed associations with several metrics of particulate matter in 23 years of follow-up in the Nurses’ Health Study (3794 cases) and the Health Professionals Follow-Up Study (688 cases).16 Relative risks were adjusted for several diabetes risk factors, including body mass index, physical activity, and diet. There was little evidence of an association with PM2.5 or 2 other classes of particulate matter, with relative risks from ranging 1.00 to 1.07 per IQR (4 μg/m3). The associations were stronger when analyses were restricted to the final 2 years of follow-up; the relative risk per IQR of PM2.5 was 1.21 (95% CI, 1.00–1.46) in the Nurses’ Health Study and 1.52 (95% CI, 0.93–2.47) in the Health Professionals Follow-Up Study. For a simpler exposure metric, living within 50 m of a major road compared with ≥ 200 m away, the IRR in the Nurses’ Health Study was 1.14 (95% CI, 1.03–1.27). The SALIA study also found an increased IRR for women living within 100 m of a major roadway, but only for those with a low level of education.15

Two studies have shown associations between the prevalence of diabetes mellitus and NO2.20,30 In addition, 2 studies have shown effects of air pollutants on indicators of insulin resistance in humans.12,31 In a Taiwanese study of older adults, fasting glucose and glycosylated hemoglobin (HbA1c) increased significantly per IQR increases in PM2.5 and NO2.12 In a study of Iranian children 10 to 18 years of age, levels of PM10 were positively associated with insulin resistance, but NO2 was not.31

There have been no previous studies of air pollution and incident hypertension. The SALIA study reported the “adjusted association” with prevalent hypertension was 1.09 (95% CI, 0.93–1.27) per IQR of NO2, but no details of the analysis were given.15 In cross-sectional analyses of National Health Interview Survey data, the odds ratios for self-reported prevalent hypertension associated with a 10 μg/m3 increase in PM2.5 were 1.05 (95% CI, 1.04–1.17) among white participants and 0.90 (95% CI, 0.79–1.03) among black participants.13 Many observational studies2 and controlled experiments32–36 have demonstrated that present-day levels of particulate matter are capable of elevating blood pressure. For example, the most recent study, from Taiwan, found significant increases of ~ 30 mm Hg in both systolic and diastolic blood pressures associated with the IQR of 1-year-averaged PM2.5 (IQR = 20.4 μg/m3) and of ~ 12 mm Hg with the IQR of NO2 (IQR = 12.8 ppb).12 Other data show blood pressure increases of a smaller magnitude associated with PM2.5 averaged over shorter time periods (2–120 days).8,10,37 Several studies have also reported that traffic-related pollutants, including NO2, are capable of elevating blood pressure.9,38,39

There are plausible mechanisms by which particulate matter could contribute to the development of hypertension and diabetes mellitus, including the production of systemic inflammation, oxidative stress, and the triggering of autonomic nervous system imbalance.40 Oxidative stress, which plays an important role in the genesis of insulin resistance,41 has been induced in animals and humans by PM2.5 exposure.42 In a rodent model, PM2.5 exposure led to insulin resistance, alterations in adipokines, and systemic inflammation.43 In addition, particulate matter is a well-known trigger of autonomic nervous system imbalance, which can promote vasoconstriction.1 Vasoconstriction, which has been demonstrated after concentrated particulate matter exposure in humans,44 contributes to hypertension and can reduce insulin sensitivity.45,46 The endothelial dysfunction that can occur after particulate matter exposure47 can also promote arterial vasoconstriction. Other pathways are theoretically possible, including a systemic stress response, increased levels and/or bioactivity of other circulating vasoactive mediators,48 and the translocation of soluble particle constituents into the systemic circulation.40

Although a direct effect of NOx, a major constituent of NOx, cannot be ruled out, it is most plausible that the association with diabetes mellitus and hypertension is due to the fact that NOx is a marker of traffic-related air pollution exposure. Recent studies do not support a direct adverse vascular effect of gaseous NOx49 but rather suggest that diesel exhaust–related adverse cardiovascular effects are likely mediated by the high numbers of fine and ultrafine particulate matter.35

Our study contributes the first data on the relation of air pollution to incident hypertension and is the first study of incident diabetes mellitus in a large population of black women. We adjusted for a number of potentially confounding variables at the individual and neighborhood levels. Although diabetes mellitus and hypertension were self-reported, validation studies demonstrated a high degree of accuracy of reporting. A limitation of the study is that it was not feasible to identify undiagnosed cases of hypertension and diabetes mellitus in the cohort. However, > 90% of BWHS participants report having health insurance and having seen a physician in the previous 2 years, which would be expected to minimize undiagnosed hypertension and diabetes mellitus. To estimate the effect of undiagnosed hypertension on the IRRs, we conducted sensitivity analyses using simulation methods under assumptions of nondifferential and differential misclassification. Under the scenario that 15% of the cohort had undiagnosed hypertension, the IRR estimates for PM2.5 and NOx were changed by < 10% for both types of misclassification. Because the rate of undiagnosed diabetes mellitus is far lower than that of hypertension (at most, 5%), effects on the IRRs for diabetes mellitus would be even less.50
With respect to the measurement of pollution exposure, we had excellent exposure assessment, based on nearly 200 monitoring sites. The very high $R^2$ (85%) between the NOx values estimated from the land use models and the monitored measurements indicates a higher power of prediction than the majority of previously developed land use models.51 PM$_{2.5}$ models had data support from 23 government monitoring stations, and the kriging methods of interpolation may have oversmoothed the pollution surface and introduced relatively more exposure error than in the NOx model. The significant results for NOx may reflect the higher precision of the NOx estimates compared with the PM$_{2.5}$ estimates. A limitation is that pollutant exposures were assessed for only 1 year (2000 for PM$_{2.5}$ and 2006 for NOx) and assigned to all years of follow-up. We expect this to introduce minimal measurement error because studies have shown that the spatial pattern of air pollution levels has remained stable over time.52 Another limitation was that pollutant exposures were assigned to residential addresses only, not work addresses. Time-activity studies show that Americans spend on average ≈68% of their time at home.51 On the other hand, we had addresses at each 2-year questionnaire cycle, so air pollution exposure was changed to reflect the change of address of women who moved within the study area during follow-up.

Conclusions

Our results suggest that exposure to air pollutants, especially traffic-related pollutants, may increase the risk of type 2 diabetes mellitus. The results for hypertension were weaker but may signal an association with the pollutants. Increased risks of diabetes mellitus and possibly hypertension could be a mechanism by which air pollution increases the risks of acute cardiovascular effects.

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Disclosures

None.

References

Hypertension affects >70 million adults in the United States and is the leading risk factor for premature mortality. The prevalence and adverse health consequences of type 2 diabetes mellitus are also large and continue to grow. Both disorders are causally related to cardiovascular diseases, the leading cause of mortality worldwide. Although lifestyle factors such as obesity, sedentary lifestyle, and poor diet play substantial roles in the development of diabetes mellitus and hypertension, emerging findings suggest that environmental exposures may predispose to both conditions. Our findings add to the evidence that present-day levels of ambient air pollution, specifically fine particulate matter with an aerodynamic diameter of \( \leq 2.5 \mu m \) and nitrogen oxides, may contribute to the genesis of these chronic disorders. Although short-term exposures to particulate- and traffic-related pollutants have been associated in many studies with acute cardiovascular events, the present results support the notion that longer-term exposures may promote the development of chronic diseases, specifically hypertension and diabetes mellitus. This may help explain the larger increase in mortality related to long-term versus short-term air pollution exposures. These observations could have major public health implications. Because of the ubiquitous and continuous exposures to air pollutants, even relatively small effects could potentially lead to serious elevations in the frequency of these disorders in the United States and globally. Our findings contribute to the evidence that characteristics of the environment, including neighborhood socioeconomic status and urban form, influence the development of chronic disease. Interventions aimed solely at the individual may not be sufficient to stem the increasing population prevalence of diabetes mellitus and hypertension.
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