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Adverse Health Effects of Particulate Air Pollution:

Modification by Air Conditioning

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Abstract

Background—The short-term effects of particulate matter (PM) on mortality and morbidity differ by geographic location and season. Several hypotheses have been proposed for this variation, including different exposures with air conditioning (AC) versus open windows.

Methods—Bayesian hierarchical modeling was used to explore whether AC prevalence modified day-to-day associations between PM_{10} and mortality, and between $PM_{2.5}$ and cardiovascular or respiratory hospitalizations, for those 65 years and older. We considered yearly, summer-only, and winter-only effect estimates and 2 types of AC (central and window units).

Results—Communities with higher AC prevalence had lower PM effects. Associations were observed for cardiovascular hospitalizations and central AC. Each additional 20% of households with central AC was associated with a 43% decrease in $PM_{2.5}$ effects on cardiovascular hospitalization. Central AC prevalence explained 17% of between-community variability in $PM_{2.5}$ effect estimates for cardiovascular hospitalizations.

Conclusions—Higher AC prevalence was associated with lower health effect estimates for PM.

Short-term associations between ambient exposure to particulate matter (PM) and health vary by geographic locations in multisite time-series studies in the United States and Europe.[1–4] Recent research suggests that differences in the chemical composition of PM partially explain this variation,[3,5,6] as particulate composition also exhibits regional variation.[7] Another hypothesis is that air conditioning (AC) alters relationships between personal and ambient exposures, thereby affecting health risk estimates based on ambient exposures. AC could decrease penetration of air pollutants from outdoors to indoors, as compared with households using open windows for temperature control. Further, some AC systems could remove a fraction of particles from penetrating indoors. In areas with lower AC prevalence (ie, a smaller fraction of households with AC), more open windows would contribute to higher PM levels indoors. We hypothesize that for a given ambient PM concentration, personal PM exposure would be higher in areas with low AC prevalence than areas with high AC prevalence; thus communities with lower AC would be anticipated to have higher PM health effect estimates. An understanding of how AC affects health risk estimates associated with PM is also important because climate change may encourage increased AC use.

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In previous work, we estimated community-specific associations between PM_{10} (PM with aerodynamic diameter ≤10 μm) and risk of mortality and between $PM_{2.5}$ (PM with aerodynamic diameter ≤2.5 μm) and risk of cardiovascular and respiratory hospital admissions.[1–3] We found that associations differed by community. In this paper, we explore whether between-community variation in PM mortality and morbidity effect estimates can be explained by variation in AC prevalence.

METHODS

Three types of PM health effects associations were examined: (1) $PM_{2.5}$ and risk of urgent cardiovascular hospitalizations for persons 65 years and older, for 168 US counties, 1999–2005; (2) $PM_{2.5}$ and risk of urgent respiratory hospital admissions for persons 65 years and older, for 168 US counties, 1999–2005; and (3) PM_{10} and risk of total nonaccidental mortality for 84 US urban communities, 1987–2000. Because PM_{10} measurements are available for a longer time period than $PM_{2.5}$, our earlier mortality work used PM_{10} rather than $PM_{2.5}$. PM effect estimates were generated for summer (June–August), winter (December–February), and for the entire study period (ie, yearly estimates) in our previous research.[1–3] Effect estimates for hospitalizations were obtained at the county level, whereas effect estimates for mortality were obtained at the community level.[1–3] Maps showing the study locations are provided in eFigures 1 and 2 (http://links.lww.com/A1227).

We used the single-day lag with the strongest effect for yearly estimates as exhibited in previous work: lag 1 (previous day) for PM_{10} and mortality; lag 0 (same day) for $PM_{2.5}$ and cardiovascular hospitalizations; and lag 2 (2 days previous) for $PM_{2.5}$ and respiratory hospitalizations.[1–3] Although results for distributed lags, reflecting risk from exposure over multiple days, would be desirable, the frequency of particle measurement prevents such analysis on a national scale. Particles are typically measured once every 6 days, and therefore we used single-day lags.

We generated 2 community-specific AC prevalence estimates for the percent of occupied households with central AC or any AC including window units. AC prevalence was calculated from the national survey US Census American Housing Survey (AHS) data, which are available every 2 years for approximately 55,000 households.[8] Earlier analysis found high correlations between the data from the AHS national survey and the AHS metropolitan survey, which collects information using a larger sample size but less frequently and for fewer communities.[9] We incorporated AC data from multiple years into a weighted average to generate community-specific long-term average AC prevalence corresponding to the study period used to generate PM effect estimates (1987–2000 for PM_{10}-mortality effect estimates, 1999–2005 for $PM_{2.5}$ hospital admissions effect estimates).

We applied Bayesian hierarchical modeling using non-informative priors.[10] Details of this modeling structure are provided elsewhere.[9] Results are provided as the percent change in PM health effect estimates (β^c) per an additional 20% of households acquiring AC. The use of an increment such as interquartile range would vary by analysis. We also report the percent of between-community variance (τ^2) of PM health effect estimates explained by AC prevalence in each community.

Given that AC would affect PM exposure more in summer than other seasons, we also considered summer-only effect estimates, as well as separate examinations of the subset of communities for which PM levels were highest in summer compared with other seasons, based on long-term seasonal averages. A sensitivity analysis was performed for winter, where an association between AC and PM effect estimates would not be anticipated. We estimated the association between community-specific PM risk estimates and AC prevalence

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in 3 ways: (1) yearly health effect estimates for all communities; (2) summer-only effect estimates for the subset of communities where the relevant PM metric peaks in summer; and (3) winter-only effect estimates for the subset of communities where the relevant PM metric peaks in winter. Each analysis was performed for central AC and any AC, and for each health effect estimate (PM_{10} and mortality, $PM_{2.5}$ and cardiovascular hospitalizations, and $PM_{2.5}$ and respiratory hospitalizations).

RESULTS

Summary statistics of AC prevalence are provided in Table 1. The communities included a wide range of AC prevalence. The community-specific variables of central AC and any AC were correlated (0.77). Neither of these AC variables exhibited strong relationships with indicators of socioeconomic conditions (poverty rate, unemployment, percent of population with high school education) based on data from the US Census.[11,12] Correlations of these socioeconomic indicator variables and AC ranged from −0.27 to 0.29, averaging 0.03. AC prevalence does exhibit some association with long-term temperatures, as warmer communities were more likely to have AC. For central AC the correlations between temperature and AC prevalence were 0.63 for both the hospital admissions and mortality datasets. The correlations between temperature and any AC were 0.45 for the hospitalization dataset and 0.48 for the mortality dataset. AC prevalence did not covary with long-term pollution levels of $PM_{2.5}$, PM_{10}, or ozone (correlations ranged from 0.1 to 0.3, averaging 0.18).

Table 2 shows the percent change in PM effect estimates per an additional 20% of the population acquiring AC. Communities with higher AC prevalence had lower PM_{10} mortality risk estimates, especially for central AC, although results were uncertain. For $PM_{2.5}$ and respiratory hospitalizations, no consistent associations between effect estimates and AC were observed. Higher summertime effect estimates were observed in communities with lower AC prevalence for either central or any AC, although these results were uncertain. AC prevalence was most strongly associated with effect estimates for $PM_{2.5}$ and cardiovascular hospital admissions, particularly for central AC, and results were larger for summertime health effect estimates than for wintertime. County-specific AC prevalence explained 17% of the between-county variability in effect estimates for $PM_{2.5}$ and risk of cardiovascular hospital admissions. In sensitivity analyses based on winter-only estimates, associations between PM effect estimates and AC were uncertain.

DISCUSSION

We found evidence that AC prevalence, as defined by the fraction of households with AC, lowered the short-term effects of $PM_{2.5}$ on cardiovascular hospital admissions. As expected, the effect modification was stronger for central AC than for any AC, which includes window units. A link between AC and ambient air pollution effects is plausible due to the lower penetration of outdoor pollutants indoors with use of central AC compared with homes using open windows for cooling. The presence of AC can affect indoor air through filtering, as PM can deposit on AC units.[13] AC may reduce airborne microbes through filtration[14] or increase their presence by providing a growth environment in high humidity conditions.[15] These processes can be affected by cleaning and maintenance of the AC system.[16]

Other studies have also hypothesized that AC can play a role in the impact of air pollutants on health, such as for the penetration of outdoor fungal spores and risk of asthma severity.[17] Many studies have demonstrated that AC modifies the impact of heat on mortality,[18,19] although not all work has shown this association.[20] AC has been demonstrated to affect indoor/outdoor relationships for PM and personal exposure to $PM_{2.5}$, along with other

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factors such as indoor sources (eg, tobacco smoke, cooking) and activity patterns.[21–23] AC also affects the relationships between indoor and outdoor levels of other pollutants, such as spore counts[24] and ozone.[25,26]

Our findings are consistent with earlier work examining effect modification of AC for health effects of PM and O_3 as displayed in Table 3. Our work and these other studies used community-level data on AC prevalence. Further research with individual-level information on AC prevalence and the use of AC from cohort studies could help explain the modifying effect of AC. Additional research is also needed to investigate why AC is more strongly linked to PM effect estimates for cardiovascular hospitalizations than respiratory hospitalizations. The fact that the association of $PM_{2.5}$ is stronger with cardiovascular admissions than with respiratory admissions may help to explain these differing results.

The association between higher AC and lower PM health risk estimates can aid the interpretation of epidemio-logic findings. However, this result does not necessarily imply that higher AC prevalence is an overall health benefit. Some health hazards may be transmitted through AC systems, especially if the systems are poorly maintained.[27–29]

Air conditioning consumes energy, thereby contributing to higher air pollution levels, including PM and greenhouse gases. The energy use and subsequent emissions vary by the design of the AC system.[30,31] Thus, while these results indicate lower health effects of particles with higher prevalence of AC, increased use of AC may not provide improved health overall when energy demands and emissions are taken into account. Additional research is needed to comprehensively assess the health effects of AC, both advantageous and detrimental.

Energy use for AC in the United States grew by a third between 1978 and 1997.[32] AC prevalence has steadily increased, with <2% of US households having AC in 1955 and over half having AC in 1980.[33] The growing use of AC reflects several factors, including strong promotion of residential AC by the AC industry; declining adjusted prices for electricity rates, window units, and central AC; rising adjusted personal incomes; changes in methods of home construction; and changes in mortgage polices allowing incorporation of central AC systems.[33] In recent years, the prevalence of AC has continued to rise. The Figure shows the prevalence of central AC in occupied US households, for the total US and by community type (urban, suburban, or rural) from 1993 to 2005. AC prevalence differs by subpopulation, such as by location (urban vs. rural), socioeconomic status, race, and age; however, a consistent trend of increasing prevalence is found among all these groups.[8]

Our findings have implications not only for current associations between PM and health, but also for future conditions, as AC use may continue to rise. Higher temperatures from climate change are likely to result in increased installation and use of AC, although this response may differ by community.[34] More AC could, in turn, result in higher emissions of greenhouse gases and air pollutants, depending on available energy technology.[35] One of the many challenges in estimating the human health consequences of climate change from weather and air pollution is predicting the degree and pace of adoption of AC use, which could differ among susceptible subpopulations based on race or income.[36] Our findings that AC modifies the association between PM and health suggest that research on the potential human health impacts of a changing climate should incorporate information on changing AC use and the subsequent impact on PM and health associations.

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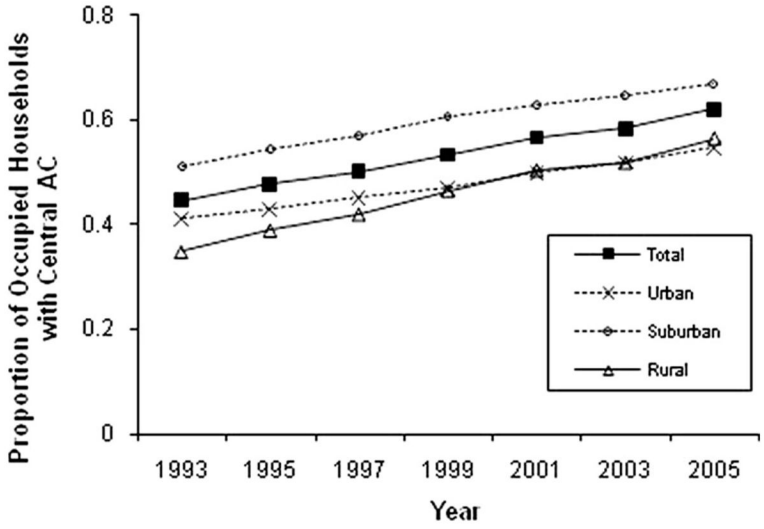

FIGURE.

Temporal trend of central AC in the United States, based on the US Census American Housing Survey.[8]

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TABLE 1

Summary Statistics on Air Conditioning Prevalence

	Average	Minimum to Maximum	Interquartile Range
AC prevalence data used in analysis for $PM_{2.5}$ and hospital admissions effect estimates (168 counties, 1999–2005)			
Central AC	0.56	0.06–0.95	0.50
Any AC	0.65	0.08–0.91	0.17
AC prevalence data used in analysis for PM_{10} and mortality effect estimates (84 communities, 1987–2000)			
Central AC	0.53	0.05–0.89	0.43
Any AC	0.66	0.06–0.91	0.27

Any AC refers to homes with central AC and/or window AC units. The minimum and maximum values refer to the lowest and highest prevalence for any individual community.

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TABLE 2

Percent Change in Community-Specific PM Effect Estimates for Mortality and Hospital Admissions per an Additional Twenty Percent of the Population Acquiring Air Conditioning

		Any AC Including Window Units		Central AC	
	No. Counties	% Change in PM Effect Estimates (95% Posterior Interval)	% Reduction in τ^2	% Change in PM Effect Estimates (95% Posterior Interval)	% Reduction in τ^2
PM_{10} risk estimates for mortality					
Yearly health effect estimates	84	−30.4 (−80.4 to 19.6)	−13	−39.0 (−81.4 to 3.3)	−5
Summer health effects, counties with PM_{10} peaking in summer	45	29.9 (−84.0 to 144)	−8.8	2.0 (−60.3 to 64.3)	−18
Winter health effects, counties with PM_{10} peaking in winter	6	−573 (−9100 to 7955)	−121	−1777 (−5755 to 2201)	−45
$PM_{2.5}$ risk estimates for cardiovascular hospital admissions:					
Yearly health effect estimates	168	−34.3 (−72.7 to 4.2)	−6.9	−42.5 (−63.4 to −21.6)	17
Summer health effects, countieswith $PM_{2.5}$ peaking in summer	103	−148 (−327 to 31.1)	3.6	−79.5 (−143 to −15.7)	12
Winter health effects, counties with $PM_{2.5}$ peaking in winter	42	−80.0 (−182 to 22.0)	4.5	−41.9 (−124 to 40.0)	−7
$PM_{2.5}$ risk estimates for respiratory hospital admissions:					
Yearly health effect estimates	168	44.5 (−87.4 to 176)	−3.8	27.6 (−46.7 to 102)	2
Summer health effects, counties with $PM_{2.5}$ peaking in summer	103	−74.8 (−417 to 267)	−1.0	−38.6 (−160 to 82.6)	−5
Winter health effects, counties with $PM_{2.5}$ peaking in winter	42	−32.5 (−245 to 180)	−6.0	43.8 (−125 to 213)	−5

τ^2 represents the between-community variability of PM health effect estimates.

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TABLE 3

Summary of Studies Investigating Air Conditioning's Modification of Air Pollution and Health Risk Estimates

Study	Location (Time Period)	Pollutant	Health Outcome	Results
This study	84 US communities (1987–2000)	PM_{10}	Mortality	Lower effect estimates with higher prevalence for yearly health effect estimates, although results uncertain
	168 US counties (1999–2005)	$PM_{2.5}$	CVD hospital admissions for those ≥65 years	Lower effect estimates with higher prevalence of AC, especially central AC. Larger effect in summer
	168 US counties (1999–2005)	$PM_{2.5}$	Respiratory hospital admissions for those ≥65 years	Lower effect estimates with higher prevalence for summertime health effect estimates, although results uncertain
Franklin et al[37]	27 US communities (1997–2002)	$PM_{2.5}$	Total non-accidental, respiratory, CVD, and stroke mortality	Risk estimates at the 25th and 75th percentiles of central AC prevalence were not statistically different, but were higher at the 25th percentile for total, respiratory, and CVD mortality. Similar risk estimates at the 25th and 75th percentiles of central AC prevalence for stroke mortality
Janssen et al[38]	14 US cities (1984–1994)	PM_{10}	CVD, COPD, and pneumonia hospital admissions for those ≥65 years	Lower effect estimates with higher prevalence of central AC, especially for CVD hospital admissions
Medina-Ramón et al[39]	36 US cities (1986–1999)	PM_{10} and O_3	Pneumonia and COPD hospital admissions for those ≥65 years	Lower effect estimates for communities with higher prevalence of central AC for PM_{10} or O_3 and pneumonia admissions
Bell and Dominici[9]	76 US communities (1987–2000)	O_3	Total non-accidental mortality	Lower effect estimates with higher prevalence of central AC. Non-statistically significant results for total AC including window units
Levy et al[40]	Meta-analysis of previously conducted time-series studies for 14 cities	O_3	Mortality	Lower effect estimates for communities with residential AC above the median AC level

CVD indicates cardiovascular disease; COPD, chronic obstructive pulmonary disease.