Association of Fine Particulate Matter from Different Sources with Daily Mortality in Six U.S. Cities

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Previously we reported that fine particle mass (particulate matter ≤ 2.5 μm; $PM_{2.5}$), which is primarily from combustion sources, but not coarse particle mass, which is primarily from crustal sources, was associated with daily mortality in six eastern U.S. cities (*1*). In this study, we used the elemental composition of size-fractionated particles to identify several distinct source-related fractions of fine particles and examined the association of these fractions with daily mortality in each of the six cities. Using specific rotation factor analysis for each city, we identified a silicon factor classified as soil and crustal material, a lead factor classified as motor vehicle exhaust, a selenium factor representing coal combustion, and up to two additional factors. We extracted daily counts of deaths from National Center for Health Statistics records and estimated city-specific associations of mortality with each source factor by Poisson regression, adjusting for time trends, weather, and the other source factors. Combined effect estimates were calculated as the inverse variance weighted mean of the city-specific estimates. In the combined analysis, a 10 μg/m^3 increase in $PM_{2.5}$ from mobile sources accounted for a 3.4% increase in daily mortality [95% confidence interval (CI), 1.7–5.2%], and the equivalent increase in fine particles from coal combustion sources accounted for a 1.1% increase [CI, 0.3–2.0%). $PM_{2.5}$ crustal particles were not associated with daily mortality. These results indicate that combustion particles in the fine fraction from mobile and coal combustion sources, but not fine crustal particles, are associated with increased mortality. *Key words*: air pollution, coal combustion, fine particles, mobile sources, mortality, $PM_{2.5}$, source apportionment. *Environ Health Perspect* 108:941–947 (2000). [Online 29 August 2000]
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In a study of six U.S. cities, we previously demonstrated that daily mortality was associated with fine particulate matter (aerodynamic diameter ≤ 2.5 μm; $PM_{2.5}$) and not coarse particulate matter (aerodynamic diameter between 2.5 and 10 μm $PM_{2.5–10}$) (*1*). Each 10 μg/m^3 increase in the 2-day mean concentration of $PM_{2.5}$ was associated with a 1.5% [95% confidence interval (CI), 1.1–1.9%) increase in daily mortality. An equivalent change in $PM_{2.5–10}$ was associated with only a 0.4% increase in total mortality (CI, 0.1–1.0%) and no increase after control for $PM_{2.5}$.

Particle size is an important determinant of the site and efficiency of pulmonary deposition, but particle size is also a surrogate for particle source and composition. $PM_{2.5–10}$ consists mainly of crustal particles mechanically generated from agriculture, mining, construction, road traffic, and related sources, as well as particles of biological origin. $PM_{2.5}$ consists mainly of combustion particles from motor vehicles and the burning of coal, fuel oil, and wood, but also contains some crustal particles from finely pulverized road dust and soils. Although a convincing body of evidence has accumulated on the adverse effects of $PM_{2.5}$ (*1–11*), the specific sources and constituents responsible for these adverse effects have not been determined.

In this study, we used the elemental composition of size-fractionated particles to identify several distinct source-related fractions of fine particles. We then examined the association of these fractions with daily mortality in each of the six cities and combined the city-specific results in a meta-analysis to derive overall relative risks for each fraction.

Materials and Methods

Air pollution data. As part of the Harvard Six Cities Studies (*12*), dichotomous virtual impactor samples were placed at a central residential monitoring site in Watertown, Massachusetts; Kingston-Harriman, Tennessee; St. Louis, Missouri; Steubenville, Ohio; Portage, Wisconsin; and Topeka, Kansas. Separate filter samples were collected of fine particles ($PM_{2.5}$) and of the coarse mass ($PM_{2.5–10}$) fraction. The 2.5 μm cutpoint for dichotomous samplers represents the aerodynamic diameter at which 50% of the particles are sent to the fine particle filter and 50% to the coarse mass filter. The cutoff is relatively sharp, but some larger particles, including some crustal material, will still be deposited on the fine fraction filter. In addition, there is crustal material between 1 and 2.5 μm, representing the low end of the coarse-mode particle size distribution. Integrated 24-hr samples were collected at least every other day from 1979 until the late 1980s (*1*), with daily sampling during health survey periods. For fine and coarse particle samples, mass concentration was determined separately by beta-attenuation (*13*). With the exception of a period between October 1981 and January 1984 in all cities, elemental composition of fine and coarse mass was determined by X-ray fluorescence (*14*). Elemental composition was available on 97% of these samples. In the fine fraction, 15 elements were routinely found above the limit of detection: silicon, sulfur, chlorine, potassium, calcium, vanadium, manganese, aluminum, nickel, zinc, selenium, bromine, lead, copper, and iron.

Source identification. In separate analyses for each city, we used specific rotation factor analysis to identify up to 5 common factors from the 15 specified elements. We specified a single element as the tracer for each factor and maximized the projection of these elements using the Procrustes rotation, a variant of the oblique rotation method that is commonly used in psychometric testing (*15,16*). This method is similar to the factor analytic approach used by Koutrakis and Spengler (*17*), but it uses standard software (*18*).

We selected tracer elements in three steps. First, we identified tracers on the basis of the chemical composition of fine particulate matter from known sources and the previous source apportionment research in

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Watertown by Thurston and Spengler (*19*) and in Steubenville by Koutrakis and Spengler (*17*). Second, we regressed total fine mass on the identified factors and rejected any factors that had negative regression coefficients. Third, we attempted to identify additional, possibly local, sources by examining elements that did not load heavily on the positive factors from step 2 and created the additional factors that were both positive predictors of total fine mass and maximized the model R^2. In steps 1 and 2, we defined three sources of fine particles in all six cities: a silicon factor classified as soil and crustal material, a lead factor classified as motor vehicle exhaust, and a selenium factor representing coal combustion sources. In city-specific analyses, we also considered vanadium (fuel oil combustion), chlorine (salt), and selected metals (nickel, zinc, or manganese) as possible targets and sources. We identified five source factors for each city, except for Topeka, where we were only able to identify three positive predictors of total $PM_{2.5}$.

Daily factor scores. For each metropolitan area, we calculated daily scores for each of the identified factors. Information on the relative concentration of each of the 15 elements in each factor is provided by the standardized scoring coefficients. Therefore, the score for each factor for each day was calculated by multiplying the normalized concentration of each element by the respective standardized scoring coefficient for that element and factor and then summing across these 15 products. We recentered these daily factor scores by calculating a factor score for a hypothetical day on which all of the elemental concentrations were zero and then subtracting this minimum factor score from the daily factor score (*19*). To rescale the factor scores from the normalized scale to the mass scale (in $\mu g/m^3$), we regressed the total daily fine particle concentrations on the daily factor scores for all of the factors in separate regression models for each city and obtained the product of each factor score with its regression coefficient (*19*). Only sources that were significant predictors of total fine particle mass ($p < 0.10$) were considered in the mortality analyses.

As in our earlier study (*1*), we assumed that mortality was associated with the 2-day mean of the non-missing particle concentrations on the same and on the previous day. Because much of the monitoring was conducted every other day during the study period, this technique imputed missing days using the non-missing values on the previous days, which increased the number of days included in the mortality analysis from 6,211 to 9,108. For this imputation, we assumed that the sampling schedule, and hence the missing values, were random with respect to daily mortality.

Meteorological data. We obtained meteorological data from the National Center for Atmospheric Research (Boulder, CO) including hourly measures of temperature, dew point temperature, and precipitation from the National Oceanographic and Atmospheric Administration (Washington, DC) weather station nearest to each city. We calculated 24-hr mean values for temperature and dew point temperature.

Mortality data. We defined the six metropolitan areas in this study as the county containing the air pollution monitor and contiguous counties (*1*). For the mortality analysis, each study area is identified by the name of its largest city (e.g., Watertown as Boston; Kingston-Harriman as Knoxville; Portage as Madison). We extracted daily deaths for people who lived and died in the selected counties from annual detail mortality tapes (from the National Center for Health Statistics, Hyattsville, MD) for the time periods with fine particulate measurements. After excluding all deaths due to accidents and other external causes [*International Classification of Diseases, Ninth Revision* (ICD-9), clinical modification codes 800–999)], we analyzed the remaining total daily deaths as well as daily deaths from ischemic heart disease (ICD-9 410–414), pneumonia (ICD-9 480–486), and chronic obstructive pulmonary disease (ICD-9 490–496). Since the 1996 analysis, the mortality data were updated to restrict deaths of those individuals who both lived and died within the specified counties and to correct for administrative changes in the county codes for St. Louis in 1982.

Poisson regression of mortality. We investigated the association of daily deaths with sources of fine particles separately for each city using Poisson regression in a generalized additive model (*20,21*). To control for trend and season, we used a locally weighted linear regression (Loess) smooth function of date with a span of 0.05 (*22*). For the smooth functions of temperature and dew point temperature, we used Loess functions with spans of 0.80. Indicator variables for day of the week also were included in the models. The relative risks for each source were evaluated by including the absolute factor scores (in micrograms per cubic meter) simultaneously in the model. That is, the estimate of the mobile source factor is in a model controlling for coal derived particles, crustal particles, and the other source factors, and vice versa. To obtain summary estimates of the association between the different sources of fine particles and daily mortality, we combined the city-specific regression coefficients using inverse variance weights. This method produces similar summary estimates as weighting by the number of deaths in each city

Table 1. Means and standard deviations of total fine particulate matter < 2.5 μm diameter (in $\mu g/m^3$) and selected elements (in ng/m^3) by metropolitan area, six U.S. cities, 1979–1988.

	Watertown (Boston)	St. Louis	Kingston-Harriman (Knoxville)	Portage (Madison)	Steubenville	Topeka
	Mean ± SD	Mean± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean± SD
$PM_{2.5}$	16.5 ± 9.2	19.2 ± 10.1	21.1 ± 9.3	11.3 ± 7.5	30.5 ± 22.4	12.2 ± 7.1
Silicon	114.2 ± 107.8	195.9 ± 256.9	203.4 ± 188.4	109.1 ± 155.7	283.3 ± 360.4	202.4 ± 281.2
Aluminum	65.5 ± 88.7	161.2 ± 211.7	152.5 ± 150.2	70.5 ± 127.0	186.8 ± 238.0	130.1 ± 205.2
Calcium	33.9 ± 31.6	78.8 ± 54.6	98.7 ± 142.3	35.2 ± 33.7	101.7 ± 155.3	134.0 ± 200.0
Iron	62.2 ± 53.5	143.7 ± 132.7	116.9 ± 89.1	44.1 ± 45.7	542.4 ± 738.3	72.0 ± 88.2
Manganese	3.7 ± 2.8	19.2 ± 27.3	8.8 ± 21.8	3.2 ± 3.1	30.4 ± 41.5	4.7 ± 3.5
Potassium	75.6 ± 56.5	118.0 ± 87.2	109.4 ± 71.8	59.6 ± 36.4	344.4 ± 411.1	84.5 ± 99.0
Lead	240.3 ± 212.1	212.7 ± 223.9	108.7 ± 95.6	33.3 ± 33.7	184.5 ± 195.3	71.5 ± 104.9
Bromine	58.7 ± 66.5	39.8 ± 59.3	21.5 ± 22.4	6.1 ± 5.7	30.2 ± 31.4	18.2 ± 32.1
Copper	11.0 ± 14.5	29.7 ± 46.6	12.7 ± 16.4	6.4 ± 8.3	11.9 ± 10.7	6.7 ± 9.7
Zinc	24.8 ± 18.7	57.0 ± 62.6	33.8 ± 54.1	15.9 ± 13.2	138.4 ± 214.6	13.8 ± 15.5
Sulfur	1921.6 ± 1,391.3	2350.3 ± 1,583.4	2555.9 ± 1491.4	1481.5 ± 1327.2	4,248.4 ± 3,185.3	1,368.3 ± 1,168.9
Selenium	0.7 ± 0.9	2.2 ± 1.9	1.9 ± 1.5	0.9 ± 0.8	5.2 ± 4.2	0.8 ± 0.7
Vanadium	23.2 ± 19.8	2.0 ± 4.4	1.4 ± 3.3	0.1 ± 2.9	10.5 ± 20.4	0.6 ± 2.8
Nickel	8.8 ± 7.0	2.2 ± 4.8	1.0 ± 1.1	0.5 ± 0.7	3.7 ± 4.7	0.6 ± 1.0
Chlorine	49.3 ± 148.6	20.5 ± 98.1	6.7 ± 15.8	9.1 ± 101.3	58.7 ± 263.0	10.6 ± 49.5

and takes into account the precision of each individual estimate.

As an alternative approach, we evaluated the association of daily deaths with individual elements. Based on previous toxicological research suggesting which elements might be important in ambient particle toxicity (*23–26*), we built city-specific models that included daily measurements of lead, iron, sulfur, nickel, vanadium, manganese, and zinc individually and in combination. Trend, season, and weather were controlled for as described above.

Results

Source apportionment. The mean and standard deviations for the 15 elements varied across the six metropolitan areas (Table 1). As the most common element in the fine fraction, the mean sulfur concentration varied by a factor of two across five areas (1.5–2.6 $\mu g/m^3$) and was much higher in Steubenville (4.2 $\mu g/m^3$). Because these measurements were conducted before the removal of lead from gasoline, the lead concentrations were relatively high (> 0.1 $\mu g/m^3$) in every city except Portage and Topeka. Vanadium was much higher in Watertown and Steubenville than in the other metropolitan areas.

The identified sources and their contribution to total daily fine mass in each community are presented in Table 2. Using silicon, lead, and selenium as tracer elements, we identified crustal, mobile, and coal combustion factors, respectively, in all six metropolitan areas. Coal and mobile sources account for the majority of fine particles in each city; the proportion of fine particulate matter accounted for by these two factors combined ranged from 0.44 in St. Louis to 0.79 in Watertown. In Watertown the crustal factor accounted for < 1% of the fine particle mass and was not a significant predictor in the regression model. Therefore, in Boston, the larger metropolitan area represented by Watertown, this factor was not included in the mortality analyses. We identified a vanadium factor, representing fuel oil combustion in Watertown and Steubenville. A chlorine factor (salt) was identified in Watertown, Kingston-Harriman, and Portage. We identified a metal factor in St. Louis (zinc), Steubenville (zinc), and Kingston-Harriman (nickel), presumably related to local manufacturing. Finally, we found a manganese factor in St. Louis and Portage. In Topeka, which had a low average $PM_{2.5}$ concentration, we were able to identify only the crustal, mobile, and coal combustion factors. The source of at least 18% of the total mass remained unexplained in all cities, except Steubenville (8% unexplained).

The crustal factor consisted predominantly of silicon (the tracer element), aluminum, iron, potassium, and calcium. The elemental composition of road dust identified by published chemical analyses was similar (*27*), and the relative contributions of each element (the standardized scoring coefficients) were fairly consistent across the six metropolitan areas (Table 3). The coefficient for silicon, the marker for sandy soils, varied only slightly from 0.25 to 0.36, whereas the coefficient for aluminum, a marker for clay soils, varied much more—from 0.17 in Watertown to 0.50 in Steubenville. Except for Kingston-Harriman, the contribution of calcium was relatively constant across the metropolitan areas. These differences in the standardized scoring coefficients for the crustal factor may reflect regional differences in the composition of soils.

Because these measurements were conducted while leaded gasoline was still in use, lead provided a good marker for mobile sources. To minimize the possibility of noise in the data in the later years when leaded gasoline was being phased out, we evaluated a measurement of lead adjusted by time. This correction did not substantially affect the results, so it was not used in the main analyses and is not presented here. For the mobile source factor, the standardized scoring coefficients were similar for lead and bromine (a constituent of commercial tetra-ethyl lead mixtures), except in Steubenville and Kingston-Harriman, where the coefficients for bromine were low (Table 4). Copper had surprisingly high scoring coefficients for this source factor, especially in Steubenville and Kingston-Harriman. Furthermore, sulfur loaded particularly high on the lead factor in Kingston-Harriman. Thus, we must be careful in the interpretation of this factor as a mobile source in Kingston-Harriman and perhaps in Steubenville.

For the selenium or coal combustion factor, the standardized scoring coefficients reflected the important contribution of sulfur from this source factor in every metropolitan area except Kingston-Harriman (Table 5). In Kingston-Harriman, this factor had high coefficients for vanadium, manganese, and potassium that were not seen in the other metropolitan areas. Again, as with the mobile factor, we should be cautious in interpreting this factor as a coal combustion source factor in Kingston-Harriman.

For the three communities in which we identified metal source factors, the pattern of high coefficients was different for each. In St. Louis, the zinc factor also had high coefficients

Table 2. Proportional composition of fine particulate matter ($PM_{2.5}$) by source and metropolitan area, six U.S. cities, 1979–1988.

Source	Target	Watertown (Boston)	St. Louis	Kingston-Harriman (Knoxville)	Portage (Madison)	Steubenville	Topeka
Crustal	Silicon	< 0.01	0.14	0.08	0.03	0.14	0.08
Mobile	Lead	0.29	0.15	0.21	0.27	0.05	0.17
Coal	Selenium	0.50	0.29	0.32	0.45	0.63	0.57
Fuel oil	Vanadium	0.03	—	—	—	0.03	—
Metals	[a]	—	0.12	0.14	—	0.08	—
Salt	Clorine	0.01	—	0.04	0.01	—	—
Manganese	Manganese	—	0.03	—	0.07	—	—
Residual		0.18	0.28	0.21	0.18	0.08	0.19

[a]The target element varied by metropolitan area: zinc in St. Louis and Steubenville and nickel in Knoxville.

Table 3. Crustal factor with silicon as the target element: standardized scoring coefficients by element and metropolitan area, six U.S. cities, 1979–1988.

Element	Watertown (Boston)	St. Louis	Kingston-Harriman (Knoxville)	Portage (Madison)	Steubenville	Topeka
Silicon	0.28	0.33	0.25	0.30	0.36	0.27
Aluminum	0.17	0.29	0.29	0.27	0.50	0.24
Calcium	0.26	0.25	–0.04	0.26	0.29	0.17
Iron	0.26	0.20	0.11	0.24	–0.01	0.27
Manganese	0.14	0.00	0.30	0.00	0.11	0.17
Potassium	0.08	0.18	0.26	0.13	0.06	0.12
Lead	0.00	0.00	0.00	0.00	0.00	0.00
Bromine	0.02	0.00	0.05	0.01	–0.17	0.01
Copper	0.06	–0.01	–0.28	–0.02	–0.04	0.00
Zinc	0.00	0.00	0.19	–0.03	0.00	–0.01
Sulfur	0.00	–0.01	–0.14	0.05	0.02	–0.02
Selenium	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	0.02	0.38	–0.14	0.00	0.04
Nickel	0.02	–0.06	0.00	–0.14	–0.25	0.03
Chlorine	0.00	0.15	0.00	0.00	–0.24	–0.01

for nickel, copper, and vanadium as well as potassium and chlorine. In Steubenville, the zinc factor had high coefficients for nickel, iron, manganese, chlorine, bromine, and calcium. Finally, in Kingston-Harriman, the nickel factor had high coefficients for iron and copper, but not for zinc.

In Watertown, vanadium and nickel were highly correlated, and both loaded high on the factor targeted by vanadium and defined as fuel oil combustion (*19*). In Steubenville, the vanadium factor had moderate scoring coefficients only for aluminum and calcium. The manganese factors in Portage and St. Louis had high factor scoring coefficients for nickel and vanadium. Therefore, manganese may serve to identify a fuel oil combustion factor in some midwestern communities.

Association of mortality with specific source factors. Because elemental composition was not available on every day in which fine mass was measured, the current data set is a subset of the data described in the 1996 analysis (*1*). Results for the combined analysis of total fine mass were similar to the previously published results: total daily mortality increased by 1.6% (CI, 1.1–2.1%) with each 10 μg/m^3 increase in the 2-day mean of $PM_{2.5}$, as compared to the previous report of a 1.5% increase (CI, 1.1–1.9%) using the full data set (*1*). The magnitude of the associations with ischemic heart disease and chronic obstructive pulmonary disease were similar to those for total mortality (approximately 2). These point estimates were slightly attenuated and the confidence intervals wider in these data compared to the earlier analysis.

For the three source factors identified in all six metropolitan areas, we found the strongest increase in daily mortality associated with the mobile source (lead) factor (Table 6). In the combined analysis across the six cities, daily mortality increased by 3.4% (CI, 1.7–5.2%) with each 10 μg/m^3 increase in the 2-day mean of the mobile-source factor. The communities are presented in the table in order of decreasing population size, and consequently decreasing contribution to the summary measure. In St. Louis, Knoxville (Kingston-Harriman), and Madison (Portage), the estimated effects were 4.3, 5.2, and 6.3%, respectively. The associations in Steubenville and Topeka were inverse, but the standard errors were large and the contribution of mobile sources to total $PM_{2.5}$ was modest in Steubenville (Table 2). Similar to the association observed with total $PM_{2.5}$, there was evidence of a 2% increase in daily mortality from ischemic heart disease with each 10 μg/m^3 increase in mobile sources; however, it was not statistically significant (CI, −1.1–5.2). We did not identify adverse effects for respiratory deaths (chronic obstructive pulmonary disease or pneumonia).

The coal combustion (selenium) factor was positively associated with mortality in all metropolitan areas, with the exception of Topeka (Table 6). The summary relative risk indicated that a 10 μg/m^3 increase in the 2-day mean mass concentration from coal combustion sources was associated with a 1.1% increase in daily mortality (CI, 0.3–2.0%). Deaths from chronic obstructive pulmonary disease and pneumonia increased by higher percentages than did deaths from all causes: 4.5% (CI, −0.4–9.3%) and 7.9% (CI, 3.1–12.7%), respectively. Unlike the motor source factor, there was no evidence of an increased effect of exposure to coal combustion sources for ischemic heart disease.

Table 4. Mobile source factor with lead as the target element: standardized scoring coefficients by element and metropolitan area, six U.S. cities, 1979–1988.

Element	Watertown (Boston)	St. Louis	Kingston-Harriman (Knoxville)	Portage (Madison)	Steubenville	Topeka
Silicon	0.00	0.00	0.00	0.00	0.00	0.00
Aluminum	–0.16	–0.09	–0.10	–0.06	0.26	–0.06
Calcium	0.09	0.19	0.34	0.15	0.04	0.16
Iron	0.11	0.11	0.05	0.09	–0.08	0.07
Manganese	0.10	0.00	–0.37	0.00	0.05	0.10
Potassium	0.04	0.10	–0.17	0.09	0.26	0.08
Lead	0.28	0.33	0.11	0.27	0.44	0.33
Bromine	0.26	0.37	0.01	0.25	0.03	0.31
Copper	0.30	–0.03	0.42	0.21	0.40	0.20
Zinc	0.14	0.00	–0.23	0.15	0.00	0.18
Sulfur	0.06	–0.07	0.24	0.08	0.01	0.05
Selenium	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium	0.00	–0.32	–0.50	–0.30	0.00	–0.11
Nickel	0.01	–0.11	0.00	–0.13	–0.54	0.06
Chlorine	0.00	0.16	0.00	0.00	–0.50	0.11

Table 5. Coal combustion factor with selenium as the target element: standardized scoring coefficients by element and metropolitan area, six U.S. cities, 1979–1988.

Element	Watertown (Boston)	St. Louis	Kingston-Harriman (Knoxville)	Portage (Madison)	Steubenville	Topeka
Silicon	0.00	0.00	0.00	0.00	0.00	0.00
Aluminum	0.10	0.05	0.11	0.08	–0.26	0.04
Calcium	–0.12	–0.10	–0.29	–0.08	–0.26	–0.06
Iron	–0.04	–0.03	–0.11	–0.04	0.06	0.00
Manganese	0.16	0.00	0.28	0.00	–0.04	0.14
Potassium	0.07	–0.07	0.26	0.09	–0.01	0.09
Lead	0.00	0.00	0.00	0.00	0.00	0.00
Bromine	–0.06	–0.10	0.09	–0.12	0.14	–0.04
Copper	–0.04	0.09	–0.42	–0.17	0.05	0.08
Zinc	0.21	0.00	0.15	0.12	0.00	0.22
Sulfur	0.41	0.56	–0.08	0.57	0.40	0.39
Selenium	0.43	0.39	0.26	0.46	0.31	0.41
Vanadium	0.00	–0.12	0.50	–0.08	0.00	0.19
Nickel	–0.01	–0.25	0.00	–0.24	0.41	0.14
Chlorine	0.00	–0.47	0.00	0.00	–0.03	–0.04

Table 6. Percent increase in daily deaths and 95% CIs associated with a 10 μg/m^3 increase in mass concentration from a specific major source of fine particles by metropolitan area, six U.S. cities, 1979–1988.[a]

City	Mean daily no. deaths	Crustal (Si) Percent increase	Crustal (Si) 95% CI	Motor (Pb) Percent increase	Motor (Pb) 95% CI	Coal (Se) Percent increase	Coal (Se) 95% CI
Boston[b]	59	—	—	1.2	–1.9–4.3	2.8	1.2–4.4
St. Louis	55	–3.0	–7.7–1.6	4.3	1.6–7.0	0.3	–1.1–1.6
Knoxville	12	–1.7	–20.0–17.0	5.2	1.2–9.2	0.8	–2.7–4.3
Madison	11	40.5	–26.8–112.5	6.3	–3.1–15.8	0.9	–2.5–4.2
Steubenville	3	–1.4	–7.1–4.2	–0.2	–20.5–20.5	1.1	–1.2–3.5
Topeka	3	–7.9	–42.4–27.9	–8.2	–29.0–13.1	–3.9	–11.2–3.5
Summary[c]		–2.3	–5.8–1.2	3.4	1.7–5.2	1.1	0.3–2.0

[a]Each multivariate model includes Loess smooth function of date with a span of 0.05, Loess functions of temperature and dew point temperature with spans of 0.80, indicator variables for day of the week, and all source factors simultaneously. [b]The crustal factor was not a statistically significant predictor of fine mass in Watertown (Boston); therefore, it was not included in the analysis. [c]Summary estimates obtained by combining the city-specific regression coefficients using inverse variance weights.

As we mentioned before, the elemental profiles for the lead (mobile) and selenium (coal) factors in Knoxville differed from the profiles in the other cities. When Knoxville is omitted from the meta-analysis, the increase in daily mortality attributed to mobile sources and coal combustion changed only slightly.

In all of the metropolitan areas combined, 46% of the total fine particle mass was attributed to coal combustion and 19% to mobile sources. Therefore, the difference between the 5th and 95th percentile is considerably different for coal combustion (28.7 $\mu g/m^3$) than for mobile sources (12.9 $\mu g/m^3$). However, the summary estimate of the change in daily mortality across this range of exposure still indicated a difference in magnitude; the increase was 4.5% (CI, 2.2–18.3) for mobile sources and 3.2% (CI, 0.7–5.8%) for coal combustion.

The crustal factor in fine particulate matter was not associated with mortality. If anything, the summary relative risk suggested a protective association between crustal particles and mortality. However, the confidence intervals were wide and the association far from statistical significance. This factor was not included in the mortality analysis in Boston (Watertown) because, even though it was identified in that city, it was not a significant predictor of and accounted for < 1% of total fine particulate matter.

There is a suggestion of a large positive association of fuel oil combustion with daily mortality in the cities in which the vanadium factor was identified; however, the confidence intervals were wide and included a null effect (Boston: 27.3% increase, CI, −2.0–57.5%; Steubenville: 13.6% increase, CI, −34.2–63.8%). If we consider the manganese factor as defining a fuel oil combustion source in Madison and St. Louis, then the summary effect estimate for the four cities is 5.6% (CI, −1.8– 13.2%) for a 10 $\mu g/m^3$ increment in $PM_{2.5}$ from this factor.

Association of mortality with specific elements. In models with measurements for the individual elements included simultaneously, sulfur, nickel, and lead were significantly associated with total mortality (Table 7). An increase of sulfur across its range of exposure (5916 ng/m^3: 5th–95th percentile for all cities combined) was associated with a 3.0% (CI, 0.9–5.2%) increase in total daily mortality. The equivalent increases in nickel (10.3 ng/m^3) and lead (461.4 ng/m^3) were associated with a 1.5% (CI, 0.5– 2.6%) and 1.6% (CI, 0.2–2.9%) increase in mortality, respectively. Vanadium and iron, although statistically significant predictors when evaluated separately, were not significant when included simultaneously with nickel, lead, and sulfur.

Discussion

Using specific rotation factor analysis, we were able to identify crustal, mobile, and coal combustion source of fine particles in each of six cities and to estimate the percentage of daily deaths attributable to changes in the concentration of each factor. In the combined analysis across the six cities, controlling for the other sources, a 10 $\mu g/m^3$ increase in $PM_{2.5}$ from mobile sources accounted for a 3.4% increase in daily mortality (CI, 1.7–5.2%) and from coal combustion sources a 1.1% increase (CI, 0.3–2.0%). $PM_{2.5}$ from crustal particles was not associated with increased daily mortality. A possible residual oil combustion source was identified in four of the six cities, and the summary effect estimate was positive but not statistically significant (5.6% increase, CI, −1.8–13.2%). Results from element-specific mortality analyses were consistent with the analysis of sources; lead and sulfur, markers for mobile and coal combustion sources, respectively, were independently associated with daily deaths. Additionally, nickel was positively associated with daily deaths.

The association between particulate air pollutants, either measured as total suspended particulates (TSP) or inhalable particles (PM_{10}; aerodynamic diameter ≤ 10 $\mu g/m^3$), has been extensively studied and is well established. The magnitude of association has been consistent across studies with the weighted mean percent change in daily mortality for each 10 $\mu g/m^3$ increase in PM_{10} concentration of approximately 0.8% (*28*). Most of the fine particles ($PM_{2.5}$) are deposited in the alveolar region and are therefore not cleared efficiently. These particles include toxic sulfates, nitrates, and bioavailable transition metals (*25,26*). Prospective studies (*6,10*) and studies of daily deaths (*1,2,5,9,11*) have observed associations of $PM_{2.5}$ with mortality. Associations with morbidity also have been reported (*3,4,7,8*).

Our previous analysis demonstrating that $PM_{2.5}$ was more strongly associated with all-cause mortality than was $PM_{2.5–10}$ has been criticized because the larger particles in the $PM_{2.5–10}$ filters were more likely to fall off the filter before being measured. Hence, it has been suggested that poorer predictive power was due to measurement error (*29*). In this study, we found that crustal material in the fine size range is not associated with daily deaths. Boston was not included in this analysis because the mass attributed to the crustal factor in that city was small and was not a significant predictor of total fine mass. The percent increase in mortality in the other cities associated with this factor were consistently null and in the same direction in all communities except Madison, Wisconsin. The crustal material on the $PM_{2.5}$ filters tends to be in particles that are > 1 μm in aerodynamic diameter. This suggests that a reduction in the size cutoff for the particles (e.g., to 1.5 μm) would more specifically focus on the most toxic particles.

In 1987, Ozkaynak and Thurston (*2*) concluded that particles from industrial sources (iron and steel emissions) and from coal combustion were more significant contributors to mortality than soil-derived particles based on analyses using 1980 U.S. Vital Statistics data and available ambient air pollution data. Recently, Schwartz and co-workers (*30*) examined dust storms in Spokane, Washington. In 17 episodes with very high concentrations of coarse but not fine particles, they found no evidence of excess mortality (*30*). In another recent study in Salt Lake City, Utah, and the neighboring Wasatch Front communities, the estimated association between PM_{10} and mortality was stronger when pollution episode days that were obviously dominated by windblown-dust were excluded (*31*). Similarly, Schwartz and Neas (*32*) reported that coarse particles were not associated with lower respiratory symptoms or peak flow deficits in panel studies of children. We believe these results present a consistent pattern of less toxic reactions to crustal particles, even when in the fine range, and no association with daily deaths.

Table 7. Percent increase in daily deaths and 95% CIs associated with an increase in mass of elements across the total range of exposure (5th to 95th percentile) by metropolitan area, six U.S. cities, 1979–1988.[a]

	Nickel		Lead		Sulfur	
	Percent increase	95% CI	Percent increase	95% CI	Percent increase	95% CI
Boston	1.9	0.4–3.4	–0.5	–2.8–1.8	7.9	3.9–12.1
St. Louis	1.0	–0.4–2.5	2.2	0.5–3.9	0.8	–2.4–4.2
Knoxville	12.2	–5.8–33.8	15.0	5.0–26.0	1.0	–6.8–9.4
Madison	–23.9	–38.1–−6.5	35.7	–1.8–81.0	4.6	–3.0–12.7
Steubenville	8.2	0.3–16.6	3.9	–4.7–13.3	0.5	–6.8–8.3
Topeka	–27.8	–50.9–6.2	–5.2	–19.3–11.3	–10.3	–23.1–4.6
Summary[b]	1.5	0.5–2.6	1.6	0.2–2.9	3.0	0.9–5.2

The equivalent increases for nickel, lead, and sulfur were 10.3, 461.4, and 5,916, respectively.
[a]Each multivariate model includes Loess smooth function of date with a span of 0.05, Loess functions of temperature and dew point temperature with spans of 0.80, indicator variables for day of the week, and nickel, lead and sulfur. [b]Summary estimates obtained by combining the city-specific regression coefficients using inverse variance weights.

The finding of a greater effect per microgram per cubic meter for mobile source particles than for coal combustion source particles, which are predominantly sulfate, is intriguing. Sulfates have long been implicated as the major toxicologic component in fine particulates (*23*) and have been shown to be associated with respiratory disease and mortality (*24*). However, Peters et al. (*33*) reported a stronger association of some health endpoints with ultrafine particles than with sulfate particles. Ultrafine particles are primarily from mobile sources (*34*), and our mobile source factor may be standing for variations in ultrafine particles. Alternatively, the organic aerosol associated with traffic pollution may be more toxic even if it is not in the ultrafine component, or an identical ambient concentration increase of mobile source particles may have a stronger relationship to personal exposure than do particles from power plant sources.

Another important issue is possible confounding by gaseous air pollutants. The traffic particles in particular may reflect carbon monoxide effects. CO is an important constituent of motor-vehicle emissions and has been shown to be correlated with adverse respiratory effects (*35*). However, a recent analysis found no confounding of the PM_{10} mortality relationship by CO in 10 U.S. cities (*36*). A second recent study (*37*) found no evidence of confounding, and also no evidence of an effect of CO on daily deaths, when examining 20 cities. Hence, we think that confounding by CO is unlikely to explain our results.

Particles from vehicle exhaust were more strongly associated with deaths due to ischemic heart disease but not with deaths due to chronic obstructive disease or pneumonia (diseases less common than ischemic heart disease). In contrast, the coal-derived particles were more strongly associated with respiratory deaths than with deaths due to ischemic heart disease. This suggests that these particles may affect health by different mechanisms. In a recent study, dogs exposed to concentrated air particles had more cardiovascular responses to the traffic-derived than to the sulfate/coal-derived particles (*38*). Further examination of this issue is warranted.

We also note that although the residual oil factor was not significant, it had a large slope. Residual oil is rich in metals that have been implicated in some of the toxicity studies (*25*,*26*). More investigation of oil burning seems warranted.

The primary limitation in this study is the identification and interpretation of the factors. In the factor analysis, we chose a priori the elements to target to identify the first three sources: silicon (crustal), lead (mobile), and selenium (coal). These choices and their interpretation are supported by the published source apportionment and chemical composition literature. Silicon is a crustal element unlikely to be related to combustion sources. In other source apportionment studies, silicon has consistently been correlated with other crustal elements, that together have been determined to be derived from soil (*19*,*39*). Lead is considered a reliable marker of mobile source particles during the years when leaded gasoline was in widespread use (*19*,*39*). Coal combustion is responsible for between 62% (*40*) and 85% (*41*) of selenium emissions in the United States.

We do not have direct confirmation that these three major factors truly represent the sources we have attributed to them. However, we are confident that, in all cities, with the possible exception of Kingston-Harriman (Knoxville), the silicon, lead, and selenium factors are identifying crustal, mobile, and coal combustion sources, respectively. The elemental profile of the crustal factor was qualitatively similar to published chemical analyses of road dust (*27*). Bromine was correlated with lead in all cities except Steubenville and Knoxville, and in chemical analyses of emissions from noncatalyst automobiles, both lead and bromine accounted for high percentages of the total mass (*42*). In all cities except for Knoxville, sulfur, a major component of coal combustion, was found predominantly on the selenium factor.

After these first three major source factors, the selection of additional factors was more problematic. We chose the targets for the remaining two factors for each city on an individual basis, guided primarily by statistical considerations. A previous source apportionment study in Watertown identified a residual oil fly-ash source with high loadings of nickel and vanadium and a salt or chlorine source (*19*). Therefore, nickel, vanadium, and chlorine were considered first as potential targets for the other factors in all cities. Manganese also would appear to be a good target for an oil source because the manganese factor identified in two cities had high loadings of nickel and vanadium.

We did not tailor our factor analysis in each city to specific local sources, and this limitation could influence the appropriateness of our selection of factor targets. As a sensitivity analysis, we performed nontargeted oblique rotation factor analysis [the "promax" rotation option of SAS software (*18*)] for each city. Factors with high relative concentrations of silicon, lead, and selenium or sulfur were identified in each city by this method as well.

The choice of targets for each of the factors influences the relative concentration of each element attributed to each factor, which in turn could affect the conclusions from the mortality analysis. We evaluated the association of factors identified by the nontargeted (promax) rotation described above with daily mortality and observed similar results for crustal, mobile and coal combustion sources. Results were also similar if, based on the source apportionment in Watertown, we selected vanadium and chlorine *a priori* as the targets for the fourth and fifth factors in the other cities.

The elemental profiles of the sources in Kingston-Harriman were not consistent with those for the other cities. However, mortality results from the meta-analysis were similar when we omitted this city.

Finally, we analyzed the elements thought to be of toxicological significance rather than focusing on sources. Two of the elements that appeared most important in this analysis were sulfates and lead. The difference in these results from the factor analysis results is the significant association with nickel. Nickel never emerged as its own factor, and it usually loaded on several factors in each city. Hence, the association of nickel with mortality may indicate a direct toxic effect of that metal. Alternatively, it may reflect the effect of particles from metal industries and residual oil combustion more broadly.

It is also important to acknowledge that this is an analysis of six communities. The results for these six cities may not be generalizable to all urban areas in the United States; however, they are internally consistent. The cities did not have equal weights in the meta-analysis due to their size; Boston and St. Louis were the largest communities included. The use of inverse variance weights is similar to weighting by the number of deaths and accounts for the precision of the estimate. Therefore, the conclusions are more heavily influenced by the results observed in Boston and St. Louis.

In conclusion, particulate matter from combustion sources was associated with increased mortality in these six U.S. cities. The relative potency of combustion-related particles were inversely related to their relative abundance, but particulate matter from mobile sources and coal combustion were associated with increased mortality. Conversely, particulate matter of crustal origin, even in the fine fraction ($PM_{2.5}$) was not associated with increased mortality. Although a small portion of the particles containing silica, aluminum, and iron may be produced from crustal inclusions in coal, most of the $PM_{2.5}$ mass associated with the crustal factor is from the lower tail of the coarse mode distribution < 2.5 μm (*43*). Thus, lack of an association between mortality and our crustal factor in the fine fraction is consistent with our earlier finding that mortality was not associated with coarse particles between 2.5 and 10 μm (*2*)

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