Acute Symptoms Associated With Asphalt Fume Exposure Among Road Pavers

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Background *Although asphalt fume is a recognized irritant, previous studies of acute symptoms during asphalt paving have produced inconsistent results. Between 1994 and 1997, the National Institute for Occupational Safety and Health (NIOSH) evaluated workers at seven sites in six states.*

Methods *NIOSH (a) measured exposures of asphalt paving workers to total (TP) and benzene-soluble particulate (BSP), polycyclic aromatic compounds, and other substances; (b) administered symptom questionnaires pre-shift, every 2 hr during the shift, and post-shift to asphalt exposed and nonexposed workers; and (c) measured peak expiratory flow rate (PEFR) of asphalt paving workers when they completed a symptom questionnaire.*

Results *Full-shift time-weighted average exposures to TP and BSP ranged from 0.01 to 1.30 mg/m^3 and 0.01 to 0.82 mg/m^3, respectively. Most BSP concentrations were <0.50 mg/m^3. Asphalt workers had a higher occurrence rate of throat irritation than nonexposed workers [13% vs. 4%, odds ratio (OR) = 4.0, 95% confidence interval (CI): 1.2–13]. TP, as a continuous variable, was associated with eye (OR = 1.34, 95% CI: 1.12–1.60) and throat (OR = 1.40, 95% CI: 1.06–1.85) symptoms. With TP dichotomous at 0.5 mg/m^3, the ORs and 95% CIs for eye and throat symptoms were 7.5 (1.1–50) and 15 (2.3–103), respectively. BSP, dichotomous at 0.3 mg/m^3, was associated with irritant (eye, nose, or throat) symptoms (OR = 11, 95% CI: 1.5–84). One worker, a smoker, had PEFR-defined bronchial lability, which did not coincide with respiratory symptoms.*

Conclusions *Irritant symptoms were associated with TP and BSP concentrations at or below 0.5 mg/m^3.* Am. J. Ind. Med. 49:728–739, 2006. *Published 2006 Wiley-Liss, Inc.*†

INTRODUCTION

In the United States, about 300,000 workers are exposed to hot-mix asphalt (HMA), the type of asphalt used for road paving. Asphalt, a brown or black solid or viscous liquid at room temperature, is the residuum from the distillation of petroleum. Its chemical composition and physical properties vary, depending on the crude petroleum source and the manufacturing processes. Asphalt generally contains aliphatic compounds,

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cyclic alkanes, aromatic hydrocarbons, and heterocyclic compounds containing sulfur, oxygen, and nitrogen. Various additives and modifiers may be added [NIOSH, 2000].

In 1977, the National Institute for Occupational Safety and Health (NIOSH) recommended an occupational exposure limit for asphalt fume of 5 milligrams per cubic meter (mg/m^3), measured as total particulate, over a 15-min period [NIOSH, 1977b]. This was intended primarily to protect against irritation of the eyes and respiratory tract. The potential for irritant effects was suggested by animal experiments and reports of health effects in workers exposed to asphalt, but none of the occupational data cited involved road paving, even though most asphalt is used for this purpose. Furthermore, NIOSH noted that reports of the "biological effects of exposure to asphalt fumes" are "often confusing and contradictory" [NIOSH, 1977b]. Since the NIOSH recommendation was published, studies of irritant effects during outdoor asphalt paving work have produced inconsistent results [Norseth et al., 1991; Gamble et al., 1999].

Between 1994 and 1997, NIOSH investigators evaluated exposures and acute health effects among asphalt paving workers at seven sites in six states. The primary purpose of the study, which was approved by the NIOSH Human Subjects Review Board, was to compare exposures and acute irritant health effects during work with crumb-rubber modified (CRM) HMA (asphalt containing scraps of rubber from discarded tires) with those during work with HMA not modified with rubber (hereafter referred to as "unmodified" asphalt). Data from these evaluations have been presented in separate NIOSH reports for each site [Almaguer et al., 1996; Hanley and Miller, 1996a,b; Kinnes et al., 1996; Miller and Burr, 1996a,b, 1998], as well as in a composite NIOSH report [Burr et al., 2001] and in a NIOSH review of asphalt's health effects [NIOSH, 2000]. In this report, data from the NIOSH evaluations is further analyzed in order to explore the relationship between exposures and acute health effects during paving operations using only the unmodified HMA. The paving process is described in the Appendix.

METHODS

Study Participants

At each site, all workers involved in paving activities were invited to participate in the NIOSH study. Most of the workers were present for 4 days, 2 days of paving with CRM asphalt and 2 days of paving with unmodified asphalt. Workers not involved in paving activities, and therefore considered not substantially exposed to asphalt fume, included water truck drivers, heavy equipment operators, and surveyors. Supervisors/foremen, inspectors, and traffic controllers were judged by the on-site investigators to be exposed or not substantially exposed to asphalt fume on a case-by-case basis, depending on their proximity to paving activities during a given day. If, prior to the shift, a worker's job assignment was judged by the NIOSH investigators not to involve substantial exposure, the worker did not participate in either the exposure monitoring or the medical survey. If a participating worker was judged after the shift to have been assigned to a job without substantial exposure, then that person's exposure and medical data for that day were excluded from the data analysis. Participating workers were categorized for analysis by job according to their predominant task on a given day, regardless of their official job title. For example, a laborer could have been categorized as a raker, a truck dumper, a traffic controller, or (if assigned to multiple tasks) a laborer.

To determine whether asphalt paving workers, as a group, had more symptoms than other workers, a comparison group of off-site road construction workers not involved in paving operations was also recruited near each study site. This latter group participated in the medical survey but did not have exposure measurements. Therefore, their data was not included in the analyses exploring the relationship between exposures and symptoms.

Exposures

Full-shift personal breathing zone (PBZ) air samples for total particulate (TP), the benzene-soluble particulate (BSP) fraction, polycyclic aromatic compounds (PAC), benzothiazole, and other organic sulfur compounds (OSC) were collected using battery-powered sampling pumps at a flow rate of 2.0 L/min. The pumps were connected by Tygon® tubing to closed-face filter cassettes containing 37-mm diameter filters. For the first four sites, tared polyvinyl chloride (PVC) filters [5-micrometer (μm) pore size] were used for TP; no PBZ samples were collected for BSP. For the last 3 sites, tared Zefluor® filters (1-μm pore size) were used for TP and BSP. PAC, benzothiazole, and OSC were collected on untared Zefluor® filters (1-μm pore size) followed up by an XAD-2 sorbent tube (an ORBO-43 was used at the first 3 sites, an ORBO-42 Large at the remaining sites) [Neumeister et al., 2003; Jaycox and Olsen, 2000].

The PVC filters were analyzed for TP by NIOSH Method 0500 [Clere and Hearl, 1994]. The tared Zefluor® filters were analyzed for both TP and BSP by NIOSH Method 5042 [Olsen et al., 1998]. The untared Zefluor® filters were analyzed for PAC by NIOSH Method 5800 [Neumeister and Key-Schwartz, 1998], and for both benzothiazole and OSC by NIOSH Method 2550 [Jaycox, 1998]. Time-weighted average (TWA) air concentrations were calculated for the actual sampling time (to allow comparison of data collected over unequal durations). PAC results (PAC-370 and PAC-400) were reported at 2 fluorescence emission wavelengths [370 nanometers (nm) and 400 nm], which are more sensitive to PACs containing 2–3 rings and PACs containing four or more rings, respectively.

Sampling and analytical procedures for volatile organic compounds (VOC), hydrogen sulfide, sulfur dioxide, ozone, carbon monoxide, and elemental and organic carbon are described in the previous NIOSH reports [Almaguer et al., 1996; Kinnes et al., 1996; Hanley and Miller, 1996a,b; Miller and Burr, 1996a,b, 1998; Burr et al., 2001].

Symptoms

All participants completed a self-administered questionnaire that asked about general health history, recent symptoms, smoking, and work history. In addition, NIOSH investigators administered a short acute symptom questionnaire before work, every 2 hr during the work shift, and after work. This questionnaire asked about work activities, cigarette smoking, presence of an ongoing cold or illness, medication usage, and occurrence of symptoms since awakening (pre-shift questionnaire) or since the previous questionnaire (intra- and post-shift questionnaires). Symptoms of concern for this report included (a) burning, itchy, painful, or irritated eyes; (b) burning, itchy, stuffy, or irritated nose; (c) sore, dry, scratchy, or irritated throat; (d) cough; (e) chest tightness or difficulty breathing; and (f) wheezing or whistling in the chest.

Symptom data from participants who reported having an acute illness, such as an upper respiratory infection, prior to arriving at work were excluded from symptom analyses for that day. Person-days with missing data for a given variable were excluded from analyses involving that variable. A symptom was considered present on a given day if a worker reported it anytime after the day's first questionnaire. (A symptom reported only on the day's pre-shift questionnaire was not counted as present that day.) We defined the occurrence rate of a symptom as the number of days the symptom occurred divided by the number of person-days of observation. Thus, if five workers each worked 2 days and 2 of them each reported a given symptom on 1 day, the occurrence rate would be 20%, the same as if one worker reported the symptom on both days.

Pulmonary Function

Each time the participants completed the acute symptom questionnaire, they had their peak expiratory flow rate (PEFR) measured with a mini-Wright peak flow meter. Each participant was instructed in the use of the device by a NIOSH investigator and performed the test maneuvers under the investigator's supervision. For each session, the NIOSH investigator recorded PEFR results from 3 exhalations; the highest PEFR was used for analysis. Bronchial lability was defined to be present when the difference between the minimum and maximum PEFR during a day exceeded 20% of the day's maximum [Scanlon and Hankinson, 1996].

Statistical Analysis

One set of analyses compared symptom occurrence between asphalt paving workers and other road construction workers. All other analyses evaluated the relationship between measured exposures and symptom occurrence among asphalt paving workers. Odds ratios and 95% confidence intervals were calculated using logistic regression for repeated measures [SAS® Proc GENMOD (SAS Institute, Inc., Cary, NC)]; this method accounted for individual workers contributing multiple observations (for each symptom, one observation each day of participation).

Full-shift TWA PBZ air concentrations of TP, BSP, PAC-370, and PAC-400 were the exposures of interest for the statistical analyses. If an air sample did not have a detectable or quantifiable amount of the substance of interest, a concentration was imputed by dividing the minimum detectable concentration or minimal quantifiable concentration, respectively, by the square root of 2 [Hornung and Reed, 1990]. Site conditions, including asphalt temperature, asphalt conveyance method (windrow pickup vs. truck dump into paver hopper), production rate, wind speed, and air temperature, were evaluated for associations with exposures by analysis of variance (SAS Proc GLM). Variables that were log-normally distributed were log-transformed for these analyses. Age, sex, job title, and cigarette smoking, as well as the change in sampling and analytical methods for TP, were evaluated as potential outcome determinants by logistic regression for repeated measures (SAS Proc GENMOD). Plots of symptom prevalence by exposure quartile were generated for each of the four exposure variables.

RESULTS

Study Participants

Study participation is depicted in Figure 1. Seventy-nine workers provided 157 person-days of enrollment in the study (one worker was off-site one of the 2 days). Ten workers (20 person-days) were excluded from the analyses because they were judged not to have been substantially exposed to asphalt fume. Another 12 workers (23 person-days) had no exposure measurements either day (on the only day in one case), and 6 others had no measurements on 1 day but did on the other. This left 57 participants, with 108 person-days of exposure measurements: 106 with TP results, 42 with BSP (all also had TP), and 66 with PAC (2 had neither TP nor BSP). On 9 of these 108 person-days, the participant reported an acute illness pre-shift, and on 20 others there was no symptom information. This left 79 person-days of usable symptom data. Of these 79 person-days, there were 78 and 32, respectively, with TP and BSP results. The 79 person-days came from 43 workers, including 10 roller operators, 8 rakers, 8 screed operators, 6 paver operators, 4 truck

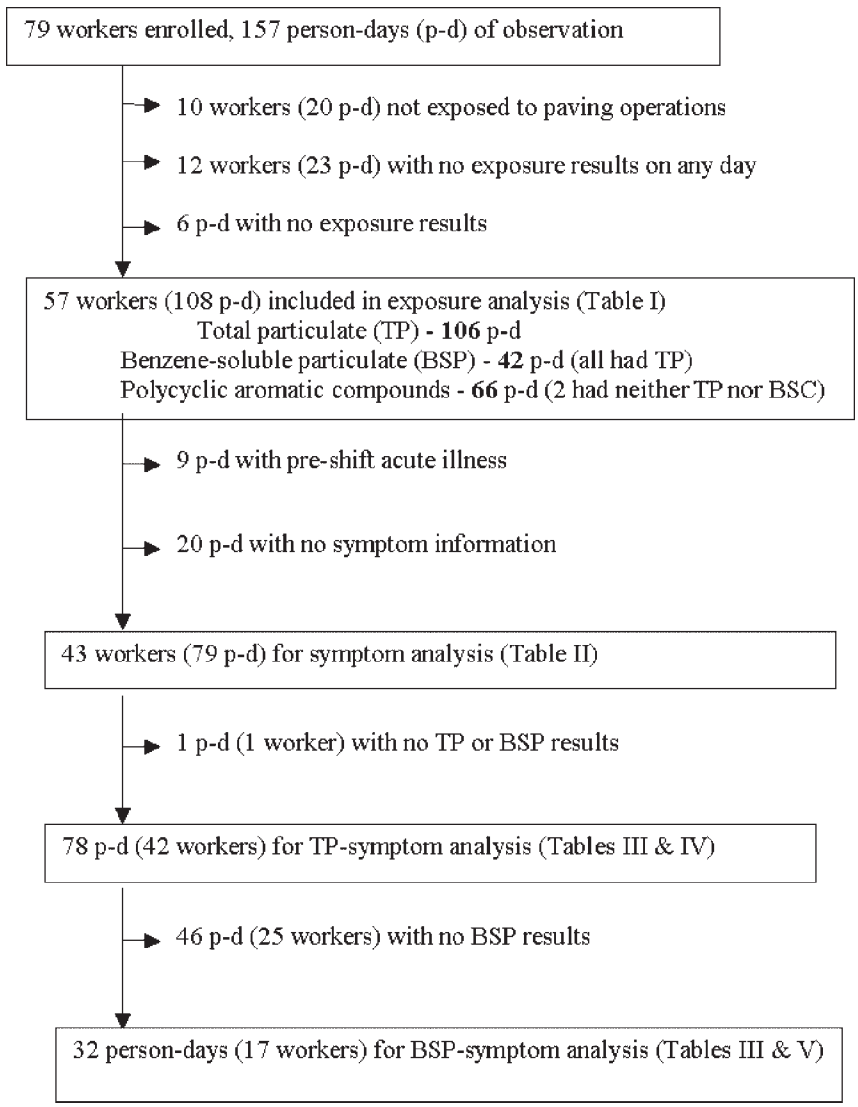

FIGURE 1. Participation in Environmental and Medical Surveys, Seven Sites, 1994–1997.

dumpers, 2 supervisors/foremen, 2 traffic controllers, 1 inspector, 1 laborer, and 1 tack truck driver.

The comparison group of off-site road construction workers not involved in asphalt paving includes 42 workers, who provided 138 person-days of symptom data. These were 16 laborers and 26 with various other job titles, each represented by only a few workers. The comparison group participants typically had more than 2 days of symptom data because they were surveyed over 4 days, the 2 days the asphalt paving workers were using CRM asphalt, as well as the 2 days they were using unmodified asphalt.

The exposed and unexposed groups each included five (12%) women. The groups had comparable numbers of workers over age 50, 33 (77%) in the exposed group and 31 (74%) in the unexposed group. The exposed group had no workers under age 30; the unexposed group had 5 (12%). The prevalence of current cigarette smoking was higher among asphalt-exposed workers (70% vs. 58%, with smoking information not available for 3 exposed and 2 unexposed workers).

Exposures

Full-shift TWA exposures to TP during 106 person-days ranged from 0.01 to 1.30 mg/m^3. Exposures to BSP during 42 person-days ranged from 0.01 to 0.82 mg/m^3; all but one were below 0.50 mg/m^3. Exposures, by job category, to these and to PAC are shown in Table I. Imputed values constituted 3%, 5%, 8%, and 17%, respectively, of the reported air concentrations of TP, BSP, PAC-370, and PAC-400. Of the 66 samples for OSC, 57 (86%) did not have a quantifiable amount, and only one of the 66 samples for benzothiazole (a marker for rubber) had a detectable amount. Geometric mean TP exposures among the various job categories ranged

TABLE I. Personal Breathing Zone Contaminant Air Concentrations* Among Asphalt Paving Workers, by Job Category, Seven Sites 1994–1997

	Job category					
Substance	**Truck dumper**	**Paver operator**	**Screed operator**	**Raker**	**Roller operator**	**Other[a]**
Total particulate[b]						
N[c]	9	15	22	16	29	11
GM[d]	0.40	0.22	0.18	0.20	0.07	0.12
Range	0.15–0.89	0.01–1.30	0.04–1.0	0.05–0.51	0.02–0.35	0.01–0.46
Benzene-soluble particulate						
N	8	6	8	6	11	3
GM	0.15	0.36	0.17	0.08	0.02	0.11
Range	0.04–0.49	0.20–0.82	0.07–0.37	0.05–0.12	0.01–0.06	0.03–0.35
Polycyclic aromatic compounds—370[e]						
N	8	10	16	6	20	6
GM	12	11	4.9	7.8	0.43	1.4
Range	8.3–22	1.1–84	0.65–191	5.0–16	0.1–17	0.30–14
Polycyclic aromatic compounds—400[e]						
N	8	10	16	6	20	6
GM	1.7	1.8	0.70	1.30	0.09	0.26
Range	1.1–2.9	0.16–12	0.09–25	0.61–4.2	0.01–3.4	0.07–2.1

*Concentrations of total and benzene-soluble particulate are in milligrams per cubic meter (mg/m^3); concentrations of polycyclic aromatic compounds are in micrograms per cubic meter ($\mu g/m^3$).
[a]Includes site supervisors, inspectors, and traffic control personnel.
[b]Additionally, air concentrations in 2 tack truck drivers were 0.16 and 0.27 mg/m^3 (geometric mean = 0.21 mg/m^3), and in 2 laborers were 0.55 and 1.2 mg/m^3 (geometric mean = 0.81 mg/m^3).
[c]Number of person-days sampled.
[d]Geometric mean.
[e]370 and 400 refer to the fluorescence emission wavelength, in nanometers.

from 0.07 mg/m^3 (roller operators) to 0.40 mg/m^3 (truck dumpers). (The 2 laborers had a higher geometric mean TP exposure, 0.81 mg/m^3, but because of their multiple tasks, their particulate exposures were not necessarily limited to asphalt fume.) Geometric mean BSP air concentrations ranged from 0.02 mg/m^3 (roller operators) to 0.36 mg/m^3 (paver operators). For PAC exposures, roller operators had the lowest geometric mean exposures, truck dumpers and paver operators the highest.

Hydrogen sulfide and sulfur dioxide were not detected in most samples; the highest concentrations were 1 and 2 parts per million (ppm), respectively. The highest ozone concentration was 0.012 ppm. At one of the sites, short-term concentrations of carbon monoxide as high as 200 ppm were measured near gasoline-powered equipment; otherwise, carbon monoxide concentrations were less than 10 ppm. (Short-term concentrations as high as 910 ppm and full-shift TWA concentrations of 8–24 ppm were measured near gasoline-powered generators used for lighting during night paving with CRM asphalt.) Elemental carbon concentrations, collected above the screed auger, ranged up to 132 $\mu g/m^3$, with elemental carbon/total carbon ratios ranging from 0.20 to 0.47 at one site, from 0.02 to 0.10 at another, and up to 0.04 at the other four sites from which data were available.

Symptoms

Comparison with workers unexposed to asphalt paving operations

Exposed workers had numerically higher symptom occurrence rates for all six symptom groups, although the difference was statistically significant only for throat symptoms (Table II).

Analyses of exposure-symptom relationships

In univariate analyses, none of the site condition variables was associated ($P < 0.05$) with measured exposures, and neither smoking nor any of the other demographic variables was associated with any of the symptoms ($P < 0.05$). TP air concentration was associated with eye and throat symptoms, and BSP air concentration was associated with throat symptoms (Fig. 2 and Table III). Other potential associations—TP and nose symptoms, BSP and nose symptoms—

TABLE II. Symptoms by Exposure Group among Road Workers, Seven Sites 1994–1997 (Adapted From Burr et al. [2001], Table 17)

	Exposure category				
	Asphalt-exposed (79 person-days)		Not asphalt-exposed (138 person-days)		
Symptom	No.[b]	%[c]	No.	%	OR (95% CI)[a]
Burning, itchy, painful, or irritated eyes	9	11	11	8.0	1.5 (0.4–5.0)
Burning, itchy, stuffy, or irritated nose	15	19	12	8.7	2.5 (0.8–7.5)
Sore, dry, scratchy, or irritated throat	10	13	5	4	4.0 (1.2–13)
Cough	7	9	5	4	2.8 (0.6–13)
Chest tightness or difficulty breathing	3	4	1	0.7	—[d]
Wheezing or whistling in chest	2	3	0	0	—[d]

[a]Odds ratio and (95% confidence interval).
[b]Number of occurrences (that is, person days with symptom).
[c](Occurrences/person-days) × 100.
[d]An odds ratio was not calculated when the number of occurrences in either exposure group was less than 3.

had 95% confidence intervals that included 1.00. Although we intended to include age, sex, and smoking in the logistic regression analyses, the models generally did not converge, and so the analyses were done without these variables. (The prevalences of the chest symptoms other than cough, even if combined, were too low for this type of analysis to yield meaningful results, and no analyses were done for OSC or benzothiazole because so few samples had quantifiable amounts of these substances.)

A TP air concentration of 0.50 mg/m^3 or greater was associated with higher occurrence rates of eye symptoms, throat symptoms, and possibly cough (Table IV). Analysis using TP air concentration dichotomized at 0.4 and 0.3 mg/m^3 yielded odds ratios greater than 1.0 for these symptoms, with the numerical values suggesting an exposure-response relationship in each case, but the 95% confidence intervals all included 1.0. These analyses included only TP concentration and TP sampling/analytical method as independent variables because the models did not converge when age, sex, and cigarette use were included.

Since all but one BSP air concentration was less than 0.50 mg/m^3, the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV®) for asphalt fume (measured as benzene-soluble inhalable aerosol) [ACGIH, 2006], analyses of symptoms by dichotomous exposure levels were done with lower BSP thresholds. Because of the small number of symptom-days, the eye, nose, and throat symptom groups were combined, and cough (only 3 cases) was not analyzed. Symptom occurrence was associated with a BSP concentration of $\geq$0.30 mg/m^3, but for $\geq$0.40 mg/m^3, the odds ratio was lower and the 95% confidence interval included 1.0 (Table V). Because there were no exposures between 0.25 and 0.30 mg/m^3, analyses dichotomized at these values yielded identical results.

Pulmonary Function

Only one worker had a PEFR pattern that met the criterion for bronchial lability. This worker, a paver operator and a cigarette smoker, had decreasing PEFR over the work shift on both days he worked with unmodified asphalt. Although he reported eye irritation the first day, he reported no respiratory symptoms either day. (He also had decreasing PEFR the third day of the study, when he worked with CRM asphalt; he reported throat irritation and cough that day. On his second day of CRM asphalt work, he reported eye and throat irritation, cough, and wheezing, but he did not have PEFR-defined bronchial lability).

DISCUSSION

Symptom occurrence rates were higher among workers involved in road paving with HMA than among road workers unexposed to asphalt. This study suggested an increased occurrence of irritant symptoms at BSP concentrations less than 0.50 mg/m^3, but the limited number of samples, especially those with concentrations above 0.40 mg/m^3, resulted in wide 95% confidence intervals around the odds ratios. A consistent trend of increasing risk with increasing exposure concentration was not apparent. TP, however, did show such a trend for eye symptoms, throat symptoms, and cough, although the confidence intervals for thresholds lower than 0.5 mg/m^3 (and for cough at 0.5 mg/m^3) all included 1.0. These results were consistent with the more statistically stable associations between symptoms and TP when the latter was analyzed as a continuous, rather than dichotomous, variable.

In a similar study, Gamble et al. [1999] found job-specific geometric mean TP exposures ranging from 0.16 (traffic controllers) to 0.72 mg/m^3 (screed operators)

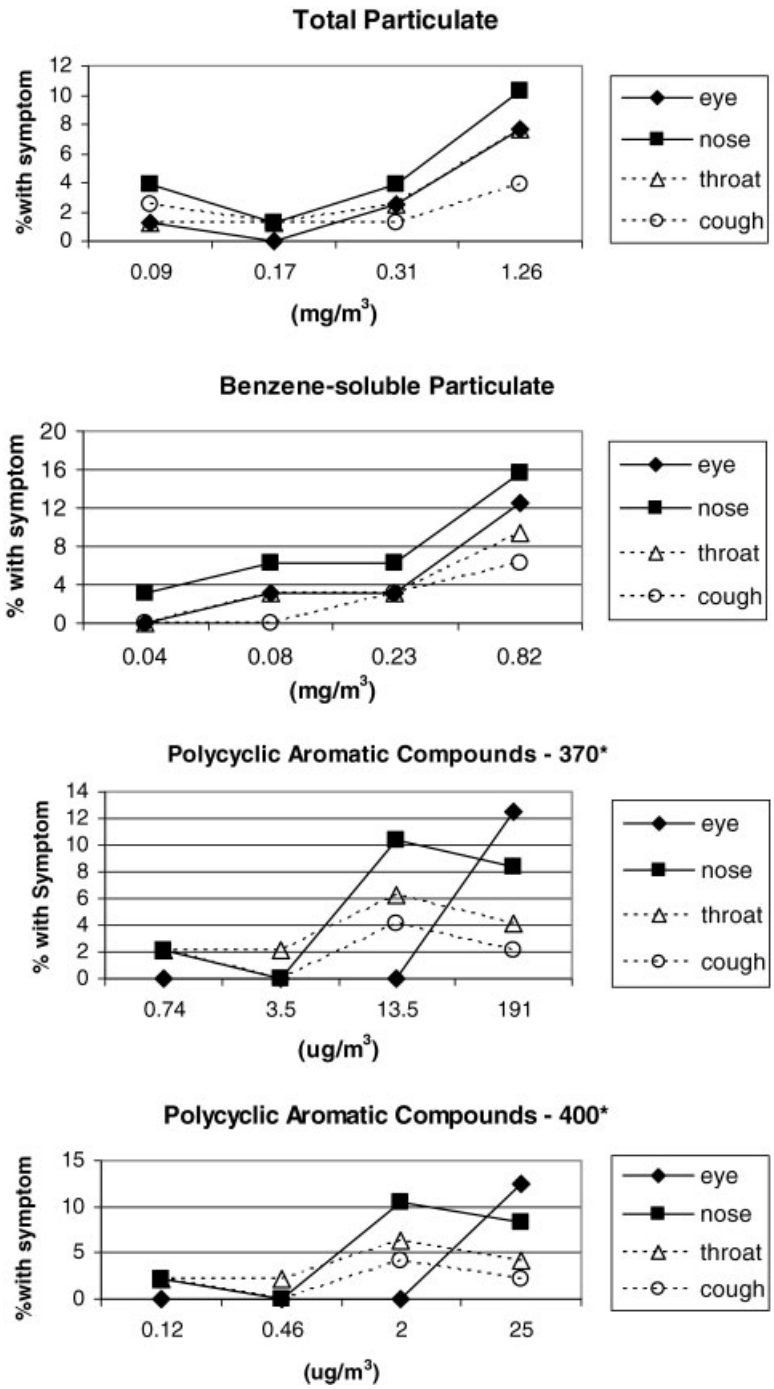

FIGURE 2. Symptom Prevalence by Exposure Quartile, Seven Sites, 1994–1997. *Number refers to fluorescence emission wavelength, in nanometers.

and BSP exposures from 0.06 (traffic controllers, roller operators, and truck drivers) to 0.27 mg/m^3 (screed operators). Laborers and paver operators, respectively, had geometric mean TP exposures of 0.39 and 0.45 mg/m^3 and BSP exposures of 0.10 and 0.11 mg/m^3. The highest exposures to TP and BSP were 1.66 and 0.65 mg/m^3, respectively, both in screed operators. Although these results were not all directly comparable to ours since the 2 studies categorized jobs differently, the ranges of individual and geometric mean TP and BSP exposures were similar overall. Yet we found acute asphalt-related symptoms where the other study did not.

Both studies used full-shift TWA air concentrations as the exposure variables. Although both studies ascertained symptoms in a similar manner, by a questionnaire adminis-

TABLE III. Associations (Logistic Regression for Repeated Measures) Between Symptoms and Exposures Among Asphalt Paving Workers, Seven Sites 1994–1997

Symptom	Exposure[a]	Odds ratio[b] and (95% confidence interval)
Eye	TP	1.34 (1.12–1.60)
	BSP	1.09 (0.99–1.19)
	PAC-370	—[c]
	PAC-400	—[c]
Nose	TP	1.22 (1.00–1.49)
	BSP	1.05 (1.00–1.11)
	PAC-370	1.00 (0.99–1.02)
	PAC-400	1.03 (0.92–1.16)
Throat	TP	1.40 (1.06–1.85)
	BSP	1.03 (1.01–1.04)[d]
	PAC-370	1.00 (0.99–1.01)
	PAC-400	1.01 (0.94–1.09)
Cough	TP	1.23 (0.98–1.53)
	BSP	—[e]
	PAC-370	1.01 (0.99–1.02)
	PAC-400	1.06 (0.95–1.18)

[a] TP, total particulate; BSP, benzene-soluble particulate; PAC, polycyclic aromatic compounds, 370 and 400 refer to the fluorescence emission wavelength, in nanometers.
[b] Odds ratio per increase of 0.1 mg/m^3 for TP, 0.01 mg/m^3 for BSP, or 1.0 μg/m^3 for PAC-370 and PAC-400.
[c] A meaningful odds ratio could not be calculated because the model did not converge.
[d] Based on five cases of sore throat.
[e] An odds ratio was not calculated because there were only 3 cases of cough.

tered every 2 hr, the analyses were different. Gamble et al. [1999] divided the work shift into four 2-hr periods and analyzed incident symptoms, whereas we analyzed prevalent symptoms for the entire shift. It was not possible to analyze our data using Gamble's methodology, as our data violated the requirements of the statistical model. Therefore, it was also not possible to compare our results directly to theirs nor compare the 2 methods using the same data.

Norseth et al. [1991] measured asphalt paving workers' exposures to asphalt fume particulate and various volatile organic compounds over 5 days and collected symptom information by questionnaire on the last day. They found a mean particulate and vapor exposure of 0.358 mg/m^3, with a median of 0.208 mg/m^3 and a range of 0.20–1.29 mg/m^3. They calculated an overall symptom score (which included fatigue and reduced appetite as well as eye, nose, and throat irritation) and found it to be associated with particulate concentration above 0.40 mg/m^3, as well as with 1,2,4-trimethylbenzene. Although they later re-analyzed their data and concluded that the symptoms they had originally associated with 1,2,4-trimethylbenzene were actually attributable to 1,2,3-trimethylbenzene, that re-analysis, to our knowledge, has been published only as an abstract [Norseth et al., 2000].

NIOSH measured VOC, sulfur dioxide, and hydrogen sulfide in area samples collected above the screed auger, the point of the most concentrated asphalt fume emission, but not in personal samples. Concentrations of the individual organic compounds and inorganic gases were low with respect to potential irritant effects. Total VOC (as Stoddard solvent) ranged from 0.24 to 74 mg/m^3, with a mean of 12 mg/m^3 [Burr et al., 2001]. (The most stringent of the U.S. occupational exposure limits for Stoddard solvent is the NIOSH recommended exposure limit, 350 mg/m^3 [NIOSH, 1977a].) Although some of the NIOSH VOC concentrations were numerically higher than those reported by Gamble et al. [1999], the latter were from personal samples. In an unpublished, more detailed report of the Gamble et al. study (obtained from the authors), eight ''source'' area samples at paving sites had a mean VOC concentration of 9.44 mg/m^3 (standard deviation 11.94), with a range of 0.01 to 34.25 mg/m^3 and a geometric mean of 2.07 mg/m^3 (geometric standard deviation 16.10). As the sample locations are not specified, the meaning of the apparent difference between the 2 studies is uncertain. The possibility that VOC exposures contributed to NIOSH study participants' symptoms cannot be ruled out.

Other irritant exposures could also have affected the NIOSH findings. Although measured concentrations of hydrogen sulfide, sulfur dioxide, and ozone were low, and (according to the elemental carbon/total carbon ratio) diesel emissions was, with the possible exception of one site, a minor contributor to TP, these substances are all potential irritants; the effect of irritant mixtures at low concentrations is uncertain. Thus, the irritant symptoms associated with asphalt paving work could be due to asphalt fume alone or to some combination of exposures.

The original purpose of the series of NIOSH studies, which was initiated following complaints about CRM HMA, was to compare the acute health effects of exposure to CRM asphalt with those of exposure to unmodified asphalt. Exposures to TP, BSP, PAC, OSC, and benzothiazole, as well as occurrence rates of irritant and respiratory symptoms, were generally higher during paving with CRM asphalt than during paving with unmodified asphalt. At each study site, the same workers used both types of asphalt and knew which type they were working with on a given day. It is thus possible that workers over-reported symptoms on days CRM asphalt was used. But there is no reason to think that such a potential bias would result in over-reporting symptoms on days unmodified asphalt was used; if anything, there might have been a bias toward under-reporting symptoms on these days. Nevertheless, the subjective nature of symptom reporting remains a methodological problem, and the attribution of the symptoms to asphalt fume is complicated by the presence of other irritant exposure at paving sites.

Neither the NIOSH study nor the Gamble et al. [1999] study found clinically significant changes in pulmonary

TABLE IV. Occurrence Rates of Symptoms among Asphalt Paving Workers, by Personal Breathing Zone Total Particulate Air Concentration,[a] Seven Sites 1994–1997

		Exposure concentration category[a]					
		<0.5	≥0.5	<0.4	≥0.4	<0.3	≥0.3
Symptom	Person-days[b]	66	12	62	16	57	21
Burning, itchy, painful, or irritated eyes	N	4	5	3	6	3	6
	%	6	42	5	38	5	29
	OR (95% CI)	7.5 (1.1–50)		6.1 (0.97–39)		4.0 (1.0–16)	
Burning, itchy, stuffy, or irritated, nose	N	11	4	8	7	7	8
	%	17	33	13	44	12	38
	OR (95% CI)	1.5 (0.28–8)		3.0 (0.63–15)		3.1 (0.85–11)	
Sore, dry, scratchy, or irritated throat	N	4	6	4	6	4	6
	%	6	50	6	38	7	29
	OR (95% CI)	15 (2.3–103)		7.8 (0.86–72)		2.5 (0.44–15)	
Cough	N	4	3	4	3	4	3
	%	6	25	6	19	7	14
	OR (95% CI)	4.6 (1.0–20)		3.1 (0.97–9.8)		1.7 (0.61–4.9)	

[a]Milligrams per cubic meter, full-shift time-weighted average.
[b]N, number of occurrences (that is, person-days with symptom); %, occurrences/person-days × 100; OR, odds ratio, CI, 95% confidence interval. The logistic regression analyses included sampling/analytical method as an independent variable, but not age, sex, or cigarette use because the models did not converge when these variables were included.

function among outdoor asphalt paving workers. But these studies do not address whether such effects occur at higher levels of exposure. A recent experimental study addressed acute pulmonary toxicity of asphalt fume [Ma et al., 2000]. Asphalt fume condensate (AFC) stimulated production of tumor necrosis factor-alpha in rat primary alveolar macrophage (AM) cell culture and at relatively high concentrations was cytotoxic. The AFC did not, however, ''cause acute pulmonary inflammation or injury . . . [or] significantly alter AM functions'' in rats exposed intratracheally [Ma et al., 2000]. A follow-up study of rats exposed to asphalt fume by inhalation, at concentrations in the 10–60 mg/m^3 range, found induction of CYP1A1 and other cellular metabolic effects in the lung, but no alteration of alveolar macrophage activity or other signs of acute lung damage or inflammation [Ma et al., 2003].

In a NIOSH study of workers involved in asphalt paving in a tunnel, where exposures were generally higher (TP:

TABLE V. Eye, Nose, or Throat Symptoms among Asphalt Paving Workers, by Personal Breathing Zone Benzene-soluble Particulate Air Concentration,[a] Seven Sites 1994–1997

	Exposure concentration category						
	Below threshold			At or above threshold			
Air concentration threshold (mg/m^3)	Person-days	No.[c]	%[c]	Person-days	No.[c]	%[c]	OR (95% CI)[b]
0.50	31	13	42	1	1	100	—[d]
0.40	28	11	40	4	3	75	5.2 (0.37–72)
0.30[e]	25	8	32	7	6	86	11 (1.5–84)
0.20	22	7	32	10	7	70	5.3 (0.90–32)
0.10	18	5	28	14	9	64	4.8 (0.99–23)

[a]Milligrams per cubic meter, full-shift time-weighted average.
[b]OR, odds ratio; CI, 95% confidence interval.
[c]Number of occurrences (that is, person-days with symptom) and occurrences/person-days × 100.
[d]An odds ratio was not calculated if the number of cases in any exposure category was less than 3.
[e]The results were identical for analyses dichotomized at 0.25 mg/m^3 (one-half the American Conference of Governmental Industrial Hygienists threshold limit value) because there were no exposures between 0.25 and 0.30 mg/m^3.

1.09–2.17 mg/m^3, BSP: 0.30–1.26 mg/m^3) than those measured outdoors in the NIOSH study reported here and in the Gamble et al. [1999] study, 3 (including 2 nonsmokers) of nine participants had a serial PEFR pattern indicative of bronchial lability [Sylvain and Miller, 1997]. The significance of this finding is uncertain due to the effort-dependent nature of the PEFR procedure [Scanlon and Hankinson, 1996], the lack of a comparison group, and the fact that only one of the workers with bronchial lability reported concurrent respiratory symptoms.

As the NIOSH recommended exposure limit (REL) for asphalt fume is based on a 15-min sampling period, the full-shift personal exposure concentrations of TP measured in this study are not directly comparable to it. Nevertheless, since the NIOSH exposure measurements are numerically an order of magnitude lower than the REL, any exposures that exceeded the REL, though possible, must have been infrequent. The ACGIH TLV for asphalt fume, based on its irritant effects, is a full-shift time weighted average of 0.50 mg/m^3 for the benzene-soluble fraction of the inhalable aerosol [ACGIH, 2006]. This study observed increased irritant symptoms below this level using total BSP as the exposure metric. Since the mass median diameter of asphalt fume is generally around 1 μm [Hanley et al., 2002], the inhalable BSP concentration approximates the total BSP concentration, a conclusion supported by experimental data [Ekström et al., 2001]. TP data suggested that exposures above the REL were probably not common, thus raising the question of whether symptoms occur with exposures below the REL. This question cannot be resolved given the limitations of the available data in this and other studies.

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APPENDIX

Asphalt Paving Process (Adapted From Burr et al. [2001])

There are 3 basic steps in constructing an asphalt pavement—manufacture of the hot-mix asphalt (HMA), placement of the mix onto the ground, and compaction. The asphalt mix contains 2 primary ingredients: a binder (typically an asphalt cement) and an aggregate (a mixture of coarse and fine stones, gravel, sand, and other mineral fillers).

Asphalt cement is typically received from a refinery by tractor-trailer tankers and transferred into heated storage tanks at the HMA plant. Aggregate of different materials and sizes is blended and dried, then coated with a thin film of asphalt cement to produce a homogeneous paving mixture. This finished paving mixture, which is kept heated so that it can be easily applied and compacted, is eventually dispensed into trucks and hauled to the paving site, where the following equipment is typically used:

Tack truck—a vehicle that precedes the paver and applies a low-viscosity asphalt (''tack coat'') to the roadway to improve adhesion of the HMA. (A tack truck was used, briefly, at only one study site.)

Paver—a vehicle that receives the HMA from the delivery trucks and distributes it on the road in the desired width and depth. The HMA is transferred from the delivery truck to the paver by (1) directly pouring it into a hopper located on the front of the paver, (2) conveying the mix with a material transfer vehicle, or (3) dumping the HMA onto the road, where it is picked up by a windrow conveyor and loaded into the paver hopper. This last method usually involves a ''truck dumper'' to monitor the emptying of the delivery truck and the placement of the windrow in front of the paving vehicle. (Each study site had one paver operator. Four of the seven sites used truck dumpers.)

Screed—located at the rear of the paver, the screed distributes the HMA onto the road to a pre-selected width and depth and grades the HMA to the appropriate slope as the paving vehicle moves forward. (Each study site had one or 2 screed operators.)

Rollers—typically, 2 or 3 roller vehicles follow the paver to compact the asphalt. (Roller operators were present at all of the study sites.)

The size of the paving crews at the seven sites typically ranged from eight to ten workers. Job titles and activities included a crew foreman; a truck dumper (also called a ''dump man''), who coordinated the arrival (and operated the hatches) of the bottom-dump trucks; a paver operator, who drove the paver; one or 2 screed operators, who controlled the depth and width of the HMA placement; one or 2 rakers (also called ''lutemen''), who shoveled excess HMA, filled in voids, and prepared joints; laborers, who performed miscellaneous tasks; roller operators who drove the rollers; and a tack truck driver, who applied the tack coat. The paver operators, screed operators, and roller operators did not usually work different jobs, but the other workers may have performed a variety of tasks throughout the workday.