# Health Effects of the 2003 Southern California Wildfires on Children

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***Rationale:*** **In late October 2003, Southern California wildfires burned more than 3,000 km$^2$. The wildfires produced heavy smoke that affected several communities participating in the University of Southern California Children's Health Study (CHS).**

***Objectives:*** **To study the acute effects of fire smoke on the health of CHS participants.**

***Methods:*** **A questionnaire was used to assess smoke exposure and occurrence of symptoms among CHS high-school students (n = 873; age, 17–18 yr) and elementary-school children (n = 5,551; age, 6–7 yr), in a total of 16 communities. Estimates of particulate matter ($PM_{10}$) concentrations during the 5 d with the highest fire activity were used to characterize community smoke level.**

***Main Results:*** **All symptoms (nose, eyes, and throat irritations; cough; bronchitis; cold; wheezing; asthma attacks), medication usage, and physician visits were associated with individually reported exposure differences within communities. Risks increased monotonically with the number of reported smoky days. For most outcomes, reporting rates between communities were also associated with the fire-related $PM_{10}$ levels. Associations tended to be strongest among those without asthma. Individuals with asthma were more likely to take preventive action, such as wearing masks or staying indoors during the fire.**

***Conclusions:*** **Exposure to wildfire smoke was associated with increased eye and respiratory symptoms, medication use, and physician visits.**

**Keywords:** air pollution; asthma; sore throat; wheezing

> ### AT A GLANCE COMMENTARY
>
> **Scientific Knowledge on the Subject**
>
> Adverse effects of fire smoke are known, but results in children are inconsistent due to a lack of large population-based studies.
>
> **What This Study Adds to the Field**
>
> The study quantifies effects of fire smoke on eye, upper, and lower respiratory symptoms. It gives first evidence of benefits of preventive actions.

In October 2003, a series of devastating wildfires burned in Southern California. The hot and dry Santa Ana winds encouraged the spread of fires across several locations to the north, east, and south of the Los Angeles metropolitan area, and dense plumes of smoke dominated much of the area for several days. Local air-quality monitors recorded hourly particulate matter concentrations approaching 1,000 $\mu g/m^3$ particles of aerodynamic diameter up to 10 $\mu m$ ($PM_{10}$); these levels were 10 to 20 times the typically observed ambient levels (1, 2). The fires occurred over a wide geographic area, over a 480-km swath affecting six Southern California counties (Ventura, Los Angeles, San Bernardino, Riverside, Orange, and San Diego). The fires consumed more than 3,100 km$^2$ (750,000 acres) and destroyed 3,640 homes, 33 commercial properties, and 1,141 other structures (including several regional air-monitoring stations).

Most wildfire investigations focus on short-term changes in hospital admissions or on segments of the population believed to be especially sensitive to respiratory stress, such as patients with chronic obstructive lung disease (COPD) or asthma, or on those individuals especially prone to exposure, such as firefighters (3, 4). Medical surveillance data from San Diego County revealed significant increases in hospital emergency room visits for asthma, respiratory problems, and eye irritation during the 2003 fire period (5). Population-based investigations of the acute respiratory health effects of fire smoke on children's health have been limited and based on small samples. The lack of data may be contributed, in part, to the logistical challenge of implementing population-based studies during fire emergencies. Australian researchers investigated the health effects of bush fires and reported increased evening wet cough among a panel of 32 children with asthma but nonsignificant results for wheeze and $\beta$-agonist use (6). $PM_{10}$ peaks were much lower (130 $\mu g/m^3$) than in the 2003 California fires. Associations of fire smoke and evening peak flow were also not conclusive (7). In Asia, the large 1997 fires resulted in an increased use of health services (4) and higher mortality rates both among infants and adults (8).

The Southern California fires offered a unique opportunity to conduct a population-based, large-scale investigation of the health consequences of the smoke from wildfires on children's health. The region affected by the wildfires included several communities participating in a long-term ongoing health study of California schoolchildren, the University of Southern California Children's Health Study (CHS) (9, 10). The goal of the CHS is to understand the contribution of long-term or lifetime exposure to ambient air pollution to children's respiratory health (9–11). Initial cohorts of children were recruited (1993 and 1996) from 12 communities across six Southern California counties. In 2002, an additional cohort of kindergarten and first-grade children

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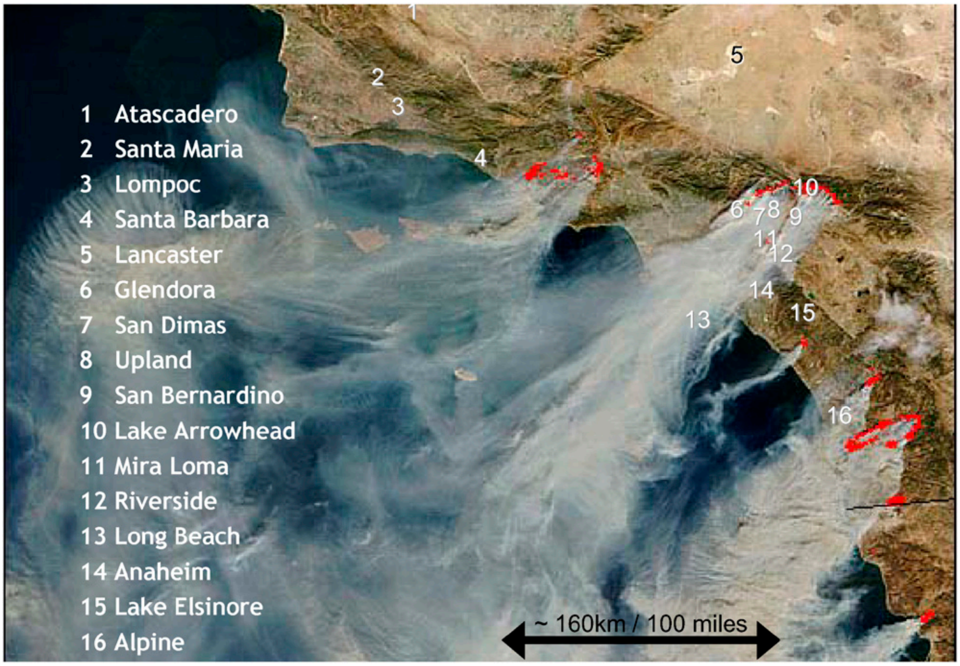


*Figure 1.* Satellite image of Southern California taken on October 24, 2003, showing the smoke plumes from numerous fires. Locations of the 16 Children's Health Study communities participating in the fire study are *highlighted*. Image courtesy of MODIS Rapid Response Project at NASA/GSFC.

(aged 5 to 6 yr) were enrolled from 13 partly overlapping communities (10). At least 12 of the 16 cohort communities were either directly affected by the fire (i.e., the community was the site of fire damage and human evacuation) or indirectly affected (by dense smoke covering the community). Figure 1 presents the cohort study towns in a satellite image of the wildfire areas taken in late October 2003.

To assess the effects of the wildfires, we implemented a questionnaire-based investigation of fire smoke exposure and symptoms for two of the existing and accessible study cohorts (12th-grade high-school students, and first- and second-grade elementary-school children). The availability of extensive socio-demographic and health data among this large sample of children offered a unique opportunity to efficiently investigate and quantify the health consequences of fire smoke exposure in both children with asthma and nonasthmatic children. Some of the results of this study have been previously reported in the form of an abstract (12).

## METHODS

The CHS methods have been published elsewhere. Details about the fire study are provided online. In brief, the CHS consists of repeated annual health assessments to monitor the course of respiratory health. The fire questionnaire study focused on participants of two ongoing CHS cohorts, including one cohort of high-school students (17 to 18 yr old during the fire), originally enrolled in 1996, and a cohort of elementary-school children (aged 6 to 7 yr), recruited in 2002. The older student cohort included high schools from the 12 (9, 10) original CHS communities and the elementary-school cohort involved 13 communities (nine of which were the same) (10). The study protocol was approved by the institutional review board for human studies at the University of Southern California, and written, informed consent was provided by participating students and a parent or legal guardian of minors.

The 2003 Southern California fires peaked between October 20 and November 2. During November–December 2003, the high-school students and the parents of the elementary-school children received the fire questionnaire by mail (*see* online supplement) and/or during the first 6 mo in 2004 as an annex activity of the ongoing CHS. The reporting period referred to the "two weeks of the October 2003 fire period." Although the first page of the fire questionnaire asked about health-related problems, the second page referred to exposure to fire smoke and personal measures taken to modify this exposure (including evacuation, wearing of masks, reduction in time spent outdoors, and changes in physical activity). To quantify exposure duration, questionnaire response categories included the following: "not at all," "1–2 d," "3–5 d," "6–10 d," or "all days" (i.e., up to 2 wk).

Objective smoke measurements (i.e., $PM_{10}$ [U.S. Environmental Protection Agency–approved Federal Reference Methods to quantify $PM_{10}$]) were available only on the community rather than on an individual level. $PM_{10}$ was the strongest marker of fire smoke pollution (1, 2). High concentration periods lasted approximately 5 d; thus, we used the 5-d mean $PM_{10}$ level to characterize fire smoke. Missing air-quality data required estimation procedures of the 5-d average $PM_{10.}$ Five-day average $PM_{10}$ concentrations were estimated for 5 of the 16 communities. San Dimas, Glendora, and Anaheim had all 5 d (October 24–28) estimated, and San Bernardino had 4 d (October 25–28) estimated. Because Alpine was directly affected by the fires from October 26 to 28, $PM_{10}$ concentrations at Alpine were averaged over the 3 fire days with 2 d estimated (October 27–28). For more details, *see* text and Table E1 in the online supplement and Reference 1.

### Statistical Analyses

To investigate the association between fire smoke exposure and symptoms, we chose multilevel approaches to distinguish within-community differences in exposure from the contrasts between communities. We used the reported "smell of fire smoke indoors" as the primary measure of exposure. We created two components of reported exposure response. The first was a between-community measure, derived from the community-specific mean response. The second was a within-community response, created by subtracting the community mean from the individual response, using a mixed-effects model with a logistic link. As described in the online supplement, the five exposure categories were combined into three levels, providing comparison across the following groups of "fire smoke smelled": no fire smoke, fire smoke smelled 1 to 5 d, and fire smoke smelled 6 d or more.

The first set of analyses was based on the reported levels of fire smoke smelled at home indoors, reflecting the change in symptoms due to an increase in the duration of (perceived) fire smell. In a second set of models, we replaced the reported community mean fire smoke response with the ambient 5-d mean $PM_{10}$. Thus, these between-community estimates reflected the change in symptoms for a change in ambient $PM_{10}$ during the 5 most extreme days of fire smoke.

**TABLE 1. HIGH-SCHOOL STUDENTS AND PARENTS (ELEMENTARY-SCHOOL CHILDREN) RESPONDING TO THE FIRE QUESTIONNAIRE WITHIN 8 WEEKS OF THE FIRE (EARLY RESPONSE, NOVEMBER/DECEMBER 2003) AND TOTAL RESPONSE (INCLUDING JANUARY TO JUNE 2004 DURING CHILDREN'S HEALTH STUDY HEALTH VISITS)**

| | High-School Students (17–18 yr old) | | | Elementary-School Children (6–7 yr old) | | |
|---|---|---|---|---|---|---|
| Community | Baseline Population | Early Response (2003), n (%) | Total Response (2003/04), n (%) | Baseline Population | Early Response (2003), n (%) | Total Response (2003/04), n(%) |
| Alpine | 75 | 35 (46.4) | 70 (93.3) | 397 | 165 (41.5) | 299 (75.3) |
| Anaheim | — | — | — | 419 | 90 (21.4) | 251 (59.9) |
| Atascadero | 74 | 68 (91.8) | 70 (94.5) | — | — | — |
| Glendora | — | — | — | 466 | 228 (48.9) | 374 (80.2) |
| Lake Arrowhead | 70 | 28 (40.5) | 67 (95.7) | 401 | 163 (40.6) | 301 (75.0) |
| Lake Elsinore | 66 | 23 (35.3) | 62 (93.9) | 386 | 254 (65.8) | 254 (65.8) |
| Lancaster | 64 | 27 (41.5) | 61 (95.3) | — | — | — |
| Lompoc | 80 | 32 (40.0) | 78 (97.5) | — | — | — |
| Long Beach | 85 | 35 (41.6) | 79 (92.9) | 366 | 87 (23.7) | 239 (65.3) |
| Mira Loma | 64 | 51 (78.4) | 62 (96.8) | 510 | 280 (54.9) | 286 (56.0) |
| Riverside | 69 | 53 (76.8) | 67 (97.1) | 439 | 150 (34.1) | 285 (64.9) |
| San Bernardino | — | — | — | 410 | 94 (22.9) | 255 (62.1) |
| San Dimas | 74 | 39 (52.7) | 74 (100) | 393 | 169 (43.0) | 213 (54.1) |
| Santa Barbara | — | — | — | 468 | 166 (35.4) | 360 (76.9) |
| Santa Maria | 66 | 25 (39.0) | 62 (93.9) | 470 | 125 (26.5) | 311 (66.1) |
| Upland | 86 | 39 (46.4) | 82 (95.3) | 426 | 198 (46.4) | 347 (81.4) |
| Total | 873 (100) | 455 (52.4) | 834 (95.5) | 5,551 (100) | 2,169 (39.0) | 3,775 (68.0) |

The final models included those covariates that were independent predictors and/or confounders in the models of at least one symptom, namely sex, ethnicity, educational level of parents, asthma status before the fire (physician-diagnosed asthma), and cohort (high-school vs. elementary-school cohort). A p value of 0.05 or less was considered statistically significant. In addition, all analyses were stratified by asthma status. All analyses were conducted with the statistical software SAS/STAT, version 9 (2002; SAS Institute, Cary, NC).

## RESULTS

Table 1 summarizes the study populations and participation. High-school students' participation rates during the first 8 wk (2003) reached 52.4%, whereas only 39.0% of the parents (younger cohort) returned the mail-in questionnaire. The extended distribution of the fire questionnaire during 2004 strongly improved response rates, ultimately reaching 95.5% in the older and 68.0% in the younger cohort.

Table 2 summarizes the distribution of reported fire exposure and the ambient levels of measured or estimated $PM_{10}$ (*see* METHODS). Both the subjective and objective measures of fire smoke showed that communities not directly affected by local fires suffered substantial smoke exposure (e.g., Mira Loma, Riverside, and Anaheim).

Table 3 summarizes the prevalence of the reported outcomes, by cohort and asthma status. As expected, prevalence rates were much higher among individuals with asthma. Dry cough, medication, and physician visits were more frequently reported by parents of elementary-school children, whereas high-school students were more likely to report eye symptoms. Home loss due to fire was reported by 35 (0.75%) study participants. In Alpine and

**TABLE 2. PREVALENCE OF REPORTED SMELL (%) OF FIRE SMOKE INDOORS (BY COHORT), 5-DAY MEAN $PM_{10}$ DURING THE FIRE PERIOD,* AND LONG-TERM AMBIENT $PM_{10}$ IN THE 16 COMMUNITIES**

| | High-School Students ($n = 834$) | | | | Elementary-School Children ($n = 3,775$) | | | | $PM_{10}$ in $\mu g/m^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Town | Not at All | 1–2 d | 3–5 d | ⩾ 6 d | Not at All | 1–2 d | 3–5 d | ⩾ 6 d | 5-d Mean (fire period) | 1992–2003, Mean |
| Alpine | 27.1 | 21.4 | 20.0 | 31.4 | 21.1 | 23.8 | 19.1 | 33.6 | 201 | 25.3 |
| Anaheim | — | — | — | — | 64.4 | 10.2 | 6.4 | 13.6 | 132 | 36.9 |
| Atascadero | 97.1 | 1.4 | 0 | 0 | — | — | — | — | 52 | 21.3 |
| Glendora | — | — | — | — | 54.4 | 20.9 | 8.4 | 13.9 | 158 | 32.5 |
| Lake Arrowhead | 63.6 | 14.6 | 12.1 | 10.6 | 57.7 | 20.1 | 10.4 | 9.4 | 172 | 19.8 |
| Lake Elsinor | 64.5 | 17.7 | 3.2 | 9.7 | 59.0 | 16.1 | 10.8 | 11.7 | 104 | 35.6 |
| Lancaster | 45.9 | 29.5 | 11.5 | 9.8 | — | — | — | — | 45 | 29.0 |
| Lompoc | 88.5 | 2.6 | 1.3 | 5.1 | — | — | — | — | 32 | 14.4 |
| Long Beach | 63.3 | 17.7 | 11.4 | 5.1 | 62.2 | 15.9 | 5.2 | 11.6 | 135 | 36.8 |
| Mira Loma | 54.1 | 16.4 | 13.1 | 16.4 | 47.1 | 13.2 | 13.2 | 23.2 | 250 | 66.3 |
| Riverside | 52.2 | 13.4 | 14.9 | 16.4 | 47.1 | 16.4 | 12.9 | 16.4 | 172 | 42.3 |
| San Bernardino | — | — | — | — | 24.2 | 15.3 | 13.3 | 41.1 | 199 | 51.0 |
| San Dimas | 55.6 | 19.4 | 11.1 | 12.5 | 45.5 | 15.8 | 18.7 | 16.8 | 191 | 36.7 |
| Santa Barbara | — | — | — | — | 80.3 | 9.7 | 2.9 | 2.6 | 30 | 28.2 |
| Santa Maria | 90.3 | 6.5 | 0 | 1.6 | 90.8 | 2.6 | 0.3 | 1.6 | 51 | 22.0 |
| Upland | 26.6 | 7.6 | 24.1 | 39.3 | 20.1 | 18.6 | 20.4 | 39.0 | 252 | 40.7 |

* Rows do not add up to 100% due to rounding and a few "don't know" answers.

**TABLE 3. PREVALENCE (%) OF SYMPTOMS REPORTED FOR THE FIRE PERIOD, BY STUDY COHORT AND BY ASTHMA STATUS (BASED ON THE LAST CHILDREN'S HEALTH STUDY QUESTIONNAIRE AVAILABLE PRIOR TO THE FIRE)**

| | High-School Students (*n* = *834*) | | | Elementary-School Children (*n* = *3,775*) | | | Both Cohorts (*n* = *4,609*) | | |
|---|---|---|---|---|---|---|---|---|---|
| Symptom | No Asthma (*n* = *616*) | Asthma (*n* = *218*) | All | No Asthma (*n* = *3,287*) | Asthma (*n* = *488*) | All | No Asthma (*n* = *3,903*) | Asthma (*n* = *706*) | All |
| Itchy/watery eyes | 41.1 | 47.7 | 42.8 | 29.9 | 51.6 | 32.8 | 31.7 | 50.4 | 34.6 |
| Irritated eyes | 41.6 | 50.9 | 44.0 | 30.9 | 51.8 | 33.6 | 32.6 | 51.5 | 35.5 |
| Sneezing/blocked nose | 38.6 | 49.3 | 41.4 | 37.6 | 65.8 | 41.3 | 37.7 | 60.7 | 41.3 |
| Cold | 26.0 | 27.5 | 26.4 | 24.4 | 33.9 | 25.7 | 24.7 | 31.9 | 25.8 |
| Sore throat | 32.3 | 41.3 | 34.6 | 30.8 | 42.5 | 32.3 | 31.0 | 42.1 | 32.7 |
| Dry cough at night | 14.3 | 22.5 | 16.4 | 24.1 | 49.3 | 27.4 | 22.6 | 41.0 | 25.4 |
| Dry cough first in morning | 13.0 | 19.3 | 14.6 | 20.7 | 43.5 | 23.7 | 19.5 | 36.0 | 22.0 |
| Dry cough other times | 17.5 | 28.4 | 20.3 | 19.3 | 43.8 | 22.4 | 19.0 | 39.0 | 22.0 |
| Wet cough | 13.7 | 16.2 | 14.5 | 12.9 | 24.0 | 14.3 | 13.0 | 21.6 | 14.3 |
| Wheeze/general | 7.3 | 18.9 | 10.4 | 6.8 | 39.9 | 11.0 | 6.8 | 33.3 | 10.9 |
| Wheeze/disturbed sleep | 2.3 | 7.0 | 3.5 | 3.5 | 21.9 | 5.8 | 3.3 | 17.3 | 5.4 |
| Wheeze/ limited speech | 1.0 | 1.9 | 1.2 | 0.9 | 4.3 | 1.3 | 0.9 | 3.5 | 1.3 |
| Asthma attack | 1.0 | 11.0 | 3.6 | 1.3 | 17.4 | 3.3 | 1.2 | 15.4 | 3.4 |
| Bronchitis | 3.3 | 2.8 | 3.1 | 3.7 | 9.9 | 4.5 | 3.6 | 7.7 | 4.2 |
| Medication* | 12.9 | 23.6 | 15.7 | 23.7 | 50.6 | 27.2 | 22.0 | 42.3 | 25.1 |
| Visit a doctor* | 5.6 | 9.7 | 6.7 | 9.8 | 22.0 | 11.4 | 9.2 | 18.2 | 10.6 |
| Missed school* | 9.8 | 14.7 | 11.1 | 11.8 | 24.8 | 13.5 | 11.5 | 21.7 | 13.1 |

* For above problems.

Lake Arrowhead, more than 3% of study participants lost their homes (n = 15 and 10, respectively).

The main results are summarized in Table 4. Six or more days of fire smell indoors was significantly associated with all outcomes, and the smaller risk estimates for 1 to 5 d of exposure reached statistical significance in all but two outcomes (asthma attacks and bronchitis). Having fire smoke smell indoors for more than 6 d was associated with more than fourfold higher rates of eye symptoms, approximately threefold increased rates of dry cough and sneezing, and more than twofold higher rates of cold, sore throat, wet cough, medication use, physician visits, and missed school due to symptoms. The three types of wheezing (general, sleep-disturbing, and speech-limiting) occurred 3.5, 4.9, and 5.5 times more often, respectively, among those with 6 or more days of fire smell indoors. Asthma attacks increased 63%. The trend across the different levels of fire smell duration was highly significant for all outcomes except for asthma attacks (p = 0. 12).

The between-community comparisons were analyzed with two different metrics, namely $PM_{10}$ and the community mean

**TABLE 4. MAIN EFFECT OF FIRE SMOKE ON ALL OUTCOMES (ODDS RATIOS AND 95% CONFIDENCE INTERVALS)**

| | Within-Community (reported) | | | | Between-Community ($PM_{10}$) | |
|---|---|---|---|---|---|---|
| Symptom | OR 1–5 d | 95% CI | OR ⩾ 6 d | 95% CI | OR 210 | 95% CI |
| Itchy/watery eyes | **2.26** | 1.90–2.68 | **4.11** | 3.36–5.02 | **2.97** | 2.00–4.40 |
| Irritated eyes | **2.38** | 2.01–2.82 | **4.42** | 3.61–5.41 | **3.13** | 2.15–4.55 |
| Sneezing; runny/blocked nose | **1.98** | 1.68–2.33 | **2.79** | 2.30–3.39 | **1.94** | 1.44–2.61 |
| Cold | **1.50** | 1.25–1.81 | **2.13** | 1.73–2.63 | 0.92 | 0.67–1.25 |
| Sore throat | **1.81** | 1.53–2.14 | **2.50** | 2.05–3.05 | **1.79** | 1.45–2.20 |
| Dry cough at night | **2.25** | 1.87–2.71 | **3.35** | 2.71–4.15 | **1.92** | 1.38–2.67 |
| Dry cough first thing morning | **2.24** | 1.85–2.72 | **2.91** | 2.33–3.63 | **1.93** | 1.36–2.73 |
| Dry cough other times | **2.67** | 2.20–3.24 | **3.27** | 2.61–4.09 | **2.49** | 1.86–3.33 |
| Wet cough | **1.42** | 1.13–1.79 | **2.15** | 1.67–2.77 | 1.01 | 0.72–1.41 |
| Wheezing or whistling | **2.15** | 1.63–2.83 | **3.53** | 2.62–4.75 | 1.37 | 0.86–2.20 |
| Wheeze/disturbed sleep | **2.29** | 1.56–3.37 | **4.94** | 3.33–7.33 | 0.89 | 0.56–1.42 |
| Wheeze/limited speech | **2.23** | 1.03–4.83 | **5.49** | 2.63–11.48 | 0.78 | 0.29–2.10 |
| Asthma attack | 1.32 | 0.84–2.07 | **1.63** | 1.00–2.67 | 1.03 | 0.58–1.80 |
| Bronchitis | 1.33 | 0.87–2.02 | **2.23** | 1.45–3.43 | 0.79 | 0.39–1.59 |
| Medication for above problems | **1.82** | 1.51–2.19 | **2.33** | 1.89–2.88 | **1.38** | 1.03–1.84 |
| Visit a doctor for above problems | **1.33** | 1.02–1.74 | **2.03** | 1.53–2.71 | 0.81 | 0.59–1.12 |
| Missed school for above problems | **1.59** | 1.25–2.02 | **2.24** | 1.72–2.91 | 0.96 | 0.72–1.27 |

*Definition of abbreviations*: CI = confidence interval; OR = odds ratio.

Within-community ORs are based on individually reported smell of fire smoke indoors (no fire smell = reference, OR = 1.0; not shown; 1-5 d; and ⩾ 6 d of fire smell). Between-community ORs show the associations scaled to the contrast in $PM_{10}$ between the communities with the highest and lowest levels, respectively (~ 210 vs. 30 μg/m³). Models are adjusted for baseline asthma, ethnicity, parental education, and study cohort. Statistically significant estimates (p ⩽ 0.05) are in bold type.

response to the fire smell question. Results are presented for the former only (Table 4) as they were similar for both metrics. The community mean of the reported level of fire smoke indoors and the estimates of the 5-d mean $PM_{10}$ were highly correlated ($r$ = 0.81) in both high-school and elementary-school students. Comparing highest with lowest community exposures, the between-community results were statistically significant and similar for both metrics in case of dry cough, eye, nose, and throat symptoms, as well as for medication. Eye symptoms were approximately three times as frequent in the communities most affected by fires as compared with lesser-affected communities. The between-community estimate for wheezing was significant only with the mean reported smoke (odds ratio [OR], 1.37 per unit change) but not with $PM_{10}$ (Table 4). The other outcomes were not significantly associated with either community-level metric.

The model presented in Table 4 also adjusted for asthma status before the 2003 fire period ("physician-diagnosed asthma"). Therefore, the model also estimates the contribution of physician-diagnosed asthma to symptom frequency in the end of October 2003, independent of the fire smoke. We present these effects (ORs) in Table E3 to highlight the much higher symptom rates among children with asthma (*see also* Table 3). Children with asthma were two to three times more likely to report symptoms than nonasthmatic children. Thus, the effect of having asthma was similar to the effects of fire smoke. In the case of wheezing, asthma status was more strongly related to the symptom (OR = 7.4; *see* Table E3.) than fire smoke (OR = 3.5; *see* Table 4).

The effect of fire smoke was, however, not restricted to children with asthma. Results of Table 4, stratified by asthma status, are presented in the online supplement (Tables E4 and E5). In fact, among nonasthmatic children, coefficients were either very similar or stronger (wheezing) than in children with asthma (n = 706) in whom point estimates tended to be smaller and not statistically significant for speech-limiting wheezing, asthma attacks, bronchitis, cold, wet cough, physician visits, and missed school. The between-community estimates followed a similar pattern as in nonasthmatic children, with significant associations among nine questionnaire items.

To evaluate the joint effects of fire and asthma status on reported symptoms, we examined five indicator variables for the combinations of fire smell (none, 1–5 d, ⩾ 6 d) and asthma status (yes/no) using nonasthmatic children without fire exposure as the reference group. Figure 2 presents the effects of fire smoke among children with and without asthma.

### Preventive Action and Fire-related Health Outcomes

We distinguished those who took action such as wearing masks, spending less time outdoors, or using air conditioners for at least 1 to 2 d from those not reporting preventive strategies. Those taking action also reported higher rates in almost all outcomes, and in many cases, these differences were statistically significant. For example, those reporting "wearing a mask" had symptom rates more than twice as high as those not using masks, whereas those reporting the use of air conditioners or spending "less time outdoors" during the fire had 1.2- to 1.6-fold rates in symptoms. Of particular interest is the interaction between preventive actions and reported duration of fire smell indoors (*see* Table 5). As a general pattern, we observed larger risk gradients related to fire smoke among those who did not take preventive action as compared with those who did. The interaction term reached statistical significance in several models (*see* Table 5). Compared with those who reported no fire smell, subjects with 1 to 5 d of smoke smell indoors who did not wear a mask were twice as likely to report sneezing (OR = 2.02 [1.7–2.4]). For those who did wear a mask (and reported 1–5 d of smoke), sneezing rates were only 25% higher. In the most exposed subgroup (> 6 d of smoke), those without masks had an OR of 2.8 [2.3–3.5], whereas the OR among those with a mask was only 1.67.

## DISCUSSION

To our knowledge, this is the largest investigation of acute effects of wildfire smoke on children's health. We confirmed very substantial effects of wildfire smoke exposure on eyes as well as upper and lower respiratory symptoms, in both children with asthma and nonasthmatic children. The study was population based; thus, findings may be generalized more broadly to other comparable populations. Our findings are consistent with other studies conducted after wildfire outbreaks and occupational studies among firefighters, which suggest that wildfire smoke leads to acute exacerbations of respiratory and eye symptoms and increased demand for health services (13). Like ambient urban air pollution, wildfire smoke contains numerous primary and secondary pollutants, including particles, polycyclic aromatic hydrocarbons, carbon monoxide, aldehydes, organic acids, organic compounds, gases, free radicals, and inorganic materials with diverse toxicologic properties (14), which may explain the wide range of acute symptoms observed in our survey (15).

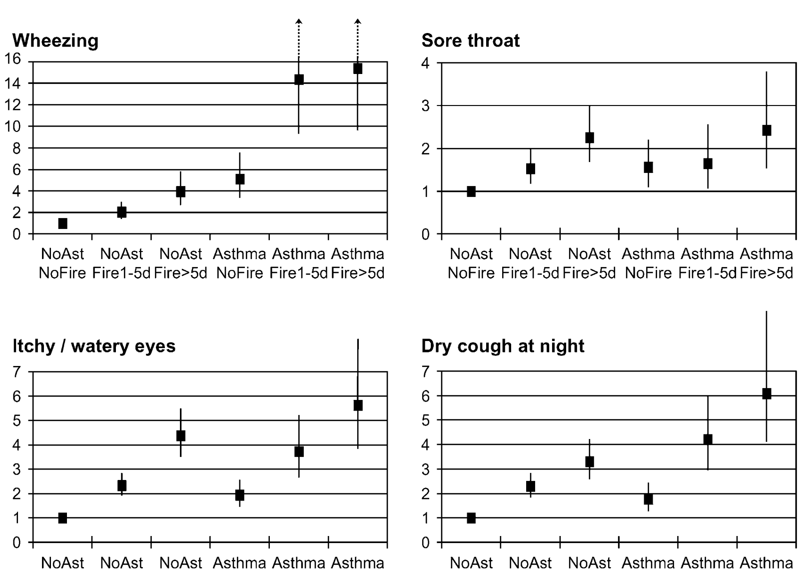


*Figure 2.* Effect of reported smell of fire smoke indoors (during 1–5, > 5 d, respectively) for four symptoms among children with and without asthma. Odds ratios and 95% confidence intervals from models with interaction terms for asthma and fire, adjusted for sex, ethnicity, educational level of parents, and cohort. No asthma (No Ast), no fire = reference.

**TABLE 5. ODDS RATIOS FOR SYMPTOMS AMONG THOSE WITH AND WITHOUT PREVENTIVE ACTIONS AND WITH NO REPORTED SMOKE EXPOSURE (REFERENT GROUP), 1–5, OR ⩾ 6 DAYS OF FIRE SMOKE SMELL INDOORS**

| | Use of Mask | | Air Conditioner Use | | Less Outdoors | |
|---|---|---|---|---|---|---|
| Symptom Exposure Level | No OR (*95% CI*) | Yes OR (*95% CI*) | No OR (*95% CI*) | Yes OR (*95% CI*) | No OR (*95% CI*) | Yes OR (*95% CI*) |
| Sneezing or runny/blocked nose, n | 3,673 | 396 | 3,158 | 911 | 1,371 | 2,698 |
| No fire smell (referent) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 1–5 d fire smell | 2.01 (1.70−2.39) | 1.58 (0.86–2.91) | 2.14 (1.77–2.59) | 1.75 (1.26–2.43) | 1.84 (1.25–2.73) | 1.76 (1.46–2.11) |
| 6 or more days fire smell | 2.81 (2.27−3.47) | 2.30 (1.22–4.31) | 3.05 (2.42–3.85) | 2.23 (1.52–3.25) | 2.54 (1.60–4.01) | 2.47 (1.98–3.09) |
| Wheezing, n | 3,630 | 387 | 3,111 | 906 | 1,357 | 2,660 |
| No fire smell (referent) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 1–5 d fire smell | 2.05 (1.51−2.79) | 1.50 (0.68–3.31) | 2.29 (1.64–3.18) | 1.79 (1.79–3.07) | 4.80 (2.51–9.20) | 1.76 (1.28–2.42) |
| 6 or more days fire smell | 3.47 (2.49−4.85) | 2.23 (1.52–3.25) | 3.46 (2.41–4.98) | 3.00 (1.71–5.27) | 7.65 (3.74–15.63) | 2.91 (2.06–4.09) |

For definition of abbreviations, *see* Table 4.

Total n varies between 4,017 and 4,069 due to varying number of "don't know" answers). The interactions of fire smell and preventive actions were statistically significant (likelihood ratio test, $p < 0.05$) for mask and air conditioner use in case of sneezing/blocked nose, and for "less outdoors" in case of wheezing. Note that in each exposure category, those taking preventive action had higher symptom rates than those not taking action (*see* text).

Biases require particular attention in the interpretation of these findings. Because many parents and students completed the fire questionnaire several months after the fire (from 1 to 7 mo later), and because both exposure and outcome are reported by participants, the study may be subject to interrelated reporting, recall, and selection biases. Due to the lack of individual-level $PM_{10}$ data, we were able to compare effects of objective ($PM_{10}$) and subjective (reported) markers of exposure in the between-community comparison only. We used the community mean of reported fire smoke as the subjective aggregate exposure.

For reported fire smoke, the estimates for individual and community mean were similar for most outcomes. However, between-community estimates using the mean reported fire smell were not entirely consistent with those based on $PM_{10}$. The latter showed no clear association with cold, cough, asthma symptoms, physician visits, and missing school. There are several possible reasons for these inconsistencies.

First, the exposure metrics are inherently different and measure different domains of exposure. $PM_{10}$ estimates the average concentration during the 5 most extreme days. In contrast, the questionnaire-based approach relates to the duration (i.e., number of days of observed smoke) rather than the level of the smoke in the community. Duration may characterize the true contrasts in exposure better than the 5-d average $PM_{10}$ because some communities experienced fire smoke for longer or shorter periods.

Second, $PM_{10}$ levels had to be estimated for five fire communities (*see* METHODS and online supplement). The unknown errors in these estimates may lead to under- or overestimation in the between-community effects. Thus, the results based on "objective" measures of community-level exposure are not necessarily unbiased.

Third, $PM_{10}$ community levels are not sensitive to spatial differences in smoke densities that may have occurred within communities. Therefore, $PM_{10}$ concentrations at the monitor may not represent the mean of the true, but unknown, home outdoor $PM_{10}$ levels. We have no objective data to validate the reported diversity on the individual level. Wu and colleagues estimated $PM_{10}$ distributions all across the Southern California area during the wildfire period, using PM measurements, light extinction, meteorologic data, and smoke information from satellite images (1) (*see* Figure E1). We used these results to investigate the range of daily mean $PM_{10}$ concentrations for small areas representing size and location of several CHS communities. For example, the $PM_{10}$ concentration estimates for a 1 × 1–km grid within a 10-km buffer around San Dimas indicated substantial temporal differences during the fire period, with daily means ranging from 115 $\mu g/m^3$ (October 28) to 220 $\mu g/m^3$ (October 26) as well as large spatial gradients across the grid points. For example, on October 25, the point estimates ranged from 54 to 250 $\mu g/m^3$, and from 90 to 337 $\mu g/m^3$ the next day, with spatial standard deviations up to 50% of the daily means (*see* Figure E1). Although these $PM_{10}$ estimates may be associated with significant uncertainties at the neighborhood scale, they demonstrated substantial spatial heterogeneity, which corroborates the notion that smoke concentrations may vary substantially within communities. The distribution of reported smoke—and thus the community mean of the reported conditions—may reflect these distinct spatial gradients that are influenced by topography and wind patterns (1, 2).

Fourth, the community-level $PM_{10}$ does not take into account $PM_{10}$ levels in locations to which the children might have been evacuated, nor does it account for other individual preventive action taken during the fire period. Thus, the monitor $PM_{10}$ value may again be offset from the true, but unknown, mean $PM_{10}$ across children.

Fifth, the reported fire smell related to the indoor environment where most of the time was spent, whereas outdoor $PM_{10}$ levels are not sensitive to differences among children's indoor environments.

The community mean of the reported fire smell was highly correlated with measured $PM_{10}$. However, others have shown that community mean reported annoyance of ambient air pollution correlates highly with objective measurements, whereas individual scores may poorly correlate with the home outdoor $NO_2$ measurements (16). Reporting was associated with health status and sex. A recent review also concluded that reported exposure to traffic was poorly associated with objective data (17). It is not clear whether findings for reported ambient air pollution also apply to fire smoke perception. Reporting of fire smoke may be less affected by personal attitudes than reported ambient air pollution, given the strong smell of fire smoke, the visibility of the problem, and the exceptional situation of the fire period. Reporting was also associated with sex. Eye symptoms, cold, medication, and physician visits were significantly more often reported among girls, whereas boys were more likely to report wheezing (data not shown). However, sex did not confound nor modify the main effects of fire smoke.

In conclusion, although it is neither possible to dismiss the possibility of biases nor to quantify their effects on our results, we believe that the arguments outlined above support the questionnaire-based results.

### Effect of Fire Smoke on Children with Asthma

With the exception of bronchitis, we consistently observed larger coefficients of reported fire smoke among the nonasthmatic children, a general pattern also true for the between-community comparison. However, the smaller effect sizes in children with asthma must be seen in light of the much higher baseline rates for all symptoms among these children (*see* Tables 3 and 4). Therefore, a small increase in the relative risk may constitute a much larger effect in the children with asthma than in the nonasthmatic children. This is apparent in Figure 2. Symptom rates among children with asthma with no fire smoke were generally as high as those among nonasthmatic children with 1 to 5 d of fire smoke.

Children with asthma were usually treated and may have had better access to medical treatment. A Centers for Disease Control and Prevention surveillance reported increased over-the-counter sales of medication after this 2003 fire period (13). The fire questionnaire did not ask about specific treatments such as steroids.

We also have evidence that children with asthma were more likely to change their behavior (data not shown). For example, 15% of children with asthma reported to have worn a mask for at least some days, whereas only 2% of nonasthmatic children reported taking this personal protective measure. More children with asthma reported reduction in time spent outdoors, outdoor sports, and indoor physical activity due to the fire than did nonasthmatic children. This is in line with results from a previous California fire study indicating that those with preexisting conditions were more likely to follow public advisories to prevent smoke exposure (18). The use of air cleaners in that study was twice as high among those with preexisting health problems.

During a 1987 fire period in California, emergency room visits due to asthma and a range of upper and lower respiratory problems increased significantly beyond the expected rates (19). This was also observed in San Diego County during this 2003 wildfire (5). Large fires in Lithuania also affected crude rates of asthma exacerbation (20). Australian scientists found inconclusive results in their investigation of bushfire effects among a panel of 32 children with asthma. Only evening wet cough was associated with fire smoke (21). Interaction with medication use was not assessed (7), but statistical power may have been a major limitation.

We conclude that the much higher background rates of symptoms was the major reason for the weaker effect estimates observed among children with asthma, and that limitations in the assessment of asthma activity, severity, and medication added further random error to the assessment of effects in children with asthma.

We did investigate effects of fire on boys and girls separately (data not shown). Although baseline frequencies differed by sex for some symptoms, sex did not confound nor did it modify the effects of fire smoke.

### Long-term Ambient Air Pollution and Fire Smoke

Some of the CHS communities with high long-term ambient pollution were heavily affected by fire; thus, we investigated confounding by long-term exposure to air pollution (data not shown). Communities with high long-term pollution had significantly higher reporting of "bronchitis" and "missed school." However, the long-term mean ambient PM did not confound the association between fire smoke and fire-related outcomes. Regular exposure to wood smoke has been reported to be a risk factor for chronic respiratory diseases (22). Tan and colleagues (23) and van Eeden and colleagues (24) have shown that acute exposure to wildfire smoke was associated with the stimulation of the bone marrow to release polymorphonuclear leukocytes in men, which reflects a systemic response that may be relevant to subsequent lung injury. However, the long-term relevance of a single wildfire exposure is not clear. Follow-up of the CHS fire study participants may allow an investigation of the long-term consequences of this unusual episode.

We stratified the analyses by cohort to investigate age-related differences in the effect of fire smoke. Results among the (larger) cohort of elementary-school children were more often statistically significant than in the cohort of high-school students. Coefficients tended to be larger in the latter, however, in particular for the between-community estimates (data not shown). It is difficult to assign these differences to age, given the differences in the study methods, with parents reporting for their young children and high-school students self-reporting symptoms.

Participation rates immediately after the fires in 2003 were low in some cities, so the presence of possible selection bias based on exposure and/or symptoms might have been an issue. However, survey administration efforts during 2004 resulted in increased response rates. We evaluated the effect of time elapsed since the fire on reported symptom prevalence. For some symptoms, the likelihood of reporting steadily decreased as time elapsed between the fire and answering the questionnaire (results not shown). Reporting of eye-related symptoms increased with elapsed time. This analysis demonstrates the importance of obtaining symptom-related information from study subjects in as timely a manner as possible after an unexpected natural event or emergency. Attempts to maximize early responses are important strategies for future studies. Inclusion of some control outcome not believed to be affected by fire smoke (e.g., stomach or digestive complaints) could have enhanced the assessment of reporting biases.

Our study suggests there was a beneficial effect of wearing masks, spending less time outdoors, and/or using air conditioning—actions that were recommended during the fire by public health agencies and the media. As recently shown in a fire smoke intervention study conducted in Colorado, ventilation patterns including the use of air filters can have substantial effects on the indoor levels of fire-related PM (25); thus, our results are plausible. However, because our assessment of exposure, symptoms, and preventive action were cross-sectional and self-reported, caution is appropriate in the interpretation of these results.

In summary, this investigation indicates substantial effects of fire smoke on children's health. The study provides suggestive evidence for protective health benefits of simple strategies, such as staying indoors, wearing a mask, or the use of air conditioners during wildfire smoke periods.

***Conflict of Interest Statement***: None of the authors has a financial relationship with a commercial entity that has an interest in the subject of this manuscript.

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