Asthma in exercising children exposed to ozone: a cohort study

Rob McConnell, Kiros Berhane, Frank Gilliland, Stephanie J London, Talat Islam, W James Gauderman, Edward Avol, Helene G Margolis, John M Peters

Summary

Background Little is known about the effect of exposure to air pollution during exercise or time spent outdoors on the development of asthma. We investigated the relation between newly-diagnosed asthma and team sports in a cohort of children exposed to different concentrations and mixtures of air pollutants.

Methods 3535 children with no history of asthma were recruited from schools in 12 communities in southern California and were followed up for up to 5 years. 265 children reported a new diagnosis of asthma during follow-up. We assessed risk of asthma in children playing team sports at study entry in six communities with high daytime ozone concentrations, six with lower concentrations, and in communities with high or low concentrations of nitrogen dioxide, particulate matter, and inorganic acid vapour.

Findings In communities with high ozone concentrations, the relative risk of developing asthma in children playing three or more sports was 3·3 (95% CI 1·9–5·8), compared with children playing no sports. Sports had no effect in areas of low ozone concentration (0·8, 0·4–1·6). Time spent outside was associated with a higher incidence of asthma in areas of high ozone (1·4, 1·0–2·1), but not in areas of low ozone. Exposure to pollutants other than ozone did not alter the effect of team sports.

Interpretation Incidence of new diagnoses of asthma is associated with heavy exercise in communities with high concentrations of ozone, thus, air pollution and outdoor exercise could contribute to the development of asthma in children.

Lancet 2002; **359:** 386–91

Department of Preventive Medicine, University of Southern California School of Medicine, Los Angeles, CA, USA (R McConnell MD, K Berhane PhD, F Gilliland MD, T Islam MS, W J Gauderman PhD, E Avol MS, Prof J M Peters MD); **National Institute of Environmental Health Sciences, Research Triangle Park, NC, USA** (S J London MD); **and California Air Resources Board, Sacramento, CA, USA** (H G Margolis MS)

Correspondence to: Dr Rob McConnell, Department of Preventive Medicine, University of Southern California School of Medicine, 1540 Alcazar Street, CHP 236, Los Angeles, CA 90089-9011, USA (e-mail: rmcconne@hsc.usc.edu)

Introduction

Asthma is the most common chronic disease of childhood; asthma prevalence and incidence have been increasing in children in developed countries during the past few decades.[1,2] Causes for this epidemic are unknown, although changes in frequency and severity of early-life infections, diet, and exposure to indoor allergens and to indoor and outdoor air pollutants have all been linked with asthma.

Cross-sectional studies[3–5] have shown that competitive athletes have a high prevalence of asthma and exercise-induced bronchospasm or bronchial hyper-reactivity. Possible mechanisms for this association include increased inhalation of cold air, allergens, or air pollutants, increased response to respiratory infections, and increased parasympathetic tone.[3–6] Various mechanisms could be linked with sports-associated asthma. However, few epidemiological investigations have all been done, and there have been no prospective studies of asthma in competitive athletes or children playing team sports.[5]

Acute exposure to ozone and other outdoor air pollutants exacerbates asthma;[7] the chronic effects of air pollution have been less studied, but combustion-related air pollution is not thought to cause asthma.[8] However, this conclusion is based on studies in which personal exposure was measured with community air pollution monitors. The true dose of outdoor air pollutants to the lung depends on local pollutant concentrations, which may vary within a community, and on personal habits such as time spent outside and physical activity. People exercising outside should receive greater doses of outdoor pollutants to the lung than those who do not, and thus be more susceptible to any chronic effects of air pollution. Because the onset of asthma might cause athletes to reduce their levels of exercise, cross-sectional studies are not an appropriate way to measure the causal relations between exercise, air pollution, and asthma.

We postulated that children engaged in team sports in polluted communities might also be at high risk of asthma. Because the amount of time spent playing sports is an individual factor that affects exposure to ambient pollution, this approach avoids many biases of studies of air pollution that have relied on between-community comparisons of rates of asthma and other illnesses. We assessed the association of playing team sports with subsequent development of asthma during 5 years of follow-up of participants in the Southern California Children's Health Study. Study communities were selected on the basis of concentrations of ambient ozone and other pollutants.[9]

Methods

Participants

We selected 12 communities in southern California for variability of concentrations of ozone, particles with aerodynamic diameter less than 10 μm (PM_{10}), and nitrogen dioxide (NO_2).[9] In 1993, in each of the 12 communities, we recruited around 150 children aged 9–10 years, 75 aged 12–13 years, and 75 aged 15–16 years from schools in areas of the communities with stable, mainly middle-income populations. All children from targeted classrooms were invited to take part; participants completed a baseline questionnaire with help from their parents. In

early 1996, we recruited an additional cohort of around 175 children aged 9–10 years from every community. Children were followed up and interviewed yearly until 1998 (or until 1995, for children aged 15–16 years at entry).

Procedures

Children were excluded if they answered yes to "Has a doctor ever diagnosed this child as having asthma?" on the baseline questionnaire sent home to every child's parents or if a child answered yes to the question "Has a doctor ever said you had asthma?" on a questionnaire administered by an interviewer in 1993 (or in 1996, for the 1996 cohort). We ascertained history of wheezing in the baseline questionnaire with the question "Has your child's chest ever sounded wheezy or whistling, including times when he or she had a cold?" A study interviewer administered a questionnaire yearly to every child. Children were classed as having newly-diagnosed asthma in the year that they first answered yes to the question "Has a doctor ever said you had asthma?"

A question on the baseline questionnaire asked "Has your child been on any sports teams in the past 12 months?" and, if the answer was yes, "what teams?" Children were grouped into those who played no team sports, and those who played one, two, and three or more sports. The question had eight answer options, including sports with high metabolic indices, typically involving six or more times resting work expenditure (basketball, football, soccer, swimming, and tennis), low metabolic indices, typically involving less than six times resting work expenditure (baseball, softball, and volleyball), and other sports.[10] For some analyses, children who played sports were grouped into those who played at least one high activity sport and children who played no high activity sports, but at least one low activity sport.

In the baseline questionnaire we also obtained information on children's sex, age, race and ethnic origin (Hispanic, non-Hispanic white, Asian or Pacific Islander, African American, or other), history of allergies, reported time spent outdoors, current maternal smoking, history of asthma in either parent, membership of a health insurance plan, and family income. We split each cohort (1993 and 1996) into children playing more than the median time outdoors and those playing less. We classed families as having low socioeconomic status if their income was less than US$15 000 (or, if income was not reported, if the responding parent had not completed a secondary school education). We defined high socioeconomic status as family income of $100 000 or more (or, if income was not reported, by responding parent having received postgraduate training). We classed remaining families as having middle socioeconomic status. Body-mass index (BMI) was calculated from children's heights and weights at the time of the first interview of the child, and was used to divide children into quartiles for analysis.

We established air pollution monitoring stations in all 12 communities, and measured pollutant concentrations from 1994 to 1998.[9,11] Every station monitored hourly concentrations of ozone, PM_{10}, and NO_2. $PM_{2.5}$ (particulate mass less than 2·5 μm in diameter) and acid vapour were measured with 2-week integrated samplers. Yearly means were calculated from 24-h mean concentrations of ozone, PM_{10}, and NO_2; from 10:00 h to 18:00 h mean concentrations of ozone ($ozone_{10-18}$); and from a daily maximum 1-h ozone concentration. We also calculated yearly means from 2-week mean concentrations of $PM_{2.5}$ and inorganic hydrochloric and nitric acid vapour. We calculated 4-year mean concentrations (1994–97) in every community for every pollutant. We used 4-year means to rank communities because between-year variation was small,[11] and these means provided more stable estimates of exposure than yearly means. For every pollutant, we grouped the 12 communities into six with high 4-year mean concentrations and six with low concentrations. For some analyses, communities were stratified by tertiles of selected pollutants.

Statistical analyses

Before grouping into high and low pollution communities, Pearson correlation coefficients were calculated to measure the relation between different pollutants in the 12 communities. Relative risks (hazard ratios) of asthma for living in a high or low pollutant community, adjusted for ethnic origin, were evaluated for every pollutant with a multivariate proportional hazards model. We stratified baseline hazards by age and sex. We selected age groups to divide the 9–10-year-old cohort by median age at study entry, and for least overlap of this cohort with other cohorts. Age groups were: younger than 9·70 years, 9·70–11·49 years, and older than 11·49 years. To establish whether ozone had more effect than NO_2 (which was highly correlated with particulate pollutants and acid), the effect of team sports on the risk of new asthma was assessed in every pollution setting. To assess whether type of sport played

	Number playing sports*
Sex (p<0·0001)†	
Girls	837 (46%)
Boys	1097 (67%)
Age (years; p=0·06)	
Younger than 9·70	646 (55%)
9·70–11·49	647 (54%)
Older than 11·49	641 (59%)
Ethnic origin (p=0·0001)†	
Non-Hispanic white	1239 (61%)
Hispanic	481 (50%)
Black	80 (46%)
Asian	82 (45%)
Other	52 (50%)
BMI quartile (p=0·09)†	
1	486 (56%)
2	493 (57%)
3	501 (58%)
4	452 (52%)
Allergies (p=0·01)†	
No	1392 (54%)
Yes	462 (59%)
Asthma in family (p=0·29)†	
No	1560 (57%)
Yes	266 (54%)
Socioeconomic status (p<0·0001)†	
Low	308 (40%)
Medium	1221 (59%)
High	373 (69%)
Maternal smoking (p=0·01)†	
No	1729 (56%)
Yes	185 (50%)
Insurance (p<0·0001)*	
No	226 (43%)
Yes	1675 (58%)
Wheeze (p=0·25)*	
No	1488 (55%)
Yes	446 (58%)
Time outside (p<0·0001)*	
Low	840 (50%)
High	948 (62%)

*Total number of participants varies because of missing values. †p value based on χ^2 test for homogeneity. BMI=body-mass index.

Table 1: **Distribution of baseline characteristics of children by participation in team sports**

	N (incidence)*	RR (95% CI)
Number of sports played		
0	104 (0·022)	1·0
1	90 (0·026)	1·3 (1·0–1·7)
2	36 (0·021)	1·1 (0·7–1·6)
≥3	29 (0·033)	1·8 (1·2–2·8)

N=number of cases of asthma; RR=relative risk (hazard ratio), adjusted for ethnic origin, and for stratified baseline hazards by sex and age group.
*Denominator=person-years of follow-up.

Table 2: **Effect of sports on incidence of asthma diagnoses**

was relevant, models containing indicator variables for each type of sport or a linear term for total number of sports played were compared with our final model with the Akaike Information Criterion (AIC) to see whether a model with information on specific sports was better than models without such information. We also assessed effects of community, history of allergy, family history of asthma, membership of a health insurance plan, BMI, current maternal smoking, and socioeconomic status. Analyses were done with the Statistical Analysis System (version 8.1) software package.

Role of the funding source
The California Air Resources Board helped establish the air pollution monitoring network and helped collect the air pollution data from this network for use in the study.

Results

5762 (79%) of eligible children completed baseline questionnaires. 479 children were excluded because they were not at school at the time of a questionnaire administered during the entry year by an interviewer, and an additional 883 were excluded for a history of asthma. We excluded 312 children because of missing or "not known" answers to questions on wheezing, and 26 for a history of cystic fibrosis, severe chest injury, or chest surgery. 527 additional children were excluded who did not have at least 1 year of follow-up. 3535 children were included who did not have a history of asthma and who were available for follow-up, 2752 (78%) of whom had no history of wheezing. At study entry, 65 children had missing information about the number of sports played. 1934 (67%) children played sports. Only 273 (8%) of 3470 children played three or more team sports. Several factors were associated with number of team sports played (table 1). Girls were much less likely to play team sports than boys, and children in the top quartile of BMI were slightly less likely to play sports than those in other quartiles. Hispanic and non-Hispanic white children were more likely to play three or more team sports. Although family history of asthma was not associated with team sports, a child's history of allergy was associated. Children from families with low socioeconomic status and with the related characteristics of a mother who smoked and lack of health insurance, were less likely to play sports. Spending more time outside was also associated with playing sports. Children with wheeze were not less likely to play sports.

We analysed the relation between newly-diagnosed asthma and number of sports played (table 2). 265 children developed asthma, 259 of whom had provided complete information on sports. Across all communities there was a 1·8-fold increased risk (95% CI 1·2–2·8) for asthma in children who had played three or more team sports in the previous year. There was a linear trend of increasing asthma for the total of eight possible team sports played (relative risk 1·1 per team sport played, 1·0–1·3).

Table 3 shows the profile of each pollutant in high and low pollution communities. Even communities with low $ozone_{10-18}$ had high mean 4-year concentrations, up to 51 parts per billion. The high and low pollution communities were the same for NO_2, PM_{10}, $PM_{2·5}$, and acid, which was not surprising as 4-year mean concentrations of these pollutants were highly correlated across communities: from $r=0·65$ for NO_2 with PM_{10}, to 0·96 for $PM_{2·5}$ with PM_{10}. $Ozone_{10-18}$, although highly correlated with mean daily 1-h maximum ozone concentration (0·98) and with 24-h mean ozone (0·72), was not strongly correlated with the other pollutants. The highest correlation of $ozone_{10-18}$ with other pollutants was with acid (0·48).

Risk of developing asthma was not greater overall in children living in the six high pollution communities than children living in the six low pollution communities, after adjustment for stratified baseline hazards for age and sex, and for ethnic origin, irrespective of which pollutant was used to classify communities as high or low. The relative risks were 0·8 (0·6–1·0, $p=0·08$) for $ozone_{10-18}$, 0·7 (0·6–0·9) for daily maximum ozone, and 1·1 (0·9–1·4) for 24-h ozone. For NO_2, PM_{10}, $PM_{2·5}$, and acid, all of which shared the same high and low communities, the relative risk was 0·8 (0·6–1·0 $p=0·08$). Communities with high NO_2 and associated pollutants, and communities with high $ozone_{10-18}$ or daily maximum ozone were associated with a decreased risk of asthma; these associations were significant ($p<0·05$) only for daily maximum ozone.

The effect of team sports was similar in communities with high and low particulate matter (and associated pollutants, all of which gave the same high or low groupings of communities as did particulate matter). In both groups of communities there was a small increase in asthma among children playing team sports, which was largest among those playing three or more sports (table 4).

In high $ozone_{10-18}$ communities, there was a 3·3-fold increased risk of asthma in children playing three or more sports; an increase that was not seen in low $ozone_{10-18}$ communities (table 5). In high ozone communities there was a trend of increasing asthma with number of team sports played (relative risk 1·3 per sport, 1·1–1·6). There was a significant interaction between total number of sports played and ozone ($p=0·004$). In assessing interaction, we also tested models that used indicator variables for each sport or dummy variables for none, one, two, and three sports. The model that used total number of sports was found to give the best fit. In high ozone communities, risk of

	Low pollution communities (n=46)		High pollution communities (n=46)	
	Concentration (mean [SD])	Median (range)	Concentration (mean [SD])	Median (range)
Maximum 1-h ozone (ppb)	50·1 (11·0)	47·6 (37·7–67·9)	75·4 (6·8)	73·5 (69·3–87·2)
$Ozone_{10-18}$ (ppb)	40·0 (7·9)	40·7 (30·6–50·9)	59·6 (5·3)	56·9 (55·8–69·0)
24-h ozone (ppb)	25·1 (3·1)	25·1 (20·6–28·7)	38·5 (11·0)	33·1 (30·7–59·8)
PM_{10} (mg/m³)	21·6 (3·8)	20·8 (16·2–27·3)	43·3 (12·0)	39·7 (33·5–66·9)
$PM_{2·5}$ (mg/m³)	7·6 (1·0)	7·7 (6·1–8·6)	21·4 (6·0)	21·8 (13·5–30·7)
NO_2 (ppb)	10·8 (4·6)	12·1 (4·4–17·0)	29·2 (8·5)	29·5 (17·9–39·4)
Acid (ppb)	1·8 (0·7)	1·7 (0·9–2·6)	3·9 (0·7)	3·7 (3·3–4·9)

*These are the same six high and six low communities for PM_{10}, $PM_{2·5}$, NO_2, and acid, but not for other pollutants. Ppb=parts per billion; Acid=inorganic acid vapour.

Table 3: **4-year pollution concentrations in high and low pollution communities***

	Low PM communities		High PM communities	
	N (incidence)*	RR (95% CI)	N (incidence)*	RR (95% CI)
Number of sports played				
0	49 (0·023)	1·0	55 (0·021)	1·0
1	54 (0·032)	1·5 (1·0–2·2	36 (0·021)	1·1 (0·7–1·7)
2	22 (0·024)	1·2 (0·7–1·9	14 (0·018)	0·9 (0·5–1·7)
≥3	13 (0·033)	1·7 (0·9–3·2	16 (0·033)	2·0 (1·1–3·6)

PM=particulate matter; N=number of cases of asthma; RR=relative risk, adjusted for ethnic origin, and for stratified baseline hazards by sex and age group. *Denominator=person-years of follow-up.

Table 4: **Effect of number of team sports played on the risk of new asthma diagnosis in high and low PM (and other pollutant) communities**

asthma was increased for children playing at least one high activity sport, compared with no sports (1·6, 1·1–2·5), but not for children playing only a low activity sport (1·2, 0·7–2·1). In low ozone communities, the relative risk for high activity sports was 1·0 (0·7–1·4) and for low activity sports the risk was 0·9 (0·5–1·7). In models with individual sports entered as dummy variables, only tennis was significantly associated with asthma and only in high ozone communities (5·2, 1·3–20·4), but power was limited for identifying the effect of specific sports.

The overall pattern of effects of sports on asthma risk was similar in models that also included socioeconomic status, history of allergy, family history of asthma, insurance, maternal smoking, and BMI at study entry. Time spent outside was also associated with asthma in high ozone communities (1·4, 1·0–2·1), but not in low ozone communities (1·1, 0·8–1·6) in models that also included team sports. There was no significant interaction of number of sports played with history of allergy, family history of asthma, or time spent outside. However, when we compared the characteristics of the 20 children who played three or more sports in high $ozone_{10-18}$ communities with the nine children who played this number of sports in low ozone communities, three of seven of those in low ozone communities (two had missing information) had a family history of asthma, compared with none of 17 in high ozone communities (p=0·02, Fisher's exact test). In these 29 children, no other demographic or personal characteristic differed significantly between low and high ozone communities.

The effect of sports was similar in boys and girls, although the effect of playing three or more sports in high ozone communities, compared with no sports in high ozone communities, was somewhat greater in girls (4·7, 2·1–10·5) than in boys (2·5, 1·1–5·4).

Among children with no lifetime history of wheeze at study entry, the relative risk of new diagnosis of asthma in children playing three or more sports in a high ozone community was 4·4 (2·1–9·3). In children with a history of wheeze, the relative risk was 2·7 (1·1–6·4).

	Low ozone communities		High ozone communities	
	N (incidence)*	RR (95% CI)	N (incidence)*	RR (95% CI)
Number of sports played				
0	58 (0·027)	1·0	46 (0·018)	1·0
1	50 (0·033)	1·3 (0·9–1·9)	40 (0·021)	1·3 (0·8–2·0)
2	20 (0·023)	0·8 (0·5–1·4)	16 (0·020)	1·3 (0·7–2·3)
≥3	9 (0·019)	0·8 (0·4–1·6)	20 (0·050)	3·3 (1·9–5·8)

N=number of cases of asthma; RR=relative risk, adjusted for ethnic origin, and for stratified baseline hazards by sex and age group. *Denominator=person-years of follow-up.

Table 5: **Effect of number of team sports played on the risk of new asthma diagnosis in high and low ozone communities**

When $ozone_{10-18}$ was used to divide communities into tertiles, playing three or more team sports was associated with asthma only in the upper tertile (3·1, 1·8–5·5). The range of exposure across the four communities in the upper tertile was 56·8–69·0 parts per billion. Playing three team sports was associated with a small, not significant decrease in relative risk of asthma in the lowest tertile (0·7, 0·3–1·8) and in the middle tertile (0·9, 0·2–3·1). However, these estimates for the effect of team sports were based on few cases, and the models converged only if Asian, Black, and other races were combined into one category.

When the effect of sports was analysed in communities divided into combinations of high and low mean $ozone_{10-18}$ with high and low mean concentrations of other pollutants, there was no interaction between sports, ozone, and other pollutants. In communities with high $ozone_{10-18}$ and low levels of other pollutants, there was a 4·2-fold (1·6–10·7) increased risk of asthma in children playing three or more sports, compared with children who played no sports. In communities with a combination of high levels of ozone and other pollutants, there was a 3·3-fold (1·6–6·9) increased risk of asthma in children playing three or more sports. There was little effect of playing team sports in low ozone communities, irrespective of whether other pollutants were present.

Discussion

Our results show that playing multiple team sports in a high ozone environment is associated with development of physician-diagnosed asthma. The results are consistent with a large increased risk both for new-onset asthma and for exacerbation of previously undiagnosed asthma, because playing multiple sports was associated with asthma in children with no lifetime history of wheezing at baseline and children with a previous history of wheezing. The larger effect of high activity sports than low activity sports, and an independent effect of time spent outdoors, also only in high ozone communities, strengthens the inference that exposure to ozone may modify the effect of sports on the development of asthma in some children. Exercise-induced asthma by itself is unlikely to have been an explanation for these results, because asthma onset was associated with exercise only in polluted communities.

The high prevalence of asthma in competitive figure skaters might be related to NO_2 generated by ice grooming equipment.[5] However, prevalence of asthma greater than 40% has been reported in competitive cross-country skiers,[3] a group inhaling cold air, but who might not be heavily exposed to air pollution. Competitive long distance and speed runners and swimmers (especially atopic individuals) have high prevalence of asthma, bronchial hyperresponsiveness, or both, and these rates were higher in atopic individuals.[4] However, the role of atopy in sports-induced asthma is unclear. Atopy did not modify the risk of asthma associated with nordic skiing.[3] We saw no interaction between history of allergy and sports, but our indicator for allergy based on reported history might have resulted in misclassification of atopy, compared with skin testing. Our results suggest that asthmatic children playing three or more team sports were less likely to have a family history of asthma in high ozone communities than in low ozone communities. In as much as family history is suggestive of atopy, this result is in contrast with those of other studies. Although previous studies of sports and asthma have focused on competitive athletes, one other prospective population-based study has been done in Danish children.[12] Information about physical activity and team sports were not provided, but physical fitness was associated with a lower risk of subsequent development of

asthma; a finding more consistent with the reduced risk of asthma (although not significant) in low ozone communities in our study.

Experimental studies have shown the acute effects of ozone in exercising individuals.[7] Combustion-related air pollution has not been associated with asthma in many, mainly cross-sectional, studies.[8] Our cross-sectional results showed that exposure to air pollution exacerbated chronic symptoms of asthma,[13] but there was no association between asthma prevalence and air pollutants.[9] This conclusion is in accord with results from a comparison of asthma prevalence between East and West Germany; a lower rate was measured in East Germany, where pollution from burning coal was much higher.[14] However, the German communities had profound differences other than pollution, which might have confounded these ecological comparisons. Large cross-sectional studies of children in Taiwan showed associations of asthma prevalence with ozone and other pollutants[15] and with traffic-related pollutants.[16] In 24 communities in the French PAARC study,[17] asthma prevalence in adults was associated with SO_2, which the investigators suggested might have been an indicator for other pollutants, such as ozone, which was not measured. In one of the few other large prospective studies of asthma and air pollution,[18] in non-smoking adult Seventh Day Adventists in California, USA, an increased risk for new-onset of asthma was noted in communities with high ozone concentrations.

The negative association between asthma and $ozone_{10-18}$ (and daily maximum ozone and particulate and related pollutants) is not inconsistent with the large effect of playing team sports, because few children (8%) played three or more team sports. Thus, the effect of sports would not be likely to affect greatly the overall rates of asthma in high ozone communities. Nevertheless, the low rates in high pollution communities are puzzling, since it is not plausible that ozone and other combustion-related pollutants protect against asthma. Possible explanations include selection bias, for example, if parents with children with a history of asthma exacerbated by air pollution (or some similar characteristic associated both with asthma and with air pollution) moved to less-polluted communities, thus increasing the prevalence of children at high risk for developing asthma in unpolluted communities. However, the association between air pollution and asthma persisted after we adjusted for family history.

Measurement error can affect studies of air pollution and health. Because we established a network of nearby community-level monitors specifically for the Children's Health Study,[9] we improved on the assignment of individual exposure levels compared with most other such studies. However, a more accurate assessment of individual dose is essential to identify the contribution of air pollution to asthma prevalence and incidence; rates of asthma vary widely between communities and between countries, for reasons that are largely unknown, but are thought to be environmental.[19]

Heavy exercise increases ventilation rates 17-fold;[20] children playing more than two team sports might have been the more highly motivated athletes. Increased ventilation rate and oral breathing displaces pulmonary uptake of ozone to more distal sites in the lung, further increasing the effect of ambient exposure on ozone deposition in the distal airways and centriacinar region, where the largest morphological effects of ozone have been seen in work in animals.[21] Additionally, outdoor activity (independent of exercise) should be an important modifier of exposure to ambient ozone, because outdoor ozone concentrations in the 12 communities can be as much as five-times higher than indoor concentrations.[22,23] Ozone concentration between 10·00 h and 18·00 h is generally higher than at other times of day, and 10·00–18·00 h is the time period when most team sports are played outdoors in southern California. The association between incident asthma and time spent outside further supports the inference that dose of ozone might affect the pathogenesis of asthma. Furthermore, the association between sports and asthma occurred only in the top tertile of communities ranked by ozone exposure, although our study did not have sufficient statistical power to identify a threshold level of exposure at which such an effect might occur.

Participation in endurance sports or in heavy physical training can result in the recognition of exercise-induced bronchospasm,[24] which might not otherwise have been diagnosed. Exercise-induced bronchospasm is associated with the bronchial hyper-reactivity characteristic of asthma, for which exercise challenge has been proposed as a screening test. The increase in asthma with sports in our study could result from chronic exacerbation of exercise-induced bronchospasm by sports to the point that medical attention was sought and a diagnosis was made that might not have been made in more sedentary children. Because the association between sports and asthma occurred only in high ozone communities, such detection bias would imply, at the least, that exercise-induced bronchospasm was being exacerbated by air pollution, a conclusion that is consistent with other studies in which ozone has been associated with asthma exacerbation.[7] However, if the results were caused only by unmasking of pre-existing asthma by sports and air pollution, a larger effect of sports might have been expected in children with a previous lifetime history of wheezing at study entry.

In healthy people, airway reactivity is increased after 5 h of exercise—equivalent to a day of moderate to heavy work or play during exposure to 0·08 parts per million ozone.[25] Ozone also increases responses to other allergens present in ambient air. Exposure to 0·16 parts per million of ozone during light exercise increased the bronchial hyper-reactivity of children with mild asthma to house dust-mite allergen.[26] In mice, ozone concentrations as low as 0·13 parts per million increased the sensitising effect of exposure to aerosol allergens.[27] The increased pulmonary dose of ambient ozone resulting from heavy exercise, combined with exposure to outdoor and indoor allergens, is one possible mechanism for inducing new onset asthma or for exacerbating existing asthma to the point that medical attention would have been sought.

Asthma could be caused by exposure to pollutants other than ozone such as ambient this gas; people with asthma have an increased response to bronchial challenge with dust-mite allergen after exposure to this gas.[28] Although no effect of sports on asthma was seen in communities with high concentrations of pollutants other than ozone, statistical power was too low to rule out an independent association of other pollutants with development of newly-diagnosed asthma, or to identify interaction between sports, ozone, and other pollutants. Additionally, other pollutants that we did not include, such as those originating from diesel exhaust, could have resulted in the association of sports with asthma.

Study limitations include the potential for misclassification of asthma, which could be affected by access to care and differences in diagnostic practice between physicians,[29] or by poor reporting by children or parents. However, participant report of physician-diagnosed asthma has been the main criterion of asthma used in epidemiological studies of children,[19] and the validity of this approach, assessed by repeatability of

response, is good.[30] Self-report, at least in adults, reflects what physicians actually said to patients, and physician assessment of asthma has been recommended as the epidemiological gold standard for this disease.[31] Our list of sports did not include some high-activity sports such as running, which has been shown to be associated with asthma in cross-sectional studies of athletes,[4] and bicycling, which has been shown in amateur cyclists exposed recreationally to low ambient levels of ozone to result in acute decreases in lung function and increases in symptoms.[32] These exceptions might have resulted in some misclassification of team sports. However, the effect of misclassification would not have been likely to have differed with stratum of ozone exposure, and so would probably have resulted in an underestimate of a true effect of sports. Finally, variation in loss to follow-up between subgroups of children might have biased estimates of associations. However, in children aged 9–10 and 12–13 years available for follow-up at study entry, 78% were examined in either year 4 or year 5 of the study, and follow-up did not differ significantly by participation in team sports, residence in a high compared with low $ozone_{10-18}$ community, or wheeze at study entry.

We conclude that the incidence of new asthma diagnoses is associated with heavy exercise in communities with high levels of ambient ozone, and that in these conditions, air pollution and outdoor exercise might contribute to development of asthma in children.

Contributors

All authors participated in study design, analysis, interpretation, and in drafting the report.

Conflict of interest statement

None declared.

Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

Acknowledgments

We thank David Bates and the rest of our External Advisory Committee: Morton Lippmann, Jonathan Samet, Frank Speizer, John Spengler, James Whittenberger, Arthur Winer, and Scott Zeger. We also thank the study field team, the 12 communities, the school principals, teachers, students, parents, Clint Taylor (California Air Resources Board), and staff at the participating air quality districts. Edward B Rappaport and Isabelo Manila provided programming support. This study was supported by the California Air Resources Board (A033–186), the National Institute of Environmental Health Science (1PO1ES0939581–02 and 5P30ES07048–05), the Environmental Protection Agency (CR824034–01–3), the National Heart, Lung and Blood Institute (1RO1HL61768), and the Hastings Foundation.

References

1 Becklake MR, Ernst P. Environmental factors. *Lancet* 1997; **350** (suppl 2): S10–13.
2 Sears MR. Epidemiology of childhood asthma. *Lancet* 1997; **350:** 1015–20.
3 Sue-Chu M, Larsson L, Bjermer L. Prevalence of asthma in young cross-country skiers in central Scandinavia: differences between Norway and Sweden. *Respir Med* 1996; **90:** 99–105.
4 Helenius IJ, Tikkanen HO, Sarna S, Haahtela T. Asthma and increased bronchial responsiveness in elite athletes: atopy and sport event as risk factors. *J Allergy Clin Immunol* 1998; **101:** 646–52.
5 Corrao W. Asthma in athletes Exercise-induced bronchoconstriction in figure skaters. *Chest* 1996; **109:** 298–99.
6 Heir T, Aanestad G, Carlsen KH, Larsen S. Respiratory tract infection and bronchial responsiveness in elite athletes and sedentary control subjects. *Scand J Med Sci Sports* 1995; **5:** 94–99.
7 Koren HS. Associations between criteria air pollutants and asthma. *Environ Health Perspect* 1995; **103** (suppl): 235–42.
8 Clark NM, Brown RW, Parker E, et al. Childhood Asthma. *Environ Health Perspect* 1999; **107** (suppl): 421–29.
9 Peters JM, Avol E, Navidi W, et al. A study of twelve Southern California communities with differing levels and types of air pollution: I prevalence of respiratory morbidity. *Am J Respir Crit Care Med* 1999; **159:** 760–67.
10 Ainsworth BE, Haskell WL, Whitt MC, et al. Compendium of physical activities: an update of activity codes and MET intensities. *Med Sci Sports Exerc* 2000; **32** (suppl): 498–504.
11 Gauderman WJ, McConnell R, Gilliland F, et al. Association between air pollution and lung function growth in southern California children. *Am J Respir Crit Care Med* 2000; **162:** 1383–90.
12 Rasmussen F, Lambrechtsen J, Siersted HC, Hansen HS, Hansen NC. Low physical fitness in childhood is associated with the development of asthma in young adulthood: the Odense schoolchild study. *Eur Respir J* 2000; **16:** 866–70.
13 McConnell R, Berhane K, Gilliland F, et al. Air pollution and bronchitic symptoms in Southern California children with asthma. *Environ Health Perspect* 1999; **107:** 757–60.
14 Wichmann HE, Heinrich J. Health effects of high level exposure to traditional pollutants in East Germany—review and ongoing research. *Environ Health Perspect* 1995; **103** (suppl): 29–35.
15 Wang TN, Ko YC, Chao YY, Huang CC, Lin RS. Association between indoor and outdoor air pollution and adolescent asthma from 1995 to 1996 in Taiwan. *Environ Res* 1999; **81:** 239–47.
16 Guo YL, Lin YC, Sung FC, et al. Climate, traffic-related air pollutants, and asthma prevalence in middle-school children in Taiwan. *Environ Health Perspect* 1999; **107:** 1001–06.
17 Baldi I, Tessier JF, Kauffmann F, Jacqmin-Gadda H, Nejjari C, Salamon R. Prevalence of asthma and mean levels of air pollution: results from the French PAARC survey: pollution atomospherique et affections respiratoires chroniques. *Eur Respir J* 1999; **14:** 132–38.
18 McDonnell WF, Abbey DE, Nishino N, Lebowitz MD. Long-term ambient ozone concentration and the incidence of asthma in nonsmoking adults: the AHSMOG Study. *Environ Res* 1999; **80:** 110–21.
19 International Study of Asthma and Allergies in Childhood Steering Committee. Worldwide variations in the prevalence of asthma symptoms: the International Study of Asthma and Allergies in Childhood (ISAAC). *Eur Respir J* 1998; **12:** 315–35.
20 McArdle WD, Katch FI, Katch VL. Exercise physiology: energy, nutrition, and human performance. Philadelphia: Williams and Wilkins, 1996: 228.
21 Miller FJ. Uptake and fate of ozone in the respiratory tract. *Toxicol Lett* 1995; **82–83:** 277–85.
22 Avol EL, Navidi WC, Colome SD. Modeling ozone levels in and around Southern California homes. *Environ Sci Technol* 1998; **32:** 463–68.
23 Tager IB, Kunzli N, Lurmann F, Ngo L, Segal M, Balmes J. Methods development for epidemiologic investigations of the health effects of prolonged ozone exposure: part II—an approach to retrospective estimation of lifetime ozone exposure using a questionnaire and ambient monitoring data (California sites). *Res Rep Health Eff Inst* 1998; **81:** 27–121.
24 Rupp NT, Guill MF, Brudno DS. Unrecognized exercise-induced bronchospasm in adolescent athletes. *Am J Dis Child* 1992; **146:** 941–44.
25 Horstman DH, Folinsbee LJ, Ives PJ, Abdul-Salaam S, McDonnell WF. Ozone concentration and pulmonary response relationships for 6·6-hour exposures with five hours of moderate exercise to 0·08, 0·10, and 0·12 ppm. *Am Rev Respir Dis* 1990; **142:** 1158–63.
26 Kehrl HR, Peden DB, Ball B, Folinsbee LJ, Horstman D. Increased specific airway reactivity of persons with mild allergic asthma after 7·6 hours of exposure to 0·16 ppm ozone. *J Allergy Clin Immunol* 1999; **104:** 1198–204.
27 Osebold JW, Zee YC, Gershwin LJ. Enhancement of allergic lung sensitization in mice by ozone inhalation. *Proc Soc Exp Biol Med* 1988; **188:** 259–64.
28 Jenkins HS, Devalia JL, Mister RL, Bevan AM, Rusznak C, Davies RJ. The effect of exposure to ozone and nitrogen dioxide on the airway response of atopic asthmatics to inhaled allergen: dose- and time- dependent effects. *Am J Respir Crit Care Med* 1999; **160:** 33–39.
29 Samet JM. Epidemiologic approaches for the identification of asthma. *Chest* 1987; **91** (suppl): 74–78.
30 Ehrlich RI, Du Toit D, Jordaan E, Volmink JA, Weinberg EG, Zwarenstein M. Prevalence and reliability of asthma symptoms in primary school children in Cape Town. *Int J Epidemiol* 1995; **24:** 1138–45.
31 Burr ML. Diagnosing asthma by questionnaire in epidemiological surveys. *Clin Exp Allergy* 1992; **22:** 509–10.
32 Brunekreef B, Hoek G, Breugelmans O, Leentvaar M. Respiratory effects of low-level photochemical air pollution in amateur cyclists. *Am J Respir Crit Care Med* 1994; **150:** 962–66.