TABLE 5—Multiple Linear Regression Results Comparing Performance on Neurobehavioral Tests, the UPSIT and the Contrast Sensitivity Test Among Structural Fumigation Workers vs Unexposed Referents: South Florida, 1992–1993

Test	Fumigation Worker		Referent		P for Adjusted Analysis	Direction of Worker Performance[b]	Worse Performance With Increasing Duration of Fumigant Exposure[c]
	n	Adjusted Mean[a]	n	Adjusted Mean[a]			
Hand-Eye Coordination, rmse	118	2.21	116	2.22	.76	+	
Simple Reaction Time, ms	118	265.4	116	265.3	.99	–	
Continuous Performance Test: response time, ms	118	399.3	116	397.0	.66	–	MB
Continuous Performance Test: NR	118	0.47	116	0.73	.19	+	
Symbol Digit, s/digit	118	2.26	116	2.24	.82	–	
Symbol Digit Recall score	118	4.67	116	4.75	.81	–	
Pattern Memory, %	118	84.9	116	87.3	.12	–	SF
Pattern Memory recall time, s	118	6.26	116	5.93	.15	–	MB, SF
Serial Digit Learning score	118	4.61	116	5.09	.40	+	
Mood Scale Score: anger	118	1.88	116	1.83	.58	–	SF
Mood Scale Score: confusion	118	2.27	116	2.26	.92	–	
Mood Scale Score: depression	118	1.89	116	1.83	.56	–	
Mood Scale Score: fatigue	118	2.63	116	2.60	.82	–	
Mood Scale Score: tension	118	2.40	116	2.35	.67	–	
Santa Ana: preferred hand	121	39.9	120	41.5	.02	–	SF
Santa Ana: nonpreferred hand	121	36.9	120	37.4	.50	–	SF
UPSIT (no. correct/40)	109	33.6	106	34.5	.11	–	SF
UPSIT, %	123	82.8	120	85.1	.10	–	SF
Contrast sensitivity: right eye	121	12.2	120	12.2	.83	+	
Contrast sensitivity: left eye	122	12.2	119	12.1	.69	+	

Note. UPSIT = University of Pennsylvania Smell Identification Test; rmse = root mean square error; NR = nonresponses.

[a] Models for the computerized neurobehavioral tests controlled for age, years of education, and test language (English or Spanish). Models for the Santa Ana Dexterity Tests controlled for age and race. Models for UPSIT controlled for smoking status (current smoker, former smoker, never smoker), years of education, and race. Models for contrast sensitivity controlled for age, acuity of the examined eye, and years of education.

[b] + = Performance of workers was better vs referents based on adjusted means. – = Performance of workers was worse vs referents based on adjusted means.

[c] SF = based on adjusted analyses, as sulfuryl fluoride exposure increased (referent, low sulfuryl fluoride years of exposure, high sulfuryl fluoride years of exposure), monotonically decreasing performance was observed.

MB = based on adjusted analyses, as methyl bromide exposure increased (referent, low methyl bromide years of exposure, high methyl bromide years of exposure), monotonically decreasing performance was observed.

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Determinants of Nitrogen Dioxide Concentrations in Indoor Ice Skating Rinks

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ABSTRACT

Objectives. The combination of poor ventilation and fuel-powered ice resurfacers has resulted in elevated nitrogen dioxide (NO_2) concentrations in many indoor ice skating rinks. This study examined the factors influencing concentrations and the effects of various engineering controls in ice rinks with different resurfacer fuels.

Methods. Indoor NO_2 concentrations were measured in 19 enclosed ice skating rinks over 3 winters by means of passive samplers, with 1-week average measurements during the first winter pilot study and single-day working-hour measurements in the final 2 winters. Personal exposures to drivers also were assessed during the last winter.

Results. Rinks in which propane-fueled resurfacers were used had a daily mean indoor NO_2 concentration of 206 ppb, compared with 132 ppb for gasoline-fueled and 37 ppb for electric-powered resurfacers. Engineering controls, such as increased ventilation and resurfacer tuning, reduced NO_2 concentrations by 65% on average, but outcomes varied widely, and concentrations increased in subsequent months.

Conclusions. Electric ice resurfacers, increased ventilation, or emission control systems are recommended to protect the health of workers and patrons, with surveillance programs proposed to track implementation and maintain an observer effect. (*Am J Public Health.* 1998;88:1781–1786)

The air quality of indoor ice skating rinks may be severely compromised by the combination of fuel-powered ice resurfacers and poor ventilation. The exhaust emitted by fossil-fueled ice resurfacers can contain significant concentrations of both carbon monoxide (CO) and nitrogen dioxide (NO_2).[1,2] Although highly elevated CO and NO_2 concentrations can be the result of malfunctioning resurfacing equipment, high concentrations have been found even in some well-maintained equipment with catalytic converters or other pollution prevention technologies.[3–6]

Exposures to elevated NO_2 concentrations have been associated with various respiratory ailments. In an ice rink in Minnesota, a group of teenage hockey players had difficulty breathing after 30 minutes of exposure to 35 to 40 ppm of NO_2.[7] In a later investigation at another Minnesota rink, symptoms such as chest tightness, cough, shortness of breath, and hemoptysis were found in hockey players exposed to 4 ppm of NO_2 (estimated based on measurements 2 days after the game).[8]

In controlled studies, healthy individuals exposed to 2.5 and 5 ppm of NO_2 for 2 hours[9,10] showed increased pulmonary airway resistance. Although increased airway resistance or decreased forced expiratory volume in 1 second (FEV_1) has been documented in a subset of asthmatic patients at concentrations as low as 0.1 or 0.2 ppm,[11,12] other studies have found no significant decrement in pulmonary function for concentrations ranging from 0.1 to 0.5 ppm.[13–15]

Increased prevalence of respiratory illness was related to chronic exposure to 100 ppb of NO_2.[16] A meta-analysis of 11 epidemiological studies concluded that the odds of a lower-respiratory infection in children would be increased by 20% with a chronic 16-ppb increase in NO_2 exposure.[17] However, other studies did not find any significant association between marginal low-level NO_2 increases and respiratory health outcomes.[18–21] Nevertheless, it is clear that an indoor environment with elevated concentrations of NO_2 in which many children exercise, such as indoor ice skating rinks, should be investigated to obviate both acute and chronic effects.

Previous work at one highly polluted ice rink investigated the effects of various pollution controls, including reducing the frequency of resurfacing and increasing ventilation levels, but no single measure was sufficient.[1] Only the combination of full ventilation and resurfacer use reduction reduced concentrations below the World Health Organization (WHO) air-quality guideline of 110 ppb for 1 hour.[22] Other studies have investigated the factors associated with increased NO_2 concentrations, such as fuel type or rink characteristics, but could find only univariate significance for the presence or absence of ventilation.[2,6] This result was largely a function of a small sample size and the relative homogeneity of the samples taken (no diesel- or electric-powered resurfacers).

The objectives of our study were to identify the subset of rinks with potential

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Note. The views expressed here are the authors' and do not necessarily reflect those of the Metropolitan District Commission in full.

indoor air-quality problems, to intervene immediately in these rinks to reduce concentrations, and to determine whether the chosen engineering controls (defined as ventilation increases or resurfacer tuning) were appropriate. This method allowed us to provide information to each rink manager on how best to maintain indoor air quality in his or her rink. Once the magnitude of the problem was assessed via a pilot study, indoor, outdoor, and personal exposure samples were taken to help determine both the predictors of NO_2 concentrations and the consequences of various controls. For rinks with daily average concentrations of higher than 200 ppb, engineering controls as those defined above were implemented by the Metropolitan District Commission (MDC).

Methods

Indoor NO_2 concentrations were measured in 19 enclosed ice skating rinks in the metropolitan Boston, Mass, area over the course of 3 winters. In year 1, a pilot study was conducted in which indoor measurements were taken for 1 week in each month between November 1994 and February 1995. In year 2, indoor measurements were taken for 7 to 17 hours on each of 3 consecutive working days in each month between January 1996 and March 1996. In year 3, indoor measurements were taken for 7 to 17 hours on each of 2 consecutive working days in each month between November 1996 and March 1997. Personal exposures also were measured for the ice resurfacer drivers during year 3. Outdoor measurements were taken on the first sampling day in each month in years 2 and3.

For year 1, Palmes diffusive tube samplers[23] were used for 1 week both at the scorer's table and at the opposite end of the rink; the mean value was considered to represent the overall rink concentration. To target working-hour exposure patterns, Yanagisawa badges[24] were used for all NO_2 measurements in years 2 and 3, with a single indoor measurement from the scorer's table each day. These passive filter badges have a lower detection limit than the Palmes tubes and could therefore be exposed over working hours during a single day. Like the Palmes tubes, the Yanagisawa badges have a measurement error of approximately 20%.[25,26]

In all years, we sent the samplers to rink managers, along with written instructions on proper sampler placement and handling. The ice resurfacer operators or other rink employees set up and collected the samplers, logging the times at which exposure began and ended. All samplers were returned to Harvard School of Public Health, Boston, Mass, where they were analyzed with a spectrophotometer (Hewlett-Packard, 8452A). Samples were analyzed within 10 days of sampling, and results were sent to rink managers immediately to expedite the implementation of any necessary controls. All engineering controls were implemented between sampling periods.

Information was also gathered on key characteristics of the ice rinks (e.g., size and composition of the rink, frequency and duration of resurfacer use, and resurfacer characteristics) that could potentially influence NO_2 concentrations or air-exchange rates.

The MDC, operators of all rinks in this study, issued guidelines to dictate when various engineering controls should occur. Under these guidelines, an indoor NO_2 concentration greater than 200 ppb required an examination of the ventilation system, concentrations above 500 ppb required full engineering controls, and concentrations above 2000 ppb necessitated immediate evacuation of the rink. The lower bound value was based on earlier WHO air-quality guidelines.

To calculate differences among multiple categories given different sample sizes and missing data, Dunn's nonparametric multiple comparison tests were used. In addition, linear regressions were used to determine whether ambient concentrations and rink characteristics could be used to predict personal exposures to the resurfacer drivers.

Results

At the 19 ice skating rinks studied, all ice resurfacers used either propane, gasoline, or electricity. Five of the 19 rinks used propane-fueled ice resurfacers throughout the study, whereas the number of electric resurfacers increased from 1 to 8 as gasoline-fueled resurfacers were replaced. The number of people using the rinks ranged from 300 to 2000 per day, with the number of resurfacings per day between 11 and 13 for all but 3 rinks (which had approximately 8, 15, and 18 resurfacings per day). The number of resurfacings was not correlated with rink size. The rinks were from 18 to 39 years old, but many other characteristics were similar across rinks, such as the amount of time taken to resurface the ice and the frequency of tune-ups. Resurfacers ranged in age from brand new to more than 20 years old.

A total of 750 samples were distributed over the 3 years of the study, and 647 samples (86%) were analyzed. Reasons for omission included samples that were lost or stolen, samples returned to the laboratory unsealed, and rinks that did not participate during certain months of the study. In addition, 2 outdoor measurements were excluded because the concentrations far exceeded reasonable ambient levels (872 ppb and 1053 ppb).

In the year 1 pilot study, median NO_2 concentrations were significantly greater for propane-fueled ice resurfacers than for gasoline-fueled or electric-powered resurfacers (Table 1). The overall mean NO_2 concentration for propane was 248 ppb, compared with 54 ppb for gasoline and 30 ppb for electricity (data not shown). This relation remained consistent throughout the 4 months of the pilot study, with some evidence of concentration reductions over time at rinks with propane-fueled resurfacers (Figure 1).

The pilot study also demonstrated the potential efficacy of engineering controls. As shown in Table 2, on the 2 occasions in which ventilation was increased to "maximum" levels, concentrations dropped 86% and 84% by the next month. For one rink requiring control under the guidelines, problems with the ventilation system made taking action impossible, resulting in a concentration increase from 651 to 707 ppb in the next month in which the rink participated.

In the main study, aggregated across years 2 and 3, the mean working-hour indoor NO_2 concentration was 206 ppb for propane-fueled ice resurfacers, compared with 132 ppb for gasoline-fueled and 37 ppb for electric-powered resurfacers (Figure 2). Rinks with propane-fueled resurfacers had significantly higher median concentrations than did rinks with electric resurfacers in both years, and rinks with gasoline-fueled resurfacers had significantly higher concentrations than did rinks with electric resurfacers in year 3 and significantly lower concentrations than did rinks with propane-fueled resurfacers in year 2 (Table 1).

Concurrently measured indoor and outdoor NO_2 concentrations were compared to assess the relative effects of the 3 ice resurfacer fuel types. For years 2 and 3 combined, the aggregate median indoor-to-outdoor ratios for rinks with propane- and gasoline-fueled resurfacers were 2.6 and 2.9, respectively, significantly greater than the median indoor-to-outdoor ratio of 1.0 for rinks with electric resurfacers (Figure 3). The mean indoor-to-outdoor ratios were 5.3 for propane-fueled, 3.8 for gasoline-fueled, and 1.8 for electric-powered resurfacers used in indoor rinks.

The influences of engineering controls and behavioral changes are apparent in the month-to-month concentration changes. For years 2 and 3, month 1 can be defined as the first month of sampling (January 1996 and November 1996), month 2 can be defined as the second month of sampling (February 1996 and January 1997), and month 3 can be defined as the third month of sampling (March 1996 and February 1997). Median concentrations decreased for all fuel types between month 1 and month 2 but increased between month 2 and month 3 (Table 3). If rinks undergoing engineering controls are removed from the sample, some of the monthly variability appears to be tempered. All rinks changing their resurfacer fuel types between these months were omitted.

TABLE 1—Comparison of Median Indoor Nitrogen Dioxide (NO_2) Concentrations Across Ice Resurfacer Fuel Types and Study Years

Sample Year	Averaging Time	NO_2 Concentration, Propane, ppb	NO_2 Concentration, Gasoline, ppb	NO_2 Concentration, Electricity, ppb
Year 1 (1994–1995)	7 days	132**,*** (n = 36)	42* (n = 92)	33* (n = 5)
Year 2 (1995–1996)	1 day, working hours	117**,*** (n = 41)	85*,** (n = 69)	29*,** (n = 31)
Year 3 (1996–1997)	1 day, working hours	164*** (n = 34)	107*** (n = 54)	34*,** (n = 46)

*Significantly different from propane, $P < .05$.
**Significantly different from gasoline, $P < .05$.
***Significantly different from electricity, $P < .05$.

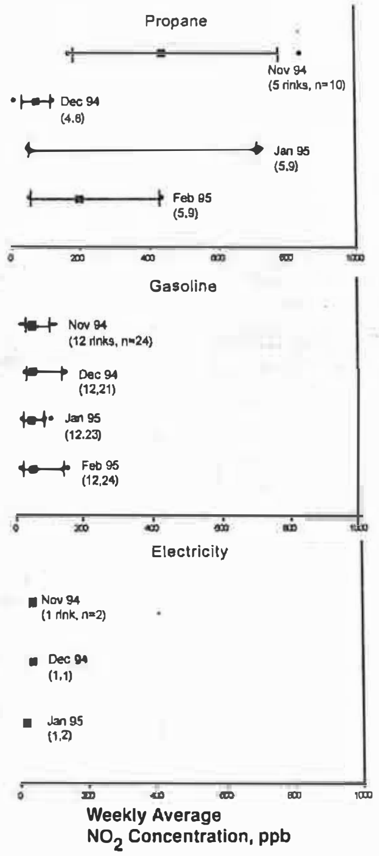
Some further supporting evidence of the effect of fuel type on NO_2 concentrations was seen in the 4 ice skating rinks that changed their resurfacer fuel from gasoline to electricity during year 2 or 3. The median NO_2 concentration among these 4 rinks declined from 124 to 35 ppb; concentrations decreased between 10% and 93% in the 4 rinks.

Another dimension of the elevated NO_2 concentrations in the ice rinks is the potential for occupational risks to ice resurfacer drivers. According to the personal samples taken in year 3, the median exposure for the ice resurfacer drivers typically working 8- to 10-hour shifts was 69 ppb (mean = 121 ppb), in comparison with the median indoor concentration of 72 ppb (mean = 139 ppb). As expected, personal exposures to drivers were more strongly correlated with indoor concentrations ($r = 0.77$) than with outdoor concentrations ($r = 0.48$).

To determine the key factors influencing personal NO_2 exposure, we used a multivariate regression that considered all simultaneously measured concentrations as well as reported rink characteristics. The only significant terms were indoor and outdoor NO_2 concentrations, with indoor concentrations having the most predictive power ($P < .0001$) and outdoor concentrations only marginally significant ($P = .046$). Rink characteristics such as fuel type, age of rink, seating capacity, skating capacity, and age of ice resurfacer were added to the multivariate regression equation, with no significant effect ($P > .05$ for all).

Discussion

The NO_2 concentrations measured in both the pilot study and the main study indicate that there is a cause for concern in many enclosed ice rinks. Given the frequent use of the ice resurfacer, we can assume that working-hour average concentrations are roughly equivalent to 1-hour average concentrations. Under this assumption, 57% of measurements from rinks with propane-fueled resurfacers, 40% from rinks with gasoline-fueled resurfacers, and 4% from rinks with electric resurfacers would exceed the WHO 1-hour air-quality guideline. Even if the MDC action level of 200 ppb were used, these numbers would only decline to 33%, 16%, and 1%, respectively. In addition, in rinks with less frequent resurfacing, some 1-hour concentrations could be significantly greater than our time-averaged values, resulting in a higher percentage of measurements that exceed the guideline. Especially for sensitive individuals whose breathing rates are elevated while skating, NO_2 concentrations must be reduced to protect public health.



Note. Means (■) and confidence intervals (|—|) are displayed.

FIGURE 1—Summary of weekly average indoor nitrogen dioxide (NO_2) concentrations during year 1, stratified by ice resurfacer fuel type.

TABLE 2—Comparison of Indoor Nitrogen Dioxide (NO_2) Concentrations and Indoor-to-Outdoor (I/O) NO_2 Ratios Immediately Before and After Mitigation Actions

Ice Rink No.	Date	Fuel Type	Indoor NO_2, Before Mitigation, ppb	Indoor NO_2, After Mitigation, ppb	I/O Ratio, Before Mitigation	I/O Ratio, After Mitigation	Mitigation Measure
14	11/94	Propane	724	99	. . .	. . .	Ventilation increased
16	11/94	Propane	447	70	. . .	. . .	Ventilation increased
4	1/96	Propane	475	119	19.0	2.3	Ventilation checked
9	1/96	Propane	423	94	13.2	2.5	Ventilation checked
15	1/96	Propane	258	162	7.2	2.6	Ventilation checked
13	11/96	Gas	188	65	2.8	3.4	Resurfacer tuned
15	11/96	Propane	302	84	7.9	2.1	Ventilation increased
19	11/96	Gas	458	169	4.5	3.5	Resurfacer tuned

Note. First months of measurement only.

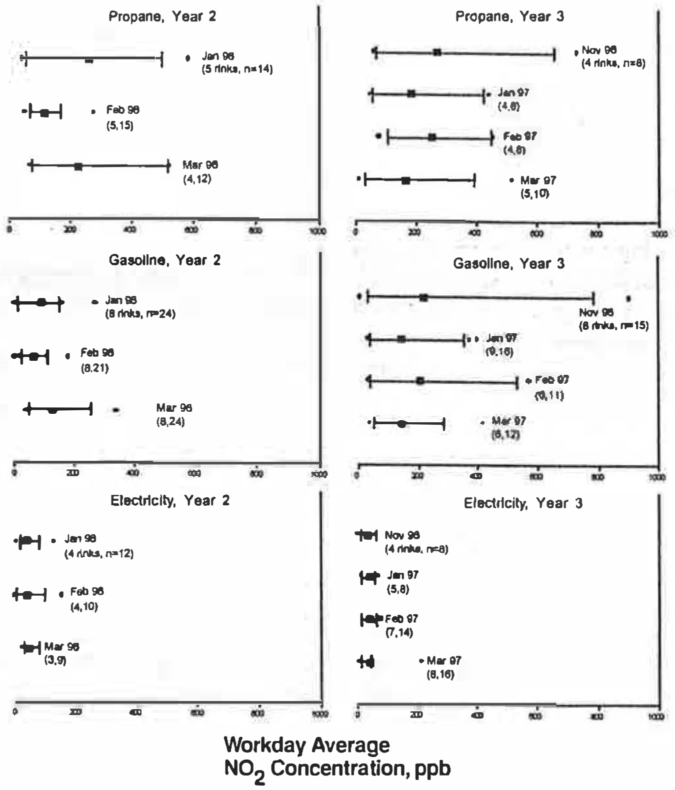
In addition, ice resurfacer drivers are exposed to elevated indoor concentrations for long periods. Although these chronic exposure levels are well below the National Institute for Occupational Safety and Health recommended exposure limit of 1 ppm, many drivers are clearly exposed to NO_2 levels greater than those encountered by the general public and are regularly exposed to levels exceeding the WHO residential air-quality standard.

The engineering controls proposed and implemented by MDC were intended to lower NO_2 exposures for patrons and workers at all rinks. Although these controls resulted in an average concentration reduction of 65% during the main study, a wide range of outcomes was documented. As indicated in Table 2, the indoor concentration decreases ranged from 37% to 86% across the rinks, with the change in indoor-to-outdoor ratio ranging from an 88% decrease to a 21% increase.

This engineering control variability must be placed in the context of a larger set of variables. Even within fuel type categories, the indoor-to-outdoor ratio varied significantly, with values ranging from 0.4 to 13.2 for rinks with electric resurfacers, 0.5 to 10.5 for rinks with gasoline-fueled resurfacers, and 0.7 to 19.0 for rinks with propane-fueled resurfacers. Although this variation can be explained in part by differential placement of outdoor samplers, variations in outdoor NO_2 source strengths, or aberrant data related to low concentrations, resurfacer fuel type alone clearly cannot predict the degree of indoor air pollution in a specific ice rink. Ventilation levels and other implemented controls are clearly critical. Because of the above variabilities and the lack of correlations between rink characteristics and concentrations, the effects of engineering controls must be monitored for each rink.

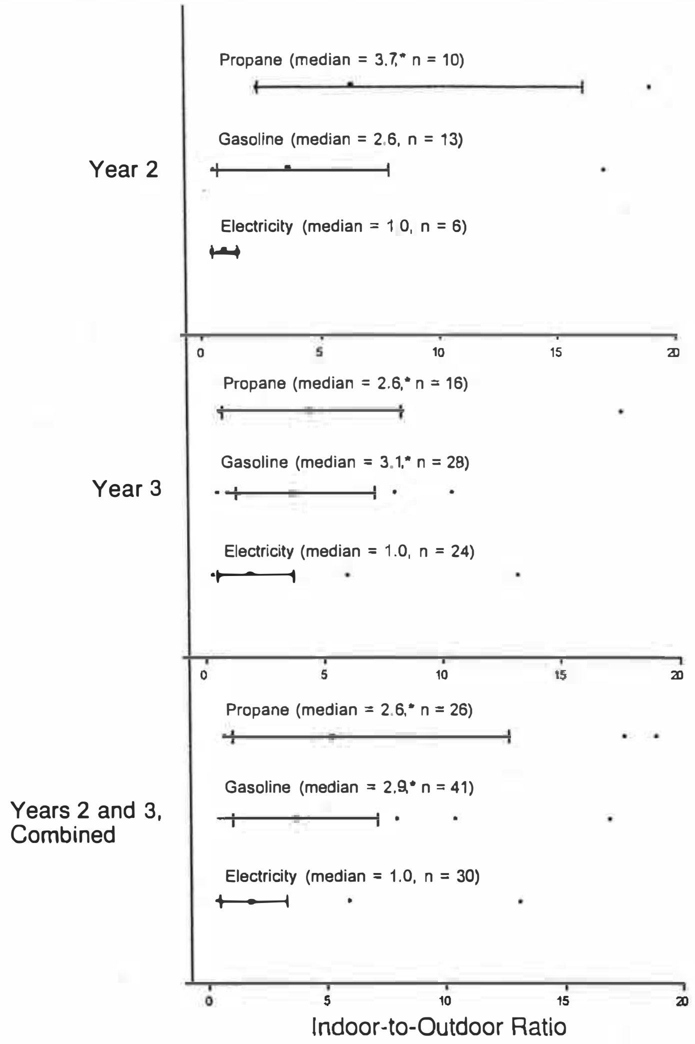
One possible explanation for part of the variability in control efficacy is that ventilation controls may have been implemented to differing degrees. Rink managers are often reluctant to increase ventilation greatly, especially on warmer days, because of issues related to ice quality. Because day-to-day behavior is difficult to monitor at 19 ice rinks, the precise effects of ventilation control policies are not easily determined. Nevertheless, ventilation controls did significantly reduce indoor NO_2 concentrations on average, implying that the MDC generally was able to find productive measures that were acceptable to rink managers.

These conclusions must be tempered somewhat, given the "slingshot" effect in the month immediately after the postcontrol measurement. In rinks that increased ventilation or tuned the resurfacer in years 2 and 3, the average 65% decline following the mitigation was offset by an average 162% increase in the following month. This could be evidence of either regression toward the mean, systematic differences in use patterns, or the inability of monitoring programs to maintain long-term improvements. This pattern was seen to a lesser degree in rinks not undergoing engineering control, with a median 20% concentration decrease from month 1 to month 2 and a median 18% concentration increase for month 2 to month 3.



Note. Means (■) and confidence intervals (⊢⊣) are displayed.

FIGURE 2—Summary of workday indoor nitrogen dioxide (NO_2) concentrations during years 2 and 3, stratified by fuel type.



Note. *Significantly different from electricity, $P < .05$. Means (■) and confidence intervals (⊢⊣) are displayed.

FIGURE 3—Indoor-to-outdoor nitrogen dioxide (NO_2) ratios for all 3 fuel types, years 2 and 3.

The robustness of the study results is limited by the design and purpose of the study. This study was conducted as an intervention study rather than an investigation of a known outcome. Thus, ventilation controls and resurfacer tuning were applied nonuniformly across the sample groups, and the sampling methodology was changed during the course of the study; these inconsistencies impede drawing aggregate statistical conclusions from the data.

Palmes tubes were chosen in year 1 for preliminary evaluation of NO_2 concentrations in ice rinks. Clearly, because the samples from year 1 were integrated over 1 week and encompassed nighttime measurements with no indoor sources operating, the measured concentrations underestimated the working-day exposures in year 1. The finding that the concentration ranges were roughly comparable between the pilot study and the main study could be related to the implementation of controls in later years. All statistical analyses in this study were conducted on the 2 studies separately, minimizing the incomparability.

Furthermore, our conclusions are limited by our lack of measurements of the ventilation levels on different sampling days. According to the MDC, the average ventilation system provided 6 air charges per hour, which was increased to a maximum of 12 air changes per hour during crowded conditions or when engineering controls were required. However, the ventilation rates at specific rinks during the sampling periods could not be quantified. The lack of rink-specific ventilation rates can be attributed both to practical concerns and to the fact that the importance of the ventilation system could be seen only retrospectively. In future studies, measurement and estimation of the air-exchange rates before and after engineering controls would help both in monitoring the actions taken and in understanding the differential effects among rinks. In addition, we did not have information about the precise timing and duration of edger use in the rinks, a potential contributor to elevated NO_2 concentrations.

Despite these limitations, the findings of this study allow us to make some general recommendations for managers of indoor ice rinks. Electric ice resurfacers are clearly benign in terms of indoor NO_2 pollution, even assuming gasoline-powered edger use, based on the indoor-to-outdoor ratios near 1.0 and only 3 indoor measurements that exceeded 80 ppb during the entire study. Future studies may wish to consider energy efficiency or life cycle impact issues, but

TABLE 3—Mean and Median Percentage Changes in Indoor Nitrogen Dioxide (NO_2) Concentrations Between Sampling Months, Aggregated Across Years 2 and 3

	Propane			Gasoline			Electricity		
	Mean	Median	n	Mean	Median	n	Mean	Median	n
% Concentration change, months 1–2	−32	−37	9	+3	−32	17	+13	−19	8
% Concentration change, months 2–3	+82	+25	8	+87	+63	14	+17	+10	7
% Concentration change, months 1–2, controlled rinks removed	−3	+9	5	+11	−28	15	+13	−19	8
% Concentration change, months 2–3, controlled rinks removed	+8	+2	4	+72	+42	13	+17	+10	7

Note. Month 1 = January 1996 and November 1996, Month 2 = February 1996 and January 1997, Month 3 = March 1996 and February 1997.

electric resurfacers can solve the NO_2 pollution problem in indoor ice rinks.

However, resurfacer replacement can be an expensive proposition, costing about $100 000.[27] For combustion resurfacers, recent studies have shown that a lambda sensor-controlled fuel supply and a 3-way catalyst can reduce NO_2 concentrations by nearly 90%, and at 5% of the cost of resurfacer replacement.[27] For resurfacers that may not be covered by this technology, or for rinks that cannot afford the cost, concentrations should be monitored periodically to determine whether the resurfacer has been properly maintained, to ensure that ventilation is sufficient, and to maintain an observer effect.

To determine the proper control of the occupational hazard to ice resurfacer drivers, further study should assess the amount of time spent by drivers in various microenvironments with different source strengths. Similarly, exposure patterns and physiological responses of ice skaters should be investigated more thoroughly to help determine an appropriate target NO_2 concentration.

Conclusions

Concentrations of NO_2 in indoor ice skating rinks were elevated beyond recommended levels at a number of sites. The concentration was highly dependent on the fuel type of the ice resurfacer and the degree of ventilation in the facility. Indoor air quality can be drastically improved by using electric ice resurfacers, by installing new emission controls, or by using proper ventilation and regular maintenance for resurfacers fueled by propane or gasoline. A continuous surveillance program has been proposed for the last case, both to help determine proper controls and to maintain a hypothesized observer effect that may prevent regression. Use of one of these pollution control strategies should help maintain low indoor NO_2 concentrations to help protect the health of ice skaters and rink employees. ☐

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Residential Magnetic Fields and Childhood Leukemia: A Meta-Analysis

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ABSTRACT

Objectives. This article uses meta-analysis methodology to examine the statistical consistency and importance of random variation among results of epidemiologic studies of residential magnetic field exposure and childhood leukemia.

Methods. A variety of meta-analytic statistical methods were applied to all available studies combined and on subgroups of studies chosen by exposure characteristics. Sample sizes and fail-safe n's were calculated to determine the robustness of results and the potential role of publication bias.

Results. Most studies show elevated but not statistically significant odds ratios. Results for exposures assessed by wire codes, distance, and/or historically reconstructed fields are relatively consistent, homogeneous, and positive, while those for direct magnetic field measurements are consistent, homogeneous, and marginally protective. Several unpublished studies, or a single unpublished study with several hundred subjects, would be needed to nullify the observed data.

Conclusions. The observed results identify a consistent risk that cannot be explained by random variation. The data supporting magnetic fields as the principal risk factor are suggestive but inconsistent. Additional studies using innovative designs that focus on highly exposed children offer the most hope of untangling this issue. (*Am J Public Health.* 1998;88:1787–1794)

Since the publication of a seminal study by Wertheimer and Leeper,[1] scientists have attempted to make sense of provocative and sometimes conflicting studies about the possible association between exposure to electric and magnetic fields and the incidence of disease. As this controversy continues, organizing and reviewing the extant data can provide important insights into the consistency of the results, gaps in our investigative strategies, and limitations in our understanding. Toward that end, this article presents a meta-analysis of the most compelling subset of these data: data on residential exposure to magnetic fields and the incidence of childhood leukemia. It is an attempt to gain an understanding of the importance of individual studies in driving overall conclusions about a possible link between magnetic fields and cancer and of the constraints that would be necessary on any future study for it to have sufficient statistical power to influence the present overall conclusions.

Meta-analysis is a statistical method used to provide a single summary risk estimate based on a set of similar epidemiologic studies.[2,3] It is applied most often to clinical trial data in which the major differences among studies are the specific populations examined rather than characteristics of the study designs. The validity of broadening the application of this method to environmental epidemiology has led to controversy because of the heterogeneity in results that often arises from design differences among studies in exposure assessment, confounder assessment, subject selection, and so forth.[4–8] However, meta-analysis methods can also be used in a less statistically rigorous manner to evaluate the strength, consistency, and robustness of an exposure–disease relationship. This article presents one such application.

Of the 16 epidemiologic studies to date (see Table 1), some have reported positive results and others have found no association. Scientists disagree about the quality, bias, accuracy, uncertainties, and many of the statistical analyses in each of these studies; thus, there are differing interpretations of the likelihood of a possible association overall.[9–11] While some investigators question the validity of drawing inferences based on 16 or fewer studies with apparently inconsistent results, the ubiquitous nature of exposure to magnetic fields from power lines makes even a weak association a public health issue of substantial concern. Meta-analysis, while no better than the data on which it is based, can help frame the public health debate while also providing insights for the design of additional studies.

Five sets of investigators have previously conducted meta-analyses of childhood cancer and residential exposure to magnetic fields. A report by Great Britain's Advisory Group on Non-Ionising Radiation of the National Radiological Protection Board summarized the results of the residential exposure studies, providing pooled odds ratio estimates for 3 studies for each exposure metric.[11] For wire codes (a categorical exposure rating scheme based on wire size and distance from the residence), excluding the Wertheimer and Leeper study,[1] the group found an elevated and statistically significant odds ratio. For distance from source of magnetic fields and for measured magnetic fields, the pooled odds ratios were elevated but not statistically significant.

Ahlbom et al.[9] combined results from 3 recent studies conducted in Nordic coun-

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