Kansanterveyslaitos
Folkhälsoinstitutet
National Public Health Institute

Publications of the National Public Health Institute A 1 / 2005

Arto Pennanen

INDOOR AIR POLLUTION AND HEALTH RISKS IN FINNISH ICE ARENAS

Department of Environmental Health
Laboratory of Toxicology
National Public Health Institute
Kuopio, Finland

Kuopio 2005

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ACADEMIC DISSERTATION

To be presented with the permission of the Faculty of Natural Sciences and Environmental Sciences of the University of Kuopio for public examination in Auditorium L23, Snellmania, University of Kuopio, on Friday 18 March 2005, at 12 o'clock noon.

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KTL A1/2005
ISBN 951-740-485-9
ISSN 0359-3584
ISBN 951-740-486-7 (pdf)
ISSN 1458-6290 (pdf)
http://www.ktl.fi/portal/suomi/julkaisut/julkaisusarjat/kansanterveyslaitoksen_julkaisuja_a/

Kopijyvä, Kuopio, Finland, 2005

Pennanen, Arto. Indoor air pollution and health risks in Finnish ice arenas.
Publications of National Public Health Institute A1/2005. 69 pages.
ISBN 951-740-485-9, ISBN 951-740-486-7 (pdf), ISSN 0359-3584, ISSN 1458-6290 (pdf)
http://www.ktl.fi/portal/suomi/julkaisut/julkaisusarjat/kansanterveyslaitoksen_julkaisuja_a/

ABSTRACT

Indoor air pollution in ice arenas due to the use of combustion engine-powered ice resurfacing machinery poses a health risk to arena users. This study characterises the indoor air pollution in the 200 Finnish ice arenas currently in use in 1992-2000, evaluates the factors contributing to pollutant levels, and makes recommendations and also undertakes a follow-up of abatement measures intended to improve indoor air quality.

The CO, NO_2, and VOC concentrations were measured in five arenas with different volumes, ventilation systems, and ice resurfacers. In addition, weekly NO_2 concentrations were measured in 69 arenas (83% of 83 arenas) in 1994. The arena and resurfacer characteristics were surveyed in 1994-1996 and in 2000 using mailed technical questionnaires. Non-regulatory recommendations on measures to abate indoor air pollution were sent to the arenas in 1994 and 1996.

The performance of emission control technology on the ice resurfacers was examined using engine emission and indoor air quality measurements. The implementation of the recommended measures by the arenas was evaluated with the help of repeated questionnaires. The health outcomes were assessed on the basis of four cases of epidemic CO poisonings in Finland and by analysing the health questionnaire data received from nearly 800 junior ice hockey players in terms of their NO_2 exposures.

The indoor air concentrations of CO and NO_2 in ice arenas were high when compared with both ambient outdoor levels and air quality guidelines. Ice arenas with propane- or gasoline-fuelled resurfacers had significantly higher weekly NO_2 concentrations than arenas with electric resurfacers. The highest levels were associated with the combination of a small arena volume and a combustion engine-powered ice resurfacer. The number of daily resurfacings, the use of ventilation, and the presence of a catalytic converter made only minor contributions to the weekly NO_2 concentration as assessed in a multivariate analysis.

The infrequent cases of epidemic CO poisonings were characterised by the combination of a malfunctioning resurfacer, small and newly opened arena, and inadequate ventilation. The acute adverse health effects of CO (headache, nausea) were clearly demonstrated in association with these cases, whereas repeated NO_2 exposure was associated with an increase in relatively mild respiratory symptoms (rhinitis, cough).

The best and probably only sustainable solution to achieve abatement of indoor air pollution was estimated to be the replacement of combustion engine-powered resurfacers with electric machines. Retrofitting of emission control technology in propane-fuelled resurfacers was regarded as a feasible option during the transition to electric resurfacers with the proviso that the use and maintenance of the resurfacer and the arena are controlled.

A substantial improvement in the indoor air quality in Finnish ice arenas was achieved during this study as indicated by the adherence to the recommended abatement measures implemented between 1994 and 2000. However, most of the newly constructed arenas were small and equipped with combustion engine-powered resurfacers, making them prone to air quality problems. Consequently, it seems likely that there will be elevated pollutant levels in Finnish ice arenas exceeding the health-based air quality guidelines also in the future.

In the end of 2000, an estimated number of 20 000 daily users of ice arenas were still at risk of breathing poor quality air.

It seems that if we wish to achieve a sustainable solution to the indoor air quality problems in ice arenas then this will require new governmental regulatory measures.

Pennanen, Arto. Indoor air pollution and health risks in Finnish ice arenas.
Publications of National Public Health Institute A1/2005. 69 pages.
ISBN 951-740-485-9, ISBN 951-740-486-7 (pdf), ISSN 0359-3584, ISSN 1458-6290 (pdf)
http://www.ktl.fi/portal/suomi/julkaisut/julkaisusarjat/kansanterveyslaitoksen_julkaisuja_a/

TIIVISTELMÄ (abstract in Finnish)

Polttomoottorikäyttöiset jäänhoitokoneet tuottavat jäähallien sisäilmaan epäpuhtauksia, jotka aiheuttavat terveysriskin jäähallien käyttäjille. Tämä tutkimus tarkastelee sisäilman epäpuhtauksia ja niihin vaikuttavia tekijöitä, esittää toimenpidesuosituksia ilmanlaadun parantamiseksi sekä seuraa näiden suositusten käyttöönottoa vuosina 1992-2000 tällä hetkellä noin 200 suomalaisessa jäähallissa.

Hään (CO), typpidioksidin (NO_2) ja haihtuvien hiilivetyjen pitoisuudet mitattiin viidessä tilavuudeltaan, ilmanvaihtolaitteiltaan ja jäänhoitokoneeltaan erilaisessa jäähallissa. Laajempana otoksena mitattiin NO_2:n viikkokeskiarvot 69 hallissa (83% halleista) vuonna 1994. Kaikkien hallien ja jäänhoitokoneiden teknisiä ominaisuuksia selvitettiin kyselyillä vuosina 1994-1996 ja 2000. Suosituksia ilmanlaadun parantamiseen tähtäävistä toimenpiteistä annettiin jäähalleille ja terveysviranomaisille vuosina 1994 ja 1996.

Jäänhoitokoneen päästöjen vähennystekniikan toimivuutta tutkittiin sekä päästö- että ilmanlaatumittausten avulla. Toimenpidesuositusten käyttöönottoa jäähalleissa selvitettiin toistetuilla teknisillä kyselyillä. Häkä- ja typpidioksidialtistuksen aiheuttamia terveysvaikutuksia arvioitiin tarkastelemalla häkämyrkytystapauksia neljässä jäähallissa sekä analysoimalla lähes 800 juniorijääkiekkoilijan terveyskyselyn vastaukset typpidioksidialtistuksen suhteen.

Suomalaisten jäähallien sisäilman CO- ja NO_2-pitoisuudet olivat korkeita sekä ulkoilman tasoihin että ilmanlaadun ohjearvoihin verrattuna. Sisäilman NO_2-pitoisuus oli merkittävästi korkeampi halleissa, joissa oli propaanilla tai bensiinillä käyvä polttomoottorikäyttöinen jäänhoitokone, kuin halleissa, joissa oli sähkökäyttöinen kone. Korkeimmat epäpuhtauspitoisuudet esiintyivät tilavuudeltaan pienissä halleissa, joissa oli polttomoottorikäyttöinen jäänhoitokone. Päivittäisten jäänhoitokertojen määrä, ilmanvaihdon käyttö ja jäänhoitokoneen varustaminen katalysaattorilla vaikuttivat vain vähän NO_2-pitoisuuden viikkokeskiarvoon.

Häkämyrkytystapauksille yhteisiä tekijöitä olivat vika jäänhoitokoneen moottorissa, hallin uutuus ja pieni tilavuus sekä puutteellinen ilmanvaihto. Hään välittömät terveysvaikutukset (päänsärky, pahoinvointi) tulivat esiin joukkomyrkytystapausten yhteydessä, kun taas toistuva NO_2-altistus oli yhteydessä lievempiin hengitysteiden oireisiin (nuha, yskä).

Paras ja ainoa kestävä ratkaisu jäähallien ilmanlaatuongelmiin on polttomoottorikäyttöisten jäänhoitokoneiden korvaaminen sähkökäyttöisillä. Pakokaasujen puhdistusjärjestelmän asentaminen propaanikäyttöisiin jäänhoitokoneisiin on hyväksyttävä vaihtoehto siirtymävaiheen aikana, mutta tämä tekniikka edellyttää hyvää jäänhoitokoneen ja hallin käytön hallintaa.

Suomalaisten jäähallien ilmanlaatu parani tutkimuksen aikana huomattavasti, koska suositeltuja toimenpiteitä tehtiin jäähalleissa lisääntyvästi vuosina 1994-2000. Epäsuotuisasti kehitykseen vaikutti se seikka, että suurin osa uusista halleista oli pieniä ja niihin hankittiin edelleen enimmäkseen polttomoottorikäyttöisiä jäänhoitokoneita, mikä teki niistä alttiita ilmanlaatuongelmille. Tämän seurauksena näyttää siltä, että suomalaisissa jäähalleissa tulee jatkossakin esiintymään ilmanlaadun ohjearvot ylittäviä epäpuhtauspitoisuuksia.

Vuoden 2000 lopussa tehdyn arvion mukaan 20 000 jäähallien käyttäjää altistui edelleen päivittäin huonolle ilmanlaadulle.

Jäähallien ilmanlaatuongelmien kestäväksi ratkaisemiseksi tarvitaan uusia hallinnollisia määräyksiä ja ohjeita.

KIITOKSET

Tämä työ tehtiin Kansanterveyslaitoksen Ympäristöterveyden osastossa vuosina 1992 – 2001. Kiitän kunnioittavasti silloista osastonjohtajaa, professori Jouko Tuomistoa ja Toksikologian laboratorionjohtajaa Hannu Komulaista tarvittavien resurssien luomisesta.

Kiitän lämpimästi pääohjaajaani, dosentti Raimo O. Salosta, väsymättömästä ja innostavasta ohjauksesta työn kaikissa vaiheissa samoin kuin lukuisten yhteistyökumppaneiden hankkimisesta. Kiitän vilpittömästi ohjaajaani, professori Juhani Ruuskasta, opastuksesta tutkimustyössä ja jatko-opinnoissani.

Kiitän työn esitarkastajia, dosentti Antti Tossavaista ja professori Heikki Savolaista, arvoikkaista kommenteista ja palautteesta. Kiitän myös Ewen MacDonaldia väitöskirjan kieliasun tarkastamisesta.

Kiitokset ansaitsevat kaikki avuliaat yhteistyökumppanit JÄÄHY-tutkimuksen eri vaiheissa: Tom Eklund, Nils-Olof Nylund ja Erkki Virtanen (VTT) pakokaasujen päästömittauksissa; Seppo Liitsola ja Pekka Paavola (Suomen Jääkiekkoliitto) yhteydenpidossa jäähalleihin ja urheiluseuroihin; Matti Hyväri (Ultralink Oy) pakokaasujen puhdistusjärjestelmiä koskevissa kysymyksissä sekä Michael Brauer (University of British Columbia) kansainvälisessä yhteistyössä. Lisäksi kiitän jäähallien, erityisesti Kuopion ja Riihimäen hallien, henkilökuntaa sekä tutkimukseen osallistuneita nuoria jääkiekkoilijoita.

Minulla on ollut Kansanterveyslaitoksessa useita loistavia työtovereita, joista tahdon kiittää tämän työn kannalta tärkeimpiä: Sari Almia ilmanlaatumittausten suunnittelusta, opastamisesta ja lopulta tekemisestä; Mikko Vahteristoa aineiston analysoinnista, mallittamisesta ja vielä sen jälkeen ymmärrettävän tuloksen esiin saamisesta; Jukka Randellia jääkiekon terveellisyyden kyseenalaistamisesta sekä Arja Hälistä työryhmän järjestyksen säilyttämisestä.

Parhaat kiitokseni kuuluvat Matti Vartiaiselle, Pertti Pasaselle ja Arto Ahoselle mittausteknisestä tuesta; Matti Jantuselle ja Tuula Putukselle avusta tutkimusten suunnittelussa sekä Liisa Koverolle, Anna Maria Helpille ja Soili Antikaiselle avusta käytännön työssä. Haluan myös lämpimästi kiittää koko YTOS:n henkilökuntaa ymmärtäväisestä suhtautumisesta näiden vuosien aikana. LI-SÄK-SI KII-TÄN TY-RÄS-MIE-HI-Ä HIE-NOS-TA HAR-RAS-TUK-SES-TA.

Erityisellä lämmöllä haluan kiittää vanhempiani rakkaasta huolenpidosta. Teillä on aina ollut aikaa ja kärsivällisyyttä ottaa kuopuksenne mukaan ja opettaa asioita kädestä pitäen. Lopuksi ja ennen kaikkea kiitän Saria kaikesta. Ilmeenkään värähtämättä olet aina hyväksynyt seuraavan uuden harrastukseni, joka vie kolme iltaa viikossa ja alakerran parhaimman huoneen.

Tätä tutkimusta ovat rahoittaneet Opetusministeriö, Jääkiekkosäätiö, MOBILE-tutkimusohjelma, Sosiaali- ja terveysministeriö, Kuopion yliopisto (YTY-keskus) ja Kansanterveyslaitos.

Lahdessa, helmikuussa 2005

Arto Pennanen

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on four original publications and one submitted manuscript referred to in the text by their Roman numerals (I-V).

I Pennanen AS, Salonen RO, Alm S, Jantunen MJ, Pasanen P. Characterization of air quality problems in five Finnish indoor ice arenas. J Air Waste Manage Assoc 1997; 47: 1079-1086.

II Pennanen AS, Vahteristo M, Salonen RO. Contribution of technical and operational factors to nitrogen dioxide concentration in indoor ice arenas. Environ Int 1998; 24: 381-388.

III Pennanen AS, Salonen RO, Eklund T, Nylund N-O, Lee K, Spengler JD. Improvement of air quality in a small indoor ice arena by effective emission control in ice resurfacers. J Air Waste Manage Assoc 1997; 47: 1087-1094.

IV Pennanen AS, Salonen RO, Vahteristo M, Lee K, Spengler JD. Two-year follow-up study of nonregulatory recommendations for better air quality in indoor ice arenas. Environ Int 1998; 24: 881-887.

V Salonen RO, Pennanen AS, Vahteristo M, Korkeila P, Alm S, Randell JT. Health risk analysis of indoor air pollution in Finnish ice arenas. Submitted.

CONTENTS

1 INTRODUCTION

Carbon monoxide (CO) and nitrogen dioxide (NO_2) are classical air pollutants that may occur at relatively high levels in urban environments with dense automobile traffic. In indoor environments where combustion appliances are used, the concentrations of CO and NO_2 can become elevated to hazardous levels. Such indoor environments may include enclosed parking facilities, road tunnels, workplaces, and homes with gas cookers or heaters. In addition to the health effects attributable to CO and NO_2, they may serve as a proxy for the pollutant mixture derived from road traffic, and NO_2 is also an important precursor of secondary pollutants (e.g. ozone, nitrate aerosol) (WHO 2000, WHO 2003).

CO is acutely toxic in high, short-term exposures, but it can also be associated with cardiovascular morbidity and myocardial infarction in long-term exposures (WHO 2000). The health effects of NO_2 in epidemiological studies include irritating symptoms in the upper (rhinitis, cold, sore throat) or lower (wheezing, persistent cough) respiratory tract, lung function changes, bronchoconstriction or bronchial hyperresponsiveness to other stimuli like cold air and allergens, increased respiratory infections, and exacerbation of chronic obstructive pulmonary disease (COPD) and asthma (IEH 1996, WHO 2000).

Indoor air pollution in ice arenas, particularly high CO and NO_2 levels, has been a recognized problem for over 30 years (Anderson 1971). The main source of CO and NO_2 is the combustion engine-powered ice resurfacers that are still used in the vast majority of arenas worldwide. The spectrum of health effects among users of ice arenas is wide, ranging from increased prevalence of respiratory symptoms and bronchoconstriction to severe poisonings requiring emergency health care. Despite the fact that the problem has been recognised and abatement measures are available, indoor air pollution still seems to be a potential health risk to ice arena users (Pelham et al. 2002).

This thesis characterises the indoor air pollution in Finnish ice arenas, evaluates the factors contributing to pollutant levels, and makes recommendations and ways to follow-up the measures needed to be taken to improve indoor air quality. The results, including the updated list of recommendations, have been brought to the attention of the national health, sports, and environmental authorities and other interested parties (e.g. Finnish Ice Hockey Association, International Ice Hockey Federation, International Skating Union) for setting guidelines for ice arenas and providing instructions to arena managers and local authorities.

2 REVIEW OF THE LITERATURE

2.1 Levels and health effects of CO and NO_2 in outdoor and indoor air

2.1.1 Carbon monoxide (CO)

Global background CO levels range between 0.01 and 0.23 mg/m^3 (0.01-0.2 ppm) in the natural environment. In European cities, the 8-h average outdoor concentrations are generally lower than 20 mg/m^3 (17 ppm), and the 1-h peak levels are lower than 60 mg/m^3 (53 ppm) (WHO 2000). The mean 8-h CO concentration surveyed at traffic sites in Western European cities was 8.3 mg/m^3 (7.2 ppm) in 1993 (IPCS 1999). In Helsinki in 2002-2003, the outdoor 1-h and 8-h CO concentrations comparable to the guidelines ranged from 0.5 to 5 mg/m^3 and from 0.4 to 3.5 mg/m^3, respectively (Myllynen et al. 2004). In urban areas, more than half of all CO emissions originate from transportation (mobile) sources with smaller contributions from residential heating and stationary sources (industry, power plants) (IPCS 1999). Automotive traffic is the major source of CO and the highest concentrations are measured near to major roads and in underground car parks, road tunnels, and other environments where combustion engines operate (WHO 2000).

In indoor environments without CO sources, the CO concentrations approximate to the average outdoor concentrations (IPCS 1999). In homes with unvented combustion appliances, indoor CO concentrations have ranged from 1 to 35 mg/m^3 (1 to 30 ppm) (WHO 1987, IPCS 1999). Short-term peak CO concentrations may rise as high as 60 mg/m^3 (53 ppm) (WHO 2000), and even values exceeding 110 mg/m^3 (96 ppm) have been reported (IPCS 1999). Emplyees in occupational environments e.g. garage workers, drivers, and some industrial workers, may experience CO concentrations in excessive of 115 mg/m^3 (100 ppm) (WHO 2000). Inside vehicles, the CO concentrations have been 3 to 5 times as high as the outdoor fixed monitoring site concentrations in several studies (IPCS 1999). Indoor CO sources include gas cooking ranges, space heaters, coal or wood stoves, and tobacco smoking (IPCS 1999).

In a study on personal exposure of preschool children in Helsinki, the average of maximum 8-h CO concentrations was 3 mg/m^3 (2.6 ppm) in 1991 (Alm et al. 2001), while the corresponding value in the working population of the EXPOLIS-study was 2 mg/m^3 (1.7 ppm) in 1997 (Hänninen et al. 2004).

Symptoms and health effects of CO exposure

Inhaled CO is not removed by the conducting airways but reaches the pulmonary airways where it diffuses across alveolar and capillary membranes into blood. Absorbed CO binds with blood haemoglobin, forming carboxyhaemoglobin (COHb) with an affinity of 200-250 times that of oxygen. Depending on the pulmonary ventilation rate, it takes 4 to 12 h for COHb level to reach equilibrium under a constant CO concentration. For example, at an ambient CO concentration of 30 mg/m^3, the COHb level is approximately 1.5% after 1 h and 4% after 8 h of exposure, and the equilibrium level is 4.7% (EPA 1991, Maynard and Waller 1999). The usual COHb levels are 0.5-1.5% in the non-smoking population and 3-8% in the smoking population (WHO 2000, IPCS 1999). In certain occupations such as car drivers, policemen, garage workers, and firemen, the long-term COHb levels may be elevated up to 5% (WHO 2000). Non-smoking garage attendants exposed to a mean CO concentration of 67 mg/m^3 (59 ppm) had a mean COHb level of 7.3% at the end of their workday (IPCS 1999).

The cardiovascular and neurobehavioural effects of CO exposure appear already at COHb levels below 10%. Maximal exercise performance is impaired at COHb levels of 2-6%, which roughly corresponds to exposure to 15-45 mg/m^3 of CO for 8 h. Psychomotor effects (reduced coordination, vigilance etc.) may appear at COHb levels of 5-8%, although significant behavioural impairments can usually be expected only at levels above 20% (WHO 2000, EPA 1991 and 2000). Symptoms and effects of actual CO poisoning (headache, fatigue, dizziness, nausea, vomiting) are usually reported at COHb levels above 10% (Table 1). Poisonings at COHb levels around 20% have occurred, for example, among warehouse workers exposed to the exhaust gases emitted by propane-fuelled forklifts (Fawcett et al. 1992, Ely et al. 1995).

Chronic exposure to ambient CO levels (from sources other than tobacco smoke) does not seem to have any clear long-term effects (Maynard and Waller 1999). However, smoking and non-smoking street tunnel officers with long-term mean COHb levels generally below 5% exhibited an increased risk of death from heart disease (Stern et al. 1988). The day-to-day variation in the daily ambient CO concentration in the range of 6 to 23 mg/m^3 (5 to 20 ppm) has been associated with hospital admissions and mortality of elderly subjects in some but not all epidemiological studies (Bascom et al. 1996, Maynard and Waller 1999). In addition, CO acts as a proxy for other combustion-related pollutants in epidemiological studies.

Table 1. CO exposure and the resultant COHb concentrations in blood with symptoms and other health effects. The estimates are for healthy adults except where differently indicated.

Exposure time[a]	CO level (mg/m^3)	COHb in blood (%)	Symptoms and other effects	Reference
2 h	40	2.3 - 4.3	Decrease in the relation between working time and exhaustion	WHO 1987
		2.9 - 4.5	Decrease in exercise capacity in patients with angina pectoris	WHO 1987
		> 4	Dose-dependent decrease in maximal exercise performance (O_2 consumption)	WHO 1987, WHO 2000
2 h	100	5.1 - 8.2	Impaired coordination, tracking, driving ability, vigilance and cognitive performance	WHO 2000
8 h	100	10 - 20	Shortness of breath, tightness across the forehead, possible headache, dilation of cutaneous blood vessels	Maynard & Waller 1999, IPCS 1999
		20 - 30	Headache and throbbing in temples, easily fatigued	"
		30 - 40	Severe headache, weakness, dizziness, dimness of vision, nausea, vomiting	"
		40 - 50	Same as above, confusion, collapse, fainting on exertion	"
		50 - 80	Increased respiratory and pulse rate, unconsciousness, intermittent convulsions, respiratory failure, death	"
		> 80	Rapidly fatal	"

[a] Exposure in light work or normal activity with pulmonary ventilation between 10-20 l/min.

Limit and guideline values

Limit and guideline values have been set to protect population groups at risk (e.g., patients with cardiovascular disease, pregnant women) from hypoxic effects by ensuring that their COHb levels stay below 2.5% (WHO 2000). Since CO has mainly acute effects and COHb has a 4-12 h stabilisation time, it is mainly the 1- and 8-h average concentrations that are usually regulated (Table 2). In Finland, the CO guideline is also used to indirectly improve the general air quality in urban areas (Council of State 1996). The occupational guidelines are set for 15-min (87 mg/m^3) and 8-h (35 mg/m^3) exposures and they are generally higher than the outdoor air guidelines (Sosiaali- ja Terveysministeriö 2002). The occupational COHb limit value in the United States is 3.5% (ACGIH 2001), whereas the Finnish Institute of

Occupational Health has a limit value of 5% for workers in general and 2.5% for pregnant women (Työterveyslaitos 2004).

Table 2. Guideline and limit values for CO in the outdoor air and in occupational settings in Finland, Europe, and the United States.

Averaging time	Finland 1996	WHO Europe 2000	EU 2005	USA 1990
Outdoor air (mg/m^3)				
15 min		100		
1 h	20	30		40^b
8 h	8	10	10^a	10^b
Occupational (mg/m^3)	(2002)			(2000)
15 min	87^a			
8 h	35^a			29^a

^{a}limit value; ^{b}air quality standard

2.1.2 Nitrogen dioxide (NO_2)

Natural background NO_2 concentrations are below 10 µg/m^3. Outdoor annual mean concentrations in urban environments usually range from 20 to 90 µg/m^3 (10 to 50 ppb) and the 1-h maximum concentrations range from 75 to 1000 µg/m^3 (40 to 500 ppb) (WHO 1995, IPCS 1997, WHO 2000). The urban outdoor NO_2 levels have remained stable or have even slightly increased during the 1990's (WHO 2000). In Helsinki, the annual mean NO_2 concentrations in various monitoring sites decreased slightly in the 1990's, but have plateaued between 22 and 37 µg/m^3 in recent years. In 2002-2003, the highest 1-h and 24-h concentrations were 164 and 113 µg/m^3, respectively. The Finnish 24-h guideline (70 µg/m^3) was exceeded 7-9 times in 2002-2003 in Helsinki, while the 1-h guideline (150 µg/m^3) was not exceeded (Myllynen et al. 2004). In general, the main sources of NO_2 are transportation, stationary source fuel combustion, industrial processes, and solid waste disposal (EPA 1993). The contribution of mobile sources to outdoor NO_2 concentration in western metropolises has been estimated at 70-90 % (IPCS 1997).

The indoor concentration of a pollutant is determined by the strength of indoor sources, its infiltration from outdoor air, and the air exchange. When no indoor sources are present, the indoor-to-outdoor (I/O) ratio of NO_2 is typically 0.5-0.8 and indoor NO_2 concentrations range from 7 to 60 µg/m^3 (4 to 30 ppb) (Berglund et al. 1993, IPCS 1997). In homes with unvented gas appliances (cooking range/oven, heater), the I/O-ratios are typically 2-3, and the weekly indoor NO_2 concentrations in such kitchens range from 40 to 210 µg/m^3 (20 to 110 ppb) (IEH 1996, IPCS 1997). The average indoor NO_2 concentration may exceed 200 µg/m^3 (100 ppb) over a period of several days, and the maximum 1-h values may reach 2000 µg/m^3 (Berglund et al. 1993, WHO 2000). In the United States, 50-70% of homes with kerosene or gas heaters had an average NO_2 concentration above 100 µg/m^3 (EPA 1993).

In Helsinki in 1997, the mean personal and workplace 48-h NO_2 exposure concentrations in the adult working population were 25 and 27 µg/m^3, respectively (Kousa et al. 2001). The geometric mean weekly personal NO_2 exposure in preschool children living in non-smoking homes in downtown Helsinki was 26 µg/m^3 in 1991, while the corresponding value inside their day-care-centres was 40 µg/m^3 (Alm et al. 1998).

Health effects of NO_2 exposure

The acute respiratory effects of NO_2 observed in human clinical studies are listed in Table 3. Generally, health effects are seen in healthy subjects only at exposure concentrations above 1880 µg/m^3 (1 ppm). In asthmatics, minor effects start to appear at concentrations (approximately 500 µg/m^3) that may be measured as peak concentrations in polluted cities. However, several studies have found no effects at similar or higher concentrations and, therefore, the results of clinical studies do not support any consistent threshold NO_2 level or dose-response relationship (Berglund et al. 1993, EPA 1993, WHO 2000). Interestingly, Randell (1997) has shown that a repeated combined exposure to NO_2 (500 µg/m^3) and cold air cumulatively increased respiratory symptoms in subjects with mild asthma, while the simultaneous bronchoconstriction was gradually attenuated.

Epidemiological studies have provided evidence for an association between health effects and exposure to a mean NO_2 level of 10-50 µg/m^3 with high hourly peak concentrations (Berglund et al. 1993). In particular, children seem to be susceptible to respiratory infections and, consequently, to NO_2-associated respiratory illness (IEH 1996). Lower respiratory morbidity in children has been associated with weekly NO_2 concentrations ranging between 15 and 120 µg/m^3, and an increase of 30 µg/m^3 (16 ppb) in long-term NO_2 exposure has been related to an increased risk for respiratory symptoms and disease of about 20% (Hasselblad et al. 1992, WHO 1995, IPCS 1997). In a Finnish study, cough prevalence was associated with a weekly personal NO_2 exposure ranging between 4 and 99 µg/m^3 among preschool children (Mukala et al. 2000). However, the causality for an NO_2 effect has not been established in epidemiological studies because of confounding by several traffic-related primary and secondary gaseous and particulate pollutants (WHO 2003).

Table 3. Health effects of experimental short-term exposures to NO_2.

NO_2 (µg/m^3)	Exposure time	Effect	Subjects	Reference
190-850	ND	NO_2 potentiates airway constriction (resistance) by bronchoconstricting agents or cold air	healthy / asthmatics	WHO 2000
560	30 min	Impaired pulmonary function, increased responsiveness	asthmatics	WHO 2000
560	3.75 h	Decrease in forced expiratory volume and vital capacity	COPD[a] patients	EPA 1993
900	ND	Subjective complaints	asthmatics	WHO 1987
1880	≥ 1 h	Subjective complaints, increased airway responsiveness	healthy	WHO 1987; EPA 1993
> 2800	ND	NO_2 may alter numbers and types of inflammatory cells in distal airways	ND	EPA 1993
> 3800	2 h	Decreased lung function, increased airway resistance	healthy	EPA 1993
> 4700	2 h	Pronounced decrease in pulmonary function	healthy	WHO 2000
9000	2 h	Clear effects: airway resistance increased by 40-60%	healthy	Berglund et al. 1993

[a] COPD = chronic obstructive pulmonary disease; ND = not determined.

In most animal studies, a long-term (1 to 6 months) exposure to a rather high NO_2 concentration of 560 to 940 µg/m^3 is required to alter lung structure, metabolism, or the pulmonary defence system. The effects are considered to be attributable more to the actual NO_2 concentration (high peak levels) rather than the duration of exposure or the total dose (WHO 1987), whereas in epidemiological studies the significances of high peak exposures and long-term exposures have not been clarified (Berglund et al. 1993). Hälinen et al. (2000a and 2000b) have shown a dose-dependent decrease in guinea-pig lung function after consecutive 10-min combined exposures to cold air and 1800-7000 µg/m^3 of NO_2, and an attenuation of the response during a continuous 1-h exposure.

Limit and guideline values

The short-term guidelines are based on the relatively small effects found in asthmatics and COPD patients observed in the NO_2 range of 360-560 µg/m^3 (0.2-0.3 ppm) in clinical studies. The WHO 1-h guideline value of 200 µg/m^3 has been set with a 50% margin of safety (WHO 1995 and 2000). The coinciding adverse respiratory effects of cold climate have contributed to the tighter guideline in Finland (Sarkkinen et al. 1993). The Finnish occupational limit values for 15 min (11 000 µg/m^3) and 8 h (5700 µg/m^3) exposures are much higher than the outdoor guidelines (Table 4).

Table 4. Guideline and limit values for NO_2 in the outdoor air and in occupational settings in Finland, Europe, and the United States.

Averaging time	Finland 1996	WHO Europe 2000	EU 2010^b	USA 1990
Outdoor air (µg/m^3)				
1 h	150	200	200	
24 h	70			
year	40^b	40	40	100
Occupational (µg/m^3)	(2002)			(2000)
15 min	11 000^a			9 400^a
8 h	5 700^a			5 600^a

^{a}limit value; ^{b}limit values to be met by 2010

2.2 Sources of CO and NO_2 in ice arenas

Ice arenas are special indoor environments. The arenas usually enclose an ice rink which is 26-30 meters wide and 56-61 meters long. The refrigerated floor is covered by an ice layer and surrounded by boards. The ice is kept at a temperature of -4 to -8°C, and the indoor air (usually -2 to +10°C) may be colder or warmer than the outdoor air depending on the climate and season. The arena volumes range from 10

000 to 250 000 m^3 and, correspondingly, there are varying numbers of spectator seats around the rink. The ventilation system may consist of mechanical units for air exhaust, air supply, recirculation, and drying, or some of these in combination. It is not unusual that the ventilation systems of ice arenas are inadequate or they are not operated appropriately. A total of 100-500 users visit the arenas daily during 10-16 occupied hours (Garcia 1986, Brauer et al. 1997).

The number of ice arenas in Finland has increased rapidly, from 83 in 1994 to 170 in 2000, in response to the popularity in indoor ice sports. There are over 3000 arenas in Canada (Hockey Canada 2004) and approximately 1000 in USA. The International Ice Hockey Federation has over 60 national member associations (IIHF 2004).

2.2.1 Ice resurfacing

The main sources of air pollutants in ice arenas are the internal combustion engines of the mobile equipment used in the care of the ice. Resurfacing (shaving and flooding) of the ice is done with an ice resurfacer that is usually powered by a regular gasoline or gas engine similar to the kind found in motorcars. The resurfacing of the ice sheet takes 10 to 15 minutes and it is usually done at 1 to 1.5-h intervals in order to maintain good quality ice. An international survey reported an average of 7-9 daily resurfacings during weekdays and 10-12 daily resurfacings during weekends (Brauer et al. 1997).

The vast majority of ice resurfacers use combustion-powered engines. In a survey of 332 arenas in 9 countries in 1997, 59% of the resurfacers were fuelled with propane, 28% with gasoline, and only 3% were electric (Brauer et al. 1997). Propane-fuelled engines usually emit less CO, hydrocarbons and particles than gasoline-fuelled engines (Clarck 1988), but they may produce more nitrogen oxides (NO_x) because of their higher combustion temperature. In general, CO is produced from incomplete combustion whereas NO_x is formed during optimal combustion at high temperatures. In the early study of Anderson (1971), the concentrations of CO and NO_2 in the exhaust gas of 28 ice resurfacers fuelled with gasoline or liquefied petroleum gas (LPG) were measured. The observed range of exhaust CO concentrations was higher in gasoline-fuelled (5 - 12 %) than in LPG-fuelled (1.6 -5.9 %) resurfacers. The ranges of NO_2 concentrations in the exhaust gas were 1.3 - 84 ppm for gasoline-fuelled and 36 - 82 ppm for LPG-fuelled resurfacers. Current gasoline-fuelled car engines generally have much smaller emissions of pollutants except for NO_x. In Finland, the CO limit value in the exhaust gas at idle run is 3.5% for gasoline-fuelled non-catalyst cars and 0.5% for catalyst cars (0.3% at 2000 rpm) (A-Katsastus 2004), but the NO_x emissions are not regulated.

2.2.2 Other sources

Cleaning the edges of the rink is usually done with a separate machine, an edger, which resembles a lawnmower and has a small, gasoline-fuelled two-stroke engine. The edger may also be an integral part of the resurfacer in newer machines. The practices vary between arenas, but usually a 5 to 30-min edging per day, or a longer period once or twice a week, is required. Since the edger in most cases has a two-stroke gasoline-fuelled engine, it is a significant source of CO, but it also contributes to the NO_2 concentration (Brauer et al. 1997).

Gas-fired space heaters may emit considerable amounts of CO, but their use in the United States is nowadays less frequent than in the 1960's and 1970's (Anderson 1971), and in Finland they are not used at all. Outdoor air may be a major source of indoor CO and NO_2 in polluted urban areas. In ice arenas however, the I/O-ratios of NO_2 were above 1 in 95% of the 332 arenas with the mean I/O-ratio of 20 indicating a major indoor source predominance (Brauer et al. 1997).

2.3 CO and NO_2 concentrations in ice arenas

2.3.1 CO concentrations

Table 5 summarises eight studies on CO concentrations in a total of 58 ice arenas, which were mostly located in North America. The information on the arenas and ice resurfacers is limited, and the CO measurement methods and averaging times vary considerably. Consequently, most reported values cannot be directly compared with the air quality guidelines and limit values. However, the upper range of the measured CO concentrations has been very high, well above 115 mg/m^3 (100 ppm), and this includes also studies done in the 1990's. The average CO concentration in the seven studies in North America ranged from 31 to 126 mg/m^3 (27 to 110 ppm) with an approximate mean of 58 mg/m^3 (50 ppm). Many studies reported inadequate ventilation as the cause for the high CO levels (Table 5).

Lee et al. (1994a) reported a mean of 52 mg/m^3 (45 ppm) and a range of 5-130 mg/m^3 (4-117 ppm) for the 2-h game average CO concentrations measured in seven indoor ice arenas in the Boston area. The resurfacers were propane-fuelled, but the authors provided no information on arena volumes or ventilation. A mean (range) game average CO concentration of 40 mg/m^3 (35 ppm) (5-116 mg/m^3; 4-101 ppm) was measured in nine arenas in Vermont. The ventilation system was missing or not in use in six arenas, and all but one arena were using propane-fuelled resurfacers (Paulozzi et

Table 5. A summary of CO surveys in ice arenas. The arithmetic mean (range) of CO concentrations along with information on the arena and resurfacer are shown.

Location	Number of arenas	Arena information[a]	CO mean (range) mg/m^3 [b]	Comments (resurfacer fuel[c], sampling method)	Reference
Hong Kong	3	small, ventilation used	4.5 (3-7)	propane 1, gasoline 2	Guo et al. 2004
Boston	7	NA[d]	52 (5-130)	all propane-fueled; game average CO	Lee et al. 1994a
Vermont	9	Ventilation: on 3, off 4, missing 2	40 (5-116)	propane 8, gasoline 1; game average CO	Paulozzi et al. 1993
Etobicoke, Ontario	4	8400-20000 m^3; ventilation off	31 (3-126)	CO samples (momentary)	Kwok 1983
Wayne County, Michigan	4	27000-32000 m^3; ventilation off	32 (3-65)	NA	Davis & Drenchen 1979
Boston area	7	NA	57 (26-103)	NA	Spengler et al. 1978
King County, Washington	6	NA	126 (14-290)	Maximum CO sample	Johnson et al. 1975
Minnesota	18	NA	72 (13-230)	CO sample after resurfacing	Anderson 1971

[a] Ventilation = mechanical units for air exchange; [b] The reported ppm-values in the original publications have been transformed to mg/m^3-values by multiplying with 1.15; [c] Number of arenas with propane- or gasoline-fuelled resurfacers; [d] NA = not available.

al. 1993). In a large, mechanically ventilated ice arena with a gasoline-fuelled resurfacer in Helsinki, the peak CO values ranged from 40 to 145 mg/m^3 (Pönkä et al. 1997).

2.3.2 NO_2 concentrations

The air quality surveys in ice arenas reveal a large range of NO_2 concentrations as well as large variations in the study designs (Table 6). The weekly average NO_2 concentration has ranged from 2 to 5000 µg/m^3 (1 to 2680 ppb), with study means from 300 to 430 µg/m^3(160 to 228 ppb) (Brauer and Spengler 1994, Yoon et al. 1996, Brauer et al. 1997). The NO_2 concentrations for shorter (2-17 h) averaging times have exhibited a larger range from 0 to 7000 µg/m^3 (0 to 3720 ppb) and study means between 130 and 2300 µg/m^3 (116 and 1240 ppb) (Paulozzi et al. 1993, Lee et al. 1994a, Berglund et al. 1994, Levy et al. 1998, Thunqvist et al. 2002, Guo et al. 2004). The reported concentrations are not directly comparable with the air quality guidelines, but the upper range seems clearly to exceed the outdoor air guideline or limit values (Table 4). In all the studies, the majority of the ice resurfacers were powered by combustion engines. Propane was the most common fuel, but gasoline was also rather frequently used. Another proposed reason for the high NO_2 levels was inadequate ventilation, although the studies provided limited information on ventilation practices (Table 6).

2.3.3 Factors contributing to air quality in ice arenas

Ice resurfacer

The ice resurfacer is the largest single source of indoor air pollutants in the ice arena (Anderson 1971, Brauer et al. 1997). Propane or LPG-fuelled resurfacers have been found to produce NO_2 levels that are 1.3-1.7 times the levels associated with gasoline-fuelled resurfacers (Anderson 1971, Brauer and Spengler 1994, Yoon et al. 1996, Brauer et al. 1997). In a 3-year follow-up study, the mean NO_2 concentrations for arenas with propane, gasoline, and electric resurfacers were 390, 250, and 70 µg/m^3, respectively (Levy et al. 1998). On the other hand, CO emissions were generally higher from gasoline engines than propane engines (Clarck 1988). Consequently, there are suggestions but no direct evidence that the CO concentrations are generally higher in arenas with gasoline-fuelled resurfacers than in arenas with propane-fuelled resurfacers (Johnson et al. 1975, Paulozzi et al. 1993). Diesel engines have accounted for about 10% of resurfacers and been associated with lower NO_2 concentrations than gasoline- and propane-fuelled resurfacers (Brauer et al. 1997), but they may emit much more particles. Electric resurfacers do not produce exhaust emissions but they have constituted only a few percents of all of the resurfacers in use worldwide.

Table 6. NO_2 surveys in ice arenas. The arithmetic mean and the range of NO_2 concentrations are shown.

Location	Number of arenas	Arena information[a]	NO_2 mean (range) µg/m^3	Comments (NO_2 averaging time; resurfacer fuel[d])	Reference
Hong Kong	3	small, ventilation in use	130 (58-242)	15-min samples; propane 1, gasoline 2	Guo et al. 2004
Sweden	15	NA	170 (2-1015)	1-day NO_2; propane 9, electric 6	Thunqvist et al. 2002
Boston, USA	19	300 to 2000 rink users per day	220 (0-1500)	3-year follow-up; 7 to 17-h NO_2; propane 5, gasoline 6, electric 8	Levy et al. 1998
Nine countries[b]	332	mean volume 40 000 m^3; 16% had no ventilation	429 (2-5040)	one-week NO_2; propane 59%, gasoline 28%, diesel 10%, electric 3%	Brauer et al. 1997
Boston, USA	18	mean seating capacity 327 (50-750)	300 (53-1360)	one-week NO_2; propane 5, gasoline 12, electric 1	Yoon et al. 1996
Northeastern USA	70	mean seating capacity 1228 10% had no ventilation	338[c] (4-4640)	one-week NO_2; propane 47%, gasoline 53%	Brauer & Spengler 1994
Boston, USA	7	NA	2100 (643-5130)	2-h NO_2; propane 6, gasoline 1	Lee et al. 1994a
Sundsvall, Sweden	2	ventilation not in use	2330 (73-7000)	12-h NO_2	Berglund et al. 1994
Vermont, USA	6	5 arenas had no ventilation	677 (0-2290)	game average (2h); propane 5, gasoline 1	Paulozzi et al. 1993

[a]Ventilation = mechanical units for air exchange; [b]Canada, China, Czech Republic, Denmark, Finland, Japan, Norway, Slovakia, USA; [c]Median value; [d]Number or percentage of resurfacer fuel types.

Brauer et al. (1997) have reported a trend that a higher number of resurfacing operations per day was associated with a higher NO_2 concentration. In a single arena, a reduction of daily resurfacings from 14 to 9 had only a minor effect on CO and NO_2 concentrations (Lee et al. 1994b). In practice, it is not possible to reduce the number of resurfacings to any significant extent without compromising the quality of the ice. Tuning of the resurfacer engine has decreased NO_2 levels in some arenas (Levy et al. 1998). The contribution of the ice edger to CO or NO_2 concentrations has not been investigated.

Ventilation and volume of ice arena

In a study of 70 ice arenas, Brauer and Spengler (1994) have shown that arenas without ventilation systems had higher NO_2 concentrations than those with ventilation systems (geometric means 607 vs. 291 $\mu g/m^3$). Lee et al. (1993) have reported that a fully effective and functioning mechanical ventilation system together with a reduced number of resurfacings could decrease the CO and NO_2 levels in an ice arena to 10-15% of the previous values. Somewhat conflicting results were obtained in an international study, in which arenas without mechanical ventilation had a lower mean NO_2 concentration than those with mechanical ventilation, and arenas with dehumidifiers only had the highest NO_2 concentrations (Brauer et al. 1997).

In the same international study, no linear association between the arena volume and NO_2 concentration was found, even though only a few of the larger arenas had elevated NO_2 concentrations. The analysis was probably confounded by several simultaneously contributing factors and by use of seating capacity as a surrogate for arena volume in some arenas (Brauer et al. 1997).

2.4 Exposure to and health effects of CO and NO_2 in ice arenas

2.4.1 Activities in ice arenas

Ice hockey is the most common sport played in ice arenas and involves a large number of people, mostly adolescents, undertaking intensive training. In Finland, ice hockey players use up approximately 60% of training time in ice arenas. In a 60-min game (stop-time), a player intermittently performs for a total of 15 to 25 min, the total duration of the game being 2-2.5 hours (Montgomery 1988). In training sessions that last 60 to 90 min, the active proportion of time is higher. Professional and other elite players have a training session or a game on practically every day of the week during the season. Teams in the Finnish National League played 65 games and had on average 180 training sessions (180-220 h) on the ice during a single season (Mölsä et al. 1997). Finnish junior players aged between 14 and 20 years train on average for 8 h per week.

The average player's heart rate values during skating are approximately 85% of the individual's maximal heart rate, while during resting periods, heart rate drops to about 55-60% of the maximum. Minute ventilations are also high (frequently over 100 l/min) as oxygen uptake may be above 90% of the maximal oxygen uptake for approximately half of the 60-minute game (Montgomery 1988).

In Finland, there are over 60 000 registered ice hockey players, of whom about 45 000 are younger than 19 years. In addition, there are about 120 000 recreational players. It is noteworthy that it is the junior players who tend to train and play in small ice arenas and thus they are the most at risk of being exposed to poor quality air. There are approximately 540 000 registered ice hockey players in Canada (Hockey Canada 2004) and 490 000 in the United States (USA Hockey 2004).

Other skating sports involve much fewer persons than ice hockey. In Finland, rink ball (about 12 000 registered players), figure and synchronised skating (2 200), ringette, short track skating, and curling are practiced in ice arenas. Ice arenas usually have 3 to 6 maintenance workers who work in two 7- to 8-h shifts. Only part of the working hours is spent inside the rink, but high peak exposures to CO and NO_2 are possible when the employee is driving the resurfacer or using the edger. Each year about 3.5 million spectators attend the ice hockey games arranged by the Finnish Ice Hockey Association. Among the spectators, susceptible groups such as patients with cardiovascular or respiratory disease, pregnant women, and children may be at risk due to indoor air pollution.

2.4.2 Health effects of CO in ice arenas

CO levels in poisonings

The CO concentrations observed in connection with epidemic CO poisonings in ice arenas have been generally higher than the concentrations in air quality screening surveys. The CO concentration in a total of 13 cases (in 8 reports) has ranged from approximately 60 to 400 mg/m^3 (50 to 350 ppm). The concentrations have usually been estimated or measured some time after the incident. However, the highest reported CO concentration of 400 mg/m^3 (350 ppm) was measured at the time of an incident (Hampson 1996), which suggests that the reported values in most cases have underestimated the actual exposure (Table 7).

Table 7. A summary of exposure and symptoms in the reported cases of epidemic CO poisonings.

Location	Number of subjects	Activity	Estimated CO concentration (mg/m^3)	Symptoms	COHb in blood (%)	Reference
Seattle, WA	78 (in EDs)	skating	max. 400	fatigue, headache, dizziness	mean 8.6% (3.3-13.9%)	Hampson 1996
Wisconsin	63 (11 in EDs)	game	CO 170; NO_2 2800 µg/m^3	respiratory (23); CNSS (6); both (34)[a]	NA	Smith et al. 1992
Vermont	40 (25 in EDs)	game	> 54	headache, nausea	8.9% (5.4-13.0%)	Paulozzi et al. 1991
Fairfax, Virginia	1	work	> 115 (exposure 10 hrs)	headache, dizziness, fatigue	30%	Miller et al. 1989
Québec, Canada	170 (in 6 cases)	game / skating	57-180	headache, nausea	NA	Andre et al. 1988
Pennsylvania	15	game	~115	nausea, lethargy, headache	9.8% (n=1), estimated max. 35%	Russel et al. 1984
New Westminster, Canada	15	game	> 115	headache, dizziness, stinging eyes	NA	Coueffin 1981
King County	15	skating	200-300	headache, nausea	NA	Johnson et al. 1975

[a] Also NO_2 poisonings; ED = emergency department or other medical care; CNSS = central nervous system symptoms.

Table 8. Ice arena characteristics in the reported cases of epidemic CO poisonings.

Location	Ice arena characteristics	Resurfacer fuel	Likely (reported) cause of high CO levels	Reference
Seattle, WA	2-rink arena, bingo hall upstairs; ventilation possibly off	propane	resurfacer malfunction + inadequate ventilation	Hampson 1996
Wisconsin	improper air intake	NA	inadequate ventilation (air intake)	Smith et al. 1992
Vermont	NA	propane	ventilation turned off; idling car ouside arena	Paulozzi et al. 1991
Fairfax, Virginia	insufficient ventilation	gasoline	high emissions	Miller et al. 1989
Québec, Canada[a]	6 arenas, 8 500-55 000 m^3	propane 3, gasoline 2	resurfacer emissions	Andre et al. 1988
Pennsylvania	no air exhaust system	gasoline	high emissions+ no ventilation	Russel et al. 1984
New Westminster, Canada	volume 17 000 m^3; no ventilation system	gasoline	resurfacer malfunction	Coueffin 1981
King County	inadequate ventilation	propane	NA	Johnson et al. 1975

[a] Six incidents between 1979 and 1985.

The eight reports on a total of 13 incidents of CO poisonings emphasize a number of common features despite the limited amount of information given. In the majority of cases, the main suspected or confirmed cause for high CO concentration was a combination of high resurfacer emissions and insufficient ventilation in the arena. More specifically, in two cases there were no ventilation units in the arenas, and in two cases the mechanical ventilation had been turned off (Table 8).

The CO emissions in the resurfacer exhaust were suspected to be abnormally high in the majority (9 out of 13) of cases, but only in two cases was a definite fault in the resurfacer reported (Table 8). The resurfacer was fuelled with propane in six cases and with gasoline in five cases (2 unknown). The volumes of the arenas are indicated in two reports, being 17 000 m^3 and 8 500-55 000 m^3 (6 arenas). Based on the descriptions of the cases and the exposed subjects, most of the other arenas were also small (<30 000 m^3) (Table 8).

CO poisonings

The reported health effects of CO consist almost entirely of cases of epidemic poisonings in North America (Johnson et al. 1975, Coueffin 1981, Russell et al. 1984, André et al. 1988, Miller et al. 1989, Paulozzi et al. 1991, Smith et al. 1992, Hampson 1996). The number of involved subjects per case has ranged from 1 to 78. In at least three cases, some of the victims went or were taken to emergency departments. The most common symptoms were headache, nausea, and dizziness. The reported COHb values varied around 10% (maximum 30%), and they were usually measured several hours after the exposure had ended (Table 7). Since the elimination half-time for CO in human blood is 4-5 hours at rest (Maynard and Waller 1999), the maximum COHb levels may have been much higher, around 30-35%, as estimated in one report (Russell et al. 1984).

So far, the most serious epidemic CO poisoning involved 78 subjects who were taken to emergency departments due to headache, dizziness, and fatigue. The ice arena was evacuated after a maximum CO level of 400 mg/m^3 (350 ppm) was detected. The COHb values of subjects ranged from 3.3% to 13.9%, and two subjects were intubated at the site (Hampson 1996). In another case, 38 high school students and 8 adults suffered from the typical symptoms of CO poisoning after an ice hockey game. The COHb levels of 25 subjects seeking medical care ranged from 5.4% to 13% (Paulozzi et al. 1991).

2.4.3 Health effects of NO_2 in ice arenas

NO_2 levels in poisonings

The NO_2 concentrations reported in association with epidemic poisonings have usually been estimated or measured some time after the incident and, therefore, they are approximate values that may underestimate the actual concentrations at the time of the poisoning (Table 9). The NO_2 levels in these ice arenas have been at least 2800 µg/m^3 (1.5 ppm), and the highest estimates are over 7500 µg/m^3 (4 ppm). The most common explanation for the high NO_2 level has been inadequate or lacking ventilation (Table 10). Two studies out of six have suggested that the resurfacer had emitted excess amounts of nitrogen oxides.

Health effects of NO_2 in ice arenas

There have been at least six reported cases of epidemic NO_2 poisonings in ice arenas (Tables 9 and 10). The poisonings occurred during an ice hockey game or a tournament, and the most common symptoms have been cough, shortness of breath, haemoptysis, and chest pain (Dewailly et al. 1988, Hedberg et al. 1989, Smith et al. 1992, Soparkar et al. 1993, Morgan 1995, Karlson-Stiber et al. 1996). One case report described two diagnoses of toxic pneumonitis (Karlson-Stiber et al. 1996), and another severe case described almost 100 subjects seeking medical care (Hedberg et al. 1989). In these two cases, the subjects were treated with oxygen, corticosteroids, and antibiotics. The typical case of epidemic NO_2 poisoning seems to feature a propane-fuelled resurfacer and inadequate ventilation. In addition, most poisonings have occurred in arenas used by school teams or recreational players, which suggests that the involved arenas have been small.

A high prevalence of exercised-induced asthma (15-19%) and a high incidence of bronchial hyperresponsiveness (24-35%) have frequently been found among ice hockey players and figure skaters who train in enclosed ice arenas (Mannix et al. 1996, Leuppi et al. 1998, Thunqvist et al. 2002, Lumme et al. 2003). Recurrent exercise-induced bronchial symptoms have been reported by as many as 52% of the players (Lumme et al. 2003). These findings have most often been explained by a combination of intense exercise and vigorous breathing of cold, dry air. However, post-exercise wheezing and nasal symptoms among junior ice hockey players have also been claimed to be associated with the NO_2 concentration present in the ice arenas (Thunqvist et al. 2002).

Table 9. A summary of exposure and symptoms in the reported cases of epidemic NO_2 poisonings.

Location	Number of subjects	Activity	Estimated NO_2 concentration μg/m^3	Symptoms	Reference
Stockholm, Sweden	55 (2 pneumonitis)	game	> 2000	cough, chest pain, shortness of breath	Rosenlund & Bluhm 1999; Karlson-Stiber et al. 1996
Ontario, Canada	1	game	7000	shortness of breath, cough	Morgan 1995
Saskatoon, Canada	ND (1 severe case)	tournament	NA	cough, hemoptysis	Soparkar et al. 1993
Wisconsin, USA	63 (11 in ED[a])	game	NO_2 2800 CO 170 mg/m^3	respiratory (n=23); CNSS[b] (6); both (34)[c]	Smith et al. 1992
Minnesota, USA	116 (92 in ED)	game	> 7000	cough, shortness of breath, hemoptysis	Hedberg et al. 1989
Quebec, Canada	9	tournament	~ 5000	cough, dyspnea, polypnea, suffocating feeling	Dewailly et al. 1988

[a] ED = emergency department or other medical care; [b] CNSS = central nervous system symptoms; [c] Also CO poisonings.

Table 10. Ice arena characteristics in the reported cases of epidemic NO_2 poisonings.

Location	Arena information	Resurfacer fuel	Likely cause of high NO_2 levels	Reference
Stockholm, Sweden	<20 000 m^3	propane	ventilation not used	Rosenlund & Bluhm 1999; Karlson-Stiber et al. 1996
Ontario, Canada	two exhaust fans for ventilation	NA	one exhaust fan not working	Morgan 1995
Saskatoon, Canada	NA	NA	ventilation units not in use	Soparkar et al. 1993
Wisconsin, USA	NA	NA	ventilation not in use, resurfacer service neglected	Smith et al. 1992
Minnesota, USA	exhaust fans for ventilation	propane	ventilation not in use, excess emissions	Hedberg et al. 1989
Quebec, Canada	NA	propane	resurfacer malfunction	Dewailly et al. 1988

2.4.4 Other pollutants

Most of the reported health problems in ice arenas during the last 20-30 years have concerned CO and NO_2. However, combustion-powered machinery, particularly diesel- and gasoline-fuelled ice resurfacers, emits also particles and volatile organic compounds (VOC). The VOC consist of a number of different compounds that may cause health effects ranging from irritation to carcinogeneity. The total VOC concentration has been reported to range from 550 to 765 $\mu g/m^3$ in ice arenas in Hong Kong (Guo et al. 2004), and from 340 to 540 $\mu g/m^3$ in one arena in Helsinki (Pönkä et al. 1997).

A mean (range) mass concentration of 42 (28-62) $\mu g/m^3$ of fine particles ($PM_{2.5}$; aerodynamic diameter < 2.5 μm) has been reported from ice arenas in Hong Kong (Guo et al. 2004), whereas a relatively high PM_{10} level (350 $\mu g/m^3$) was measured during an ice hockey game where smoking was allowed inside the arena (Junker et al. 2000). A mean (range) number concentration of 104 000 (42 000-255 000) per cm^3 has been measured for particles smaller than 1 μm in ten arenas in New York (Rundell 2003). The particle number concentration was associated with a decrease in lung function, and it was suggested to play a role in the increased incidence of asthma symptoms suffered by ice hockey players (Rundell 2004a and 2004b).

Decades ago, when ammonia was still broadly used in the ice refrigerating system of arenas, there was the potential for serious health effects due to possible leaking (evaporation) into the indoor air. Ammonia has caused poisonings even in outdoor skating rinks (Maltau 1979). Gas (e.g. propane, liquefied petroleum gas) leaks from gas cylinders may cause accidental health risks due to explosion.

2.5 Control measures in ice arenas

In general, the most effective abatement measures in air pollution control are the removal of the emission source or a substantial reduction (filtering, catalytic converter) in its emissions. A less effective measure is achieved by increased dilution, for example, by increasing the pipe height (outdoor source) or air exchange (indoor source). Finally, influencing subjects' behaviour by better training or the introduction of regulations can reduce human exposure.

2.5.1 Emission control

A replacement of combustion engine-powered resurfacers with electric resurfacers is condidered to be the best solution to indoor air pollution in ice arenas as was already recommended by Anderson (1971). He also discussed catalytic converters as a method to reduce exhaust emissions, but at that time catalyst technology was not well developed. More recently, McNabb et al. (1997) showed an 87% (from 3600 to 470 $\mu g/m^3$) reduction in the NO_2 concentration and a 57% reduction in the CO concentration (from 16 to 7 mg/m^3) after retrofitting of a three-way catalytic converter into a propane-fuelled resurfacer. It was concluded that retrofitting a catalytic converter is, either alone or together with other methods, a practical and affordable option to reduce pollutant concentrations inside ice arenas.

2.5.2 Ventilation

Ventilation of an ice arena is a difficult task for several reasons. Warm or humid inlet air cannot be blown against the ice sheet, the boards enclosing the rink form a natural bowl resisting air movement, the cold ice sheet at the bottom creates a temperature gradient that resists air mixing, new ice arenas are built energy-efficiently and their natural ventilation is low, and resurfacer exhausts are released straight on the ice (Anderson 1971, Garcia 1986). In addition, the use of mechanical ventilation is often neglected because of reasons related to energy conservation or humidity problems (water condensation).

Ventilation and other methods (reduced number of resurfacings, resurfacer tuning, increased ventilation) have been studied as possible means to improve air quality (Lee et al. 1993 and 1994b, Levy et al. 1998). Increased ventilation or resurfacer tuning decreased the mean NO_2 concentration in 8 arenas by 65% (from 770 to 205 $\mu g/m^3$) immediately after the intervention, but the NO_2 levels were virtually back to their original levels after a 2-month follow-up period (Levy et al. 1998). In a single arena, acceptable air quality was achieved only with a maximal air exchange combined with a reduction in the number of resurfacings (Lee et al. 1993). It was concluded that the maintenance of good air quality in ice arenas is difficult as long as combustion engine-powered resurfacers are used and that a surveillance program is needed to maintain the positive effect of abatement measures (Lee et al. 1993 and 1994b, Levy et al. 1998).

2.5.3 Legislation and recommendations

Air quality in ice arenas is covered in most countries by general indoor regulations that are often directly derived from outdoor regulations. However, these do not seem to sufficiently address the problem considering the continuing reports on poor air quality or health problems during the past 30 years. In the United States, two states have specific laws regulating pollutant concentrations in indoor ice arenas (State of Rhode Island 1990, State of Minnesota 1991, Pribyl and Racca 1996).

In Boston, recommendations given in co-operation with local authorities to selected arenas with detected NO_2 pollution produced a marked but not a permanent decrease in the NO_2 levels (Levy et al. 1998). General recommendations concerning the resurfacer and the use of ventilation to improve air quality in ice arenas have been presented earlier (Anderson 1971, Kwok 1983, Paulozzi et al. 1993). Monitoring CO levels has been recommended to prevent CO poisonings and high CO exposures (Sorensen 1986, Miller et al. 1989). One-hour concentrations of 23 mg/m^3 (20 ppm for CO and 470 $\mu g/m^3$ (250 ppb) for NO_2 have been recommended as limit values in arenas (Levesque et al. 1990, Lee et al. 1994b). An ad hoc working group formed by scientists, health officers, and arena managers in Vancouver, Canada, has devised a detailed list of recommendation to be distributed to health officials and arena managers (Brauer et al. 1996).

Recommended limit values for CO and NO_2 concentrations as well as abatement measures studied in ice arenas have recently been reviewed by Pelham et al. (2002). It seems that a sustainable improvement in the indoor air quality of ice arenas has not yet been achieved anywhere as a result of a control and follow-up program or by legislative action.

3 AIMS OF THE STUDY

The specific aims of this thesis were:

1) to characterise the indoor air quality in Finnish ice arenas,

2) to identify factors that contribute to high NO_2 concentrations and to CO poisonings,

3) to evaluate the efficacy of abatement measures to improve air quality in ice arenas,

4) to provide recommendations and to follow up their implementation, and

5) to assess health risks associated with the poor air quality inside ice arenas.

4 MATERIALS AND METHODS

4.1 Selection of ice arenas

The first sample of five ice arenas (I) was selected with the expectation that there would be clear differences in their air quality. The arenas differed from each other in age, volume, and the fuel used by the resurfacers. In the second phase (II), questionnaires were mailed to all 83 Finnish ice arenas at the end of the ice hockey season in February 1994, and measurements of weekly average NO_2 concentration were made in all compliant arenas (n = 77). Identical follow-up questionnaires were mailed to the arenas in 1995 (83) and 1996 (115). The efficacy and feasibility of an emission control technology (ECT) in ice resurfacers were evaluated in 1996 in 16 arenas where the recommended equipment had been installed in 1994 or 1995 (IV). A final follow-up questionnaire with additional questions on recommended abatement measures was distributed in December 2000 (V; n = 170). The Finnish Ice Hockey Association provided the addresses of the ice arenas.

4.2 Study designs

4.2.1 Characterisation of air quality and contributing factors (I, II)

The aim in the study of the five ice arenas was to confirm the source of indoor air pollution, and to focus on short-term concentrations of selected pollutants capable of inducing health effects in users and maintenance personnel of the arenas (I). The concentrations of CO, NO_2, and volatile organic compounds (VOC) were measured during routine training sessions and during a game simulation. Since relatively high NO_2 levels seemed to be a common problem, the weekly NO_2 concentration was measured in all the participating Finnish arenas to obtain an estimate of the indoor concentration range, prevalence of high concentrations, and indoor-to-outdoor (I/O) concentration ratios (II). In addition, technical questionnaires were used to discover the associations of the arena and resurfacer characteristics with the indoor NO_2 concentration.

4.2.2 Abatement measures and their implementation (III, IV, V)

First, an ECT consisting of a lambda-controlled fuel system and a three-way catalyst inside of the ice resurfacer was tested in one arena by means of exhaust emission measurements and indoor air quality measurements (III). Second, the efficacy and feasibility of this technology was evaluated by NO_2 measurements in 1994-1996 in 16 arenas where the ECT had been installed (IV). Third, non-regulatory recommendations were issued to the ice arenas in 1993-94 by publishing reports in Finnish (Salonen et al. 1993 and 1994), mailing information to the arena managers, and lobbying via the Finnish Ice Hockey Association. As a result of subsequent research findings from this thesis, the recommendations were updated in 1996 in a Finnish publication (Salonen et al. 1996) that was again distributed to all arena managers, health and recreational boards of municipalities, and regional health and recreational authorities in collaboration with the Finnish Ice Hockey Association, the Ministry of Social Affairs and Health, and the Ministry of Education. The implementation of the recommendations was evaluated in 1996 (IV) and 2000 (V) by repeating the survey of technical features of arenas using a mailed questionnaire.

4.3 Questionnaire on arena characteristics (II, IV, V)

The managers of the arenas were sent a standardised questionnaire in Finnish (Appendix 1). The age and volume of the arena, and the type and use of the ventilation system were enquired. Questions on the ice resurfacing machinery included the power source/fuel of the resurfacer, the existence of a catalytic converter, and the resurfacing frequency. In addition, the existence and use of a gasoline-fuelled ice edger, possible complaints about the indoor air quality, and recent abatement measures introduced by the arena management were enquired. The final questionnaire in 2000 focused on the recommended abatement measures with additional questions on the resurfacer and ECT properties and maintenance, plans to purchase an electric resurfacer, and other abatement measures.

4.4 Measurement of indoor air pollutants

Indoor air quality measurement devices were usually placed at a height between 1 and 3.5 meters along the skating rink boards, on the scorekeeper’s bench, and in the penalty box (I, II, III, IV). Some measurements were also made inside the ice rink (I). Outdoor measurements were made in the immediate vicinity of the ice arena.

4.4.1 Carbon monoxide (I, III, V)

The CO concentrations were measured and recorded as 1-min average values using comparable portable electrochemical monitors (PAM 2140 BX, Interscan Co, Chatsworth, CA, USA; and Langan L15 CO, Langan Products Inc., San Francisco, USA). In study V, an electrochemical CO-meter (Ecolyzer, Energetics Science Inc., USA) and manual recording of the readings were used because of the high CO level (above 100 mg/m^3). A two-point calibration with zero air and calibration gas (Aga Gas, Lidingö, Sweden) was made before and after every measurement period inside the ice arenas.

4.4.2 Nitrogen dioxide (I-V)

Concentrations of NO_2 and nitric oxide (NO) were continuously measured with a chemiluminescence analyser (Environnement AC 30 M, Poissy, France) and recorded as 1-min average values (I, III). The analyser was calibrated with NO calibration gas (Messer Griesheim, Duisburg, Germany) before each measurement period.

The measurements in a large number of arenas were made with integrating passive samplers including one third of duplicates and field blanks. Most often, Palmes diffusive tubes were used to measure 3-h (I) and weekly (II, IV) average NO_2 levels (Palmes et al. 1976). In studies II and IV, the samplers were mailed to the arenas and the arena personnel did the sampling following written instructions. The collected NO_2 was analysed as nitrite by ion chromatography (I) (Miller 1984) or spectrophotometry (II, IV). The two analysis methods are comparable but ion chromatography is more sensitive (Miller 1984). In general, passive samplers tend to slightly overestimate the NO_2 concentration but agree within 10% with the chemiluminescent measurements (Bush et al. 2001).

In study III, more sensitive badge-type passive samplers (Advantec, Toyo Roshi Kaisha Ltd, Japan) (Yanagisawa and Nishimura 1982) were used to monitor the variation in 14-h (occupied hours) NO_2 concentrations in one arena. The results showed a high correlation (R^2=0.91) with the chemiluminescent measurements (III).

4.4.3 Volatile organic compounds (I)

Volatile organic compounds (VOC) were sampled as two consecutive 90-min sets in tubes containing Tenax TA absorbent (Pasanen et al. 1990). The compounds were analysed with a gas chromatograph (Hewlett Packard 5890 A, Santa Clara, CA, USA) fitted with a mass selective detector (Hewlett Packard 5970). The sample was injected using a cold trap and a thermal desorption technique (Chrompack Thermodesorption Cold Trap Injector, TCT-1, NL). The total VOC content (TVOC) of the sample was calculated as the sum of all detected compounds (I).

4.5 Resurfacer exhaust emission measurements (III)

A commercially available closed loop stoichiometric emission control system (ECT) was installed in the ice resurfacer. The system included equipment for evaporation and mixing of liquid fuel gas (propane), a lambda sensor and an electronic control unit (AFCP-1, IMPCO Technologies, Cerritos, USA), and a metallic three-way catalyst (Kemira Oy, Vihtavuori, Finland).

The operation of the ice resurfacer was simulated in a temperature-controlled (0 to +4°C) laboratory of the Technical Research Centre of Finland by performing 11-min runs at hourly intervals on a chassis dynamometer (Froude-Consine, Worcester, UK). Three series of tests were made to measure the engine emissions without the catalyst in place, with the ECT at factory settings, and with the ECT at optimal settings. The exhaust gas concentrations of CO, nitrogen oxides (NO_x), and hydrocarbons (HC) were measured both continuously and from 11-min samples with a multi-gas analyser (Pierburg AMA 2000, Neuss, Germany).

4.6 Health risk assessment (V)

4.6.1 Epidemic CO poisonings

The information on the four cases of epidemic CO poisonings in Finnish ice arenas in 1988-1997 was mostly collected by personal interviews within a few weeks after the incidents, from reports of local health officials, and from hospital records. In one case in 1992, 76 junior ice hockey players out of a total of about 100 exposed players completed a health questionnaire on the incident, and CO and NO_2 measurements were made during a simulated tournament in the respective arena. The information on the oldest incident was gleaned from a case report published in Finnish (Junnila 1988). Factors common to all four cases were identified and characterised in more detail as possible causes of the poisonings.

4.6.2 NO_2 exposure and respiratory symptoms

A health questionnaire was distributed to 57 registered ice hockey teams with a total of 1082 players in Finnish A, B and C junior series at the end of the training season (March-April) in 1994 (Appendix 2). The completed forms were collected by the team managers and sent to the researchers at the National Public Health Institute. The questions concerned the preceding 6-month period and included the following items: time spent in active training in the team’s home arena (h/week), occurrence of respiratory symptoms during or after training session in the arena, respiratory illnesses (upper and lower respiratory tract infections, fever), medical treatment needed for those symptoms or illnesses, absences from training or games, general health status (allergies, chronic diseases), smoking, and exposure to environmental tobacco smoke. The estimation of pollutant exposure was based on the weekly NO_2 measurements made in 77 ice arenas in February-March 1994 (II).

4.7 Data analysis

The arena characteristics in the questionnaire were grouped into two or three categories before statistical analyses. The ice arenas were grouped according to their volume (small, medium, large) and the ice resurfacers were grouped according to the power source/fuel (propane, gasoline, electric). Two categories were formed for mechanical ventilation in the arena (adequate, inadequate) (II, IV).

In the analysis of air quality data, the 1-min values produced by the CO and NO_2 analysers were calculated as moving averages for 15-min, 1-h, or longer time periods. The 1-week or 14-h average concentrations from the integrating samplers were used as such. The mass concentrations were calculated for 25 °C temperature from the measured volume ratio (ppm) values using the following conversion factors: CO 1 ppm = 1.15 mg/m^3 and NO_2 1 ppm = 1880 µg/m^3 (WHO 1987 and 2000).

The statistical associations between the arena characteristics and the indoor NO_2 concentration were tested either with T-test (two-class variables) or with the analysis of variance (several-class variables). The relative contribution of different variables to the I/O-ratio of NO_2 concentrations was estimated with multivariate regression models (SAS/STAT 1989) (II). The differences between the weekly average NO_2 concentrations measured in eleven arenas in 1994 and 1996 were tested with Wilcoxon's signed rank test for paired samples (IV). The association of several respiratory symptoms with NO_2 exposure was examined by logistic regression modelling (generalised linear models) (SAS/STAT 1989). The model was adjusted for the variables that had an effect of at least 10% on the beta estimate of NO_2 exposure (V). In all the statistical analyses, p-values smaller than 0.05 were regarded as significant.

5 RESULTS

5.1 Characterisation of indoor air pollution in ice arenas

Table 11 shows a summary of the characterisation of the indoor air quality in five selected ice arenas in Finland (I). In addition, CO and NO_2 measurements were conducted in association with one case of epidemic CO poisonings (V) and with the questionnaire survey of a large sample of arenas in 1994 (II).

Table 11. Background information and the highest 1-h (CO and NO_2) and 3-h (TVOC) pollutant concentrations in five selected ice arenas in 1993.

Arena	Opening year	Volume (m^3)	Ventilation system	Resurfacer fuel	CO (mg/m^3)	NO_2 ($\mu g/m^3$)	TVOC[a] ($\mu g/m^3$)
1	1980	81 800	In / out	Propane	23	610	150
2	1972	50 000	In / out	Gasoline	33	270	1200
3	1987	54 500	In / out	Batteries	2	10	140
4	1991	29 200	None	Propane	20	7440	170
5	1991	20 400	In / out	Propane	16[b]	7770	900

[a]TVOC -total volatile organic compounds; [b]mean of manually registered CO monitor readings.

5.1.1 Carbon monoxide (I, V)

In the study of five indoor ice arenas, the temporal variation in the CO concentration followed the use of the combustion engine-powered ice resurfacer indicating that CO was emitted from the resurfacer (I: Figure 2). The CO peaks were not equally clear in each arena, probably due to differences in the CO emissions between the resurfacer engines and in the ventilation rates between the arenas.

In the arenas with combustion-powered resurfacers, the indoor levels of CO were 5-39 times as high as the levels in ambient outdoor air, and they were usually at their highest during the 3-h game simulation when there was frequent ice resurfacing. The maximum 1-h CO concentrations ranged from 20 to 33 mg/m^3 and the 3 to 5-h mean concentrations ranged from 11 to 24 mg/m^3 (I: Table 2). The CO concentration was highest in Arena 2, where a gasoline-fuelled resurfacer was used (Table 11). In this arena, also the Finnish and WHO 1-h guidelines of that time (30 mg/m^3) were exceeded. In Arena 3, where an electric resurfacer was used, the indoor CO concentration was the lowest (1-2 mg/m^3) and was equivalent to the outdoor concentration (I: Table 2).

The estimated CO levels in two cases of epidemic CO poisonings were 140-170 mg/m^3 (V: Table 1). The CO concentration in Case 2 was measured in conditions simulating the actual tournament in which the poisonings took place.

5.1.2 Nitrogen dioxide (I, II)

In the sample of five ice arenas, the short-term variations in NO concentration were strongly associated with the use of a combustion engine-powered ice resurfacer (I: Figure 2), whereas the concomitant NO_2 concentration was much more stable over time. The average NO/NO_2-ratio varied both temporally and from one arena to another. In the smallest arenas (Arenas 4 and 5) the NO/NO_2-ratio was about 1, whereas in the largest arenas (1 and 2) it was around 10 (I: Figure 2).

The NO_2 levels in arenas with combustion engine-powered resurfacers (Arenas 1, 2, 4, and 5) were 6 to 150 times as high as the levels present in ambient outdoor air, and they exhibited a large range from 130 to 7400 µg/m^3. The concentrations in small, tightly built and poorly ventilated Arenas 4 and 5 were 4 to 30 times the concentrations in the larger, better ventilated Arenas 1 and 2 (I: Table 3). The NO_2 concentration was lowest in Arena 3 which utilized an electric resurfacer, and the second lowest in Arena 2 with a gasoline-fuelled resurfacer. The two small arenas (4 and 5) with the highest NO_2 levels utilized propane-fuelled resurfacers.

The effect of the vertical temperature gradient (I: Figure 1) on the vertical distribution of NO_2 concentration was successfully measured in two arenas. Higher NO_2 concentrations were found at 0.5-1.5 meters than at 3-7 meters (I: Figure 3).

In the large sample of Finnish ice arenas (II), the weekly average indoor NO_2 concentrations ranged from 2 to 1838 µg/m^3 (n = 69) with an arithmetic mean of 332 µg/m^3. The geometric mean value was 173 µg/m^3, indicating that there was a positively skewed (log-normal) distribution. The indoor-to-outdoor (I/O) -ratios for all ice arenas ranged between 0.9 and 636 (n=65) with the arithmetic and geometric means of 37.5 and 16.4, respectively. The mean NO_2 concentrations in arenas with propane-, gasoline-, or electrically powered ice resurfacers were 396, 283, and 25 µg/m^3, respectively.

5.1.3 Volatile organic compounds (I)

There were considerable differences between the five selected ice arenas in TVOC concentrations measured both indoors and outdoors. The TVOC concentrations inside the arenas ranged from 140 to 1200 µg/m^3 (Table 11), while the concomitant outdoor concentrations ranged from 8 to 380 µg/m^3. The number of different compounds in the samples varied between 12 and 90, but there were practically no halogenated compounds detected. The alkylbenzenes detected were mainly toluene or di- and trimethylbenzenes. The indoor TVOC and alkylbenzene concentrations were highest in Arena 2 (gasoline-fuelled resurfacer) and in Arena 5 (propane/gasoline-fuelled resurfacer) and, in both of these arenas, the indoor air levels were several times higher than the respective outdoor air levels (I: Table 4).

5.2 Determinants of NO_2 concentration (II)

A total of 77 arenas (93% of 83 arenas) participated in the questionnaire survey conducted in early 1994. About half (51%) of the responding ice arenas were small (volume < 30 000 m^3), 39% of the arenas were medium-sized (30 000 - 80 000 m^3) and the remaining 10% were large (> 80 000 m^3). The majority (66%) of the arenas were less than 10 years old and built in small municipalities being used for training and recreational purposes. These arenas usually had small volumes and they were air-tightly constructed for reasons of energy conservation. The ice resurfacers were fuelled with propane (68%) or gasoline (23%), or they had electric engines (9%) (II: Table 1).

The contribution of several variables (e.g. resurfacer power source/fuel, arena volume, number of resurfacings, use of ventilation) to the I/O-ratio of NO_2 was estimated by statistical modelling. Only the variables with a separate, significant or nearly significant effect on the determination coefficient of the model were included. In Model I, all of the data was taken from the questionnaire, and it accounted for about 75% of the total variation in the I/O-ratio. Due to missing values, 52 arenas (75% of 69 arenas with valid indoor NO_2 samples) could be used in the construction of this model. In Model II, the data for the number of resurfacings and the use of ventilation were actual data recorded by the arena personnel during the NO_2 measurement (II). This model included 45 arenas (65%) and it accounted for about 70% of the total variation in the I/O-ratio.

5.2.1 Resurfacer power source/fuel

There was a highly significant association (p= 0.0001) between the weekly indoor NO_2 concentration and the resurfacer power source/fuel. The arenas with electric resurfacers had the lowest mean NO_2 concentration (25 µg/m^3), which was significantly different from the two other arena types using propane (396 µg/m^3) or gasoline (283 µg/m^3) fuelled resurfacers (II: Table 3). The corresponding median NO_2 concentrations and selected percentiles are shown in Figure 1.

In the statistical modelling taking into account several contributing variables, the power source/fuel was the most important determinant of the I/O-ratio of NO_2 (II: Table 4). The significance was driven by the large difference between the electric and combustion-fuelled (propane, gasoline) resurfacers (Figure 1).

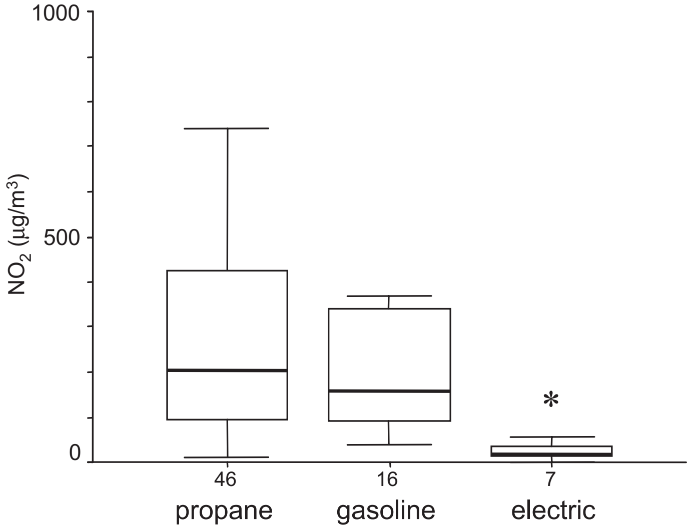

Figure 1. Indoor NO_2 concentration by the resurfacer power source/fuel. The top and bottom of the box indicate the 75 th and 25 th percentiles, and the upper and lower whiskers indicate the largest and smallest measured values within one interquartile distance from the 75 th and 25 th percentiles, respectively. The line inside the box indicates the median value and the numbers below the x-axis indicate the number of arenas in each power source/fuel category. *Significantly different from the other two categories.

5.2.2 Arena volume

There was a clear but statistically non-significant ($p = 0.10$) association between the weekly indoor NO_2 concentration and the arena volume. The arithmetic mean NO_2 concentrations in small (< 30 000 m^3), medium-size (30 000-80 000 m^3) and large (> 80 000 m^3) arenas were 420, 300, and 150 $\mu g/m^3$, respectively (II: Figure 1).

In statistical models, the arena volume was the second most important contributing factor to the I/O-ratio of NO_2 (II: Table 4). In fact, the resurfacer power source/fuel and arena volume together accounted for most of the variation in the weekly indoor NO_2 concentration in Finnish ice arenas (II: Figure 2). The mean NO_2 concentrations in nine different categories were estimated by linear regression modelling without weighing the regression fit by the number of arenas in each category. In small arenas, the mean NO_2 concentrations in association with the use of propane and gasoline-fuelled resurfacers were estimated at 1.7 and 3.4 times the respective concentrations in medium-size arenas, and 3.2 and 9.3 times the concentrations in large arenas.

5.2.3 Other factors

The statistical modelling indicated that the number of daily resurfacings, the presence of a catalyst in the ice resurfacer, and the ventilation of the arena building made weak but significant or nearly significant contributions to the weekly NO_2 concentration (II: Table 4). The arenas underwent a mean of 11 resurfacings per day (range 5-15) in 1994 with more daily resurfacings during weekends than during weekdays. Only 10 resurfacers out of 70 had a catalytic converter, and only six of these were modern three-way catalysts in propane-fuelled engines (13% of all propane-fuelled resurfacers).

There was a wide spectrum of ventilation systems in use in the ice arenas: 12 arenas (16 %) did not have any mechanical ventilation unit for the air supply and 9 arenas (12 %) lacked a mechanical air exhaust unit. The ventilation system of an ice arena was considered as adequate only if it included mechanical units for both air supply and exhaust, and if the units were reported to be used during normal opening hours (Anderson 1971, Ympäristöministeriö 1987 and 2003). According to these criteria, 34% of the arenas did not have adequate ventilation (II: Table 1). The arenas with inadequate ventilation had a slightly higher mean NO_2 concentration than the arenas with adequate ventilation (399 vs. 317 $\mu g/m^3$), but the difference was not statistically significant ($p=0.45$).

5.3 Emission control of ice resurfacer

5.3.1 Operation of emission control technology (III)

In Series 1 (no catalyst) of the emission measurements of ice resurfacer, the exhaust pollutant concentrations (CO: 6200 ppm, HC: 250 ppm, NO_x: 1200 ppm) were typical of a combustion engine that runs with a stoichiometric lambda value (III: Table 1). The emissions of CO and HC were minimal in Series 2 (catalyst with factory settings for an electronical unit), but more than a quarter of the NO_x emissions still remained. In Series 3 (catalyst with optimal settings for an electronical unit), an optimal situation with low emissions of all the measured pollutants was achieved by setting the engine to run slightly rich. The corresponding pollutant concentrations were CO: 600 ppm, HC: 26 ppm, and NO_x: 52 ppm. This compromise increased only modestly CO and HC emissions, and it produced a marked further reduction in NO_x emissions (III: Table 3). In comparison with Series 1, the optimal ECT produced at least a 90 % reduction in the specific emission rates of all the measured exhaust pollutants (Table 12).

Table 12. Emission rates of the propane-fuelled resurfacer and indoor air pollutant concentrations in the ice arena before and after installation of the optimally adjusted emission control technology (ECT).

Pollutant	Before ECT	After ECT	Reduction (%)
Emission rate (g/h)			
CO	730	68	91
NO_x	230	10	96
Indoor air concentration[a]			
CO (mg/m^3)	8.8	1.8	80
NO_2 (µg/m^3)	600	82	86

[a] Mean 14-h concentration during opening hours on 4-6 days.

The indoor CO and NO_2 concentrations in the ice arena were measured in three consecutive periods. In Period I, the mechanical ventilation was standardised for continuous use during opening hours, which alone reduced the mean NO_2 concentration from 6200 to 600 µg/m^3 and the CO concentration from 16 to 9 mg/m^3. In Period II (catalyst with factory settings for an electronical unit), the median 1-h NO_2 concentration decreased from 430 µg/m^3 in Period I to 200 µg/m^3. At the same time, the median 1-h CO concentration decreased from 4.4 to 0.4 mg/m^3. In Period III (catalyst with optimal settings for an electronical unit), the median NO_2 level decreased further to 58 µg/m^3 (86% reduction from the level in Period I), and the CO level (1.5 mg/m^3) was elevated only slightly from Period II. In Period III, there were no longer any incidents when the values exceeded the national indoor air guideline values for either NO_2 or CO (III: Figure 2). Table 12 shows a summary of the indoor air pollutant concentrations in the ice arena before and after installation of ECT in the propane-fuelled resurfacer.

5.3.2 Follow-up of air quality improvement by emission control technology (IV)

At the time of the follow-up study in 1994-1996, all the electronic units as a part of the ECT were provided by the same distributor in Finland, and they were similar to the one investigated in Study III. All the three-way catalytic converters were not necessarily from the same manufacturer as that examined in Study III.

The long-term effect of ECT resurfacers on indoor NO_2 concentration was measured in seven small and four medium-sized ice arenas in which ECT was installed after the initial NO_2 measurement in 1994. The mean weekly NO_2 concentration in these eleven arenas decreased significantly from 650 µg/m^3 in 1994 to 147 µg/m^3 in 1996 ($p=0.013$; Wilcoxon's paired test). The individual NO_2 concentrations decreased in all but one of the arenas during the 2-year follow-up period, and particularly the occurrence of very high NO_2 concentrations (above 400 µg/m^3) had disappeared (IV: Figure 1). According to the questionnaire data, the use of ventilation units and the number of daily resurfacings in each arena did not change during this period.

For the assessment of the durability of ECT on propane-fuelled resurfacers, the weekly average NO_2 concentration was measured three times during the course of two years in four small and one medium-sized ice arena. The five arenas had ECT already installed in the resurfacer before the first NO_2 measurement in 1994. In these arenas, the NO_2 concentrations remained clearly lower than the mean of 332 µg/m^3 for all the Finnish arenas in 1994 (II). The mean weekly NO_2 concentrations in the five arenas in 1994, 1995, and 1996 were 125, 69, and 161 µg/m^3, respectively (IV: Figure 2). The highest NO_2 concentration (311 µg/m^3) was measured in an arena, where the ventilation was considered to be inadequate.

5.4 Abatement measures in Finnish ice arenas

5.4.1 Non-regulatory recommendations to improve air quality

In order to improve the indoor air quality in ice arenas, the National Public Health Institute of Finland and the Finnish Ice Hockey Association issued recommended abatement measures to the arena managers and local health authorities in 1994. The recommendations, as presented in publications I and III, were as follows: 1) all arenas must have mechanical ventilation systems to provide air exchange; 2) the ventilation units for air supply and exhaust should be continuously used during the opening hours of the arena; 3) all new ice resurfacers should be electric; 4) all combustion engines in the existing resurfacers should be fuelled with propane and retrofitted with a three-way catalyst and a lambda-operated fuel management system; and 5) suspected adverse health effects due to indoor air pollution in ice arenas should be examined in collaboration with local health authorities. In spring 1996, an additional recommendation was given: 6) arenas with any combustion engine-powered resurfacer should have a CO monitor and an indoor alarm system. In addition, an updated list of recommendations was published in 2002 (Salonen and Pennanen 2002).

5.4.2 Follow-up of implementation of recommendations (IV, V)

The total number of indoor ice arenas in Finland increased rapidly during the course of the follow-up years: 83 in 1994, 115 in 1996 and 170 in 2000. The corresponding response rates to our questionnaire surveys were 92, 89, and 75%, respectively. The large majority of 88% of the new ice arenas built in 1991-2000 were small (<30 000 m^3) and, therefore, prone to indoor air quality problems. In 2000, 66% of the responding arenas were small and 57% of them were less than 10 years old (V: Table 4).

The third recommendation stated that all new ice resurfacers should be electric. However, the vast majority, 15 out of 17 (88%) responding arenas built in 1994-1996, had purchased either propane- (9) or gasoline-fuelled (6) resurfacers, while only two arenas had purchased electric resurfacers (IV: Table 2). Of the 45 arenas built between 1996-2000, 31 (69%) had purchased propane-fuelled resurfacers, 2 (4%) gasoline-fuelled resurfacers, and 12 (27%) electric resurfacers. By the end of 2000, only 27% of all the ice arenas had an electric resurfacer (V: Table 4).

The use of ECT on propane-fuelled resurfacers increased from 6 (8%) to 69 (55%) between 1994 and 2000 (Table 13). All of these installations were three-way catalysts with lambda-operated fuel management systems as recommended (III). By the end of the skating season in 1996, 46 (46%) arenas complied with the recommendations concerning the resurfacer (electric engine or propane engine + ECT) (IV: Table 2). The corresponding number in 2000 was 102 (82% of 125) arenas.

Between 1994 and 1996, a relatively high proportion of arenas (33-34%) had inadequate ventilation (IV: Table 1). In 2000, the situation had slightly improved (25%) (V: Table 4). Inadequate ventilation was invariably most common in the small arenas. On the whole, only 32 arenas (34%) in 1996 and 65 (52%) in 2000 complied with all six recommendations including the ice resurfacer characteristics, and the use of mechanical ventilation and CO alarm (Table 13).

Table 13. Implementation of recommended abatement measures as the number (%) of Finnish ice arenas in 1994-2000.

	1994	1995	1996	2000
Total number of responsive arenas	77	77	103	125
Electric resurfacer	7 (9)	7 (9)	9 (9)	33 (26)
ECT[a] + propane in resurfacer	6 (8)	24 (31)	37 (36)	69 (55)
Adequate ventilation[b]	46 (66)	46 (67)	63 (67)	93 (74)
CO alarm	NA[c]	NA	NA	60 (48)
Compliant arenas[b,d]	11 (16)	23 (33)	32 (34)	65 (52)

[a]ECT - emission control technology; [b]Data missing from 7, 8, 9, and 0 arenas in 1994, 1995, 1996, and 2000, respectively; [c]NA - not applicable; [d]Compliant = ice arena had either 1) electric resurfacer or 2) propane resurfacer + ECT + adequate ventilation + CO alarm (only 2000)

5.5 Analysis of health risks (V)

5.5.1 Survey of epidemic CO poisonings

The four cases of epidemic CO poisonings in 1988-1997 shared a number of common features (V: Table 1). All four ice arenas were small (< 30 000 m^3), the combustion engine of the resurfacer did not operate properly, and the ventilation in the arena was grossly inadequate. The combination of these three factors was the reason for highly elevated, acutely toxic CO levels. In addition, all the ice resurfacers were fuelled with propane and all the arenas were very new (less than one year in use).

Children (aged 11-13) were involved in three cases, and in two cases there was a prolonged exposure of 3-9 hours since they were playing in an ice hockey tournament. The vast majority of the affected subjects in all four cases suffered from headache (86-97%) and dizziness (18-78%) (V: Table 1). Nausea and fatigue were also commonly reported. These symptoms made many subjects incapable in continuing with their sports activity. In addition, 18 adult subjects in Case 4 were taken to the hospital overnight for hyperbaric oxygen therapy and clinical follow-up. None of the affected subjects suffered life-threatening symptoms.

5.5.2 Association of NO_2 exposure with respiratory symptoms

A total of 793 junior ice hockey players (73%) returned the health questionnaire (V). The effect of NO_2 exposure was examined by modelling separately the four most prevalent post-exercise symptoms. Rhinitis (prevalence 18.3%) and cough (13.7%) were statistically significantly associated with the estimated NO_2 exposure (Figure 2), whereas mucus production (16.1%) and sore throat (8.3%) exhibited weaker positive associations. The models were adjusted for smoking, asthma, allergy, atopy (infantile eczema), and resurfacer fuel; in other words, all the variables with an effect of at least 10% on the beta estimate of NO_2 exposure. The estimated odds ratios in the prevalences of rhinitis and cough corresponding to an increase of 100 $\mu g/m^3$ NO_2 were 1.54 and 1.62, respectively (V: Table 3).

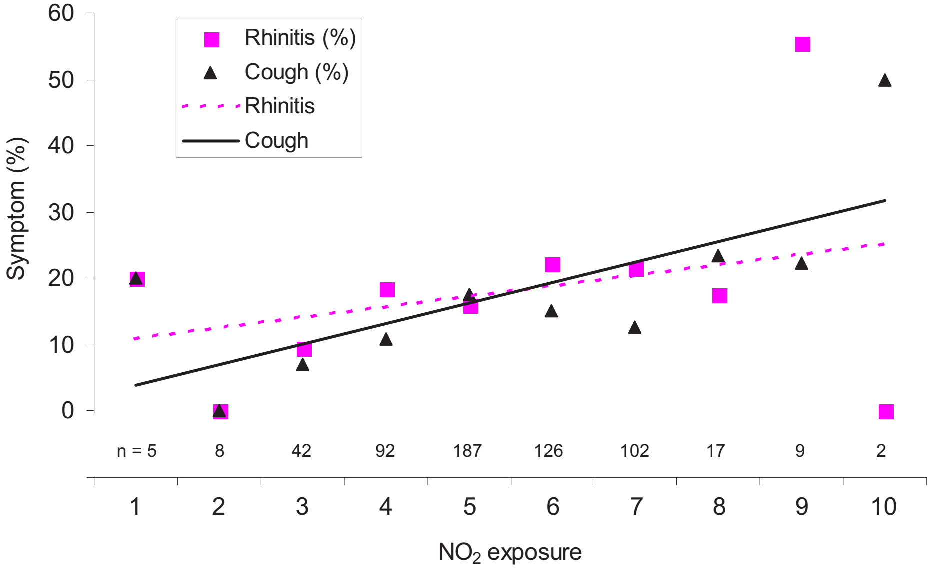

Figure 2. The prevalences of rhinitis and cough by NO_2 exposure. The dashed and solid lines indicate linear fits of the rhinitis and cough prevalence in the regression model. The NO_2 exposure ($\ln(NO_2)\ln(t)$) is divided into 10 categories (NO_2 – nitrogen dioxide concentration in the ice arena; t - weekly training hours by the subject). The numbers above the x-axis indicate the number of subjects.

6 DISCUSSION

6.1 Levels of indoor air pollutants in ice arenas

The CO concentrations were measured only in a limited sample of five arenas. The arenas were, however, selected to represent the entire anticipated range of relevant characteristics in Finland: arena volume, age, ventilation system, and resurfacer power source/fuel (Table 11). None of the arenas was known to have any pre-existing air quality problems and they were studied during normal use and also during a simulated ice hockey game. The 3 to 5-h average CO concentrations (11-24 mg/m^3) in arenas with combustion engine-powered ice resurfacers were clearly higher than the concomitant levels in the ambient outdoor air. In the arena with a gasoline-fuelled resurfacer, the maximum 1-h CO concentration exceeded marginally the Finnish (Ympäristöministeriö 1987) and WHO (WHO 1987) guideline value of 30 mg/m^3. The 8-h guideline of 10 mg/m^3 (Ympäristöministeriö 1987, WHO 1987) was likely to be exceeded more frequently in arenas which had a combustion engine-powered resurfacer, but this guideline is not as relevant as the 1-h guideline because most arena users only exercise for 1 to 1.5 hours at a single time. The occupational limit value for CO was exceeded only in association with CO poisonings.

The CO levels in Finland seemed to be clearly lower than those measured in the United States and Canada (31-126 mg/m^3) (Table 5). One reason for this may be that arenas and resurfacers are newer in Finland (mean age about 10 years in 1994) than in North America (mean age over 20 years). Further, the proportion of gasoline- or diesel-fuelled resurfacers was lower in Finland (23%) than in the United States (41%) (Brauer et al. 1995 and 1997), where most of the CO surveys have been conducted. In general, gasoline engines emit more CO than propane engines (Anderson 1971, Clarck 1988).

In arenas with combustion engine-powered resurfacers, the NO_2 concentrations were 6-150 times (I) and 2-636 times (II) higher than the concomitant NO_2 concentrations in ambient outdoor air. The Finnish (Ympäristöministeriö 1987) and WHO (WHO 1987) guideline values for NO_2 were exceeded by 2 to 20-fold in three arenas with propane-fuelled resurfacers (I). Moreover, the highest measured short-term NO_2 concentrations verged on the occupational limit values (Sosiaali- ja Terveysministeriö 2002). In study II, the highest 1-h average concentrations could be estimated to have been at least twice as high as the measured weekly average values (I) (Brauer et al. 1997). Using that estimate, the 1-h guideline of that time (300 µg/m^3) was likely to have been exceeded in every other arena, and the majority, 65%, of the sampled arenas would have exceeded the current European 1-h guideline value of 200 µg/m^3 (WHO 1995 and 2000).

The NO_2 concentrations in Finland (mean weekly value 332 µg/m^3, hourly values up to 7770 µg/m^3) were comparable to NO_2 concentrations from other countries, where the mean long-term values have been around 300 µg/m^3 (160 ppb) and the short-term values up to 7000 µg/m^3 (Paulozzi et al. 1993, Brauer & Spengler 1994, Lee et al. 1994a, Berglund et al. 1994, Yoon et al. 1996, Brauer et al. 1997, Levy et al. 1998, Thunqvist et al. 2002). In a Swedish study including two ice arenas (Berglund et al. 1994), the highest 12-h and 1-h average NO_2 concentrations were 7000 µg/m^3 (3.7 ppm) and 7900 µg/m^3 (4.2 ppm), respectively.

The I/O-ratios of NO_2 were clearly highest in Finland when analysed in a total of nine countries (Brauer et al. 1997). This may result not only from the relatively low NO_2 levels in ambient outdoor in Finland, but more from the fact that Finnish arenas were new, air-tightly built and rather commonly had poor ventilation. As a result, the NO_2 present in ice arenas could make a large contribution to the total NO_2 exposure of regular arena users. In addition, indoor air pollution tended to be highest in the small arenas built especially for training and games of young ice hockey players and skaters.

In this study, higher levels of TVOC (around 1000 µg/m^3) and alkylbenzenes were found in association with gasoline fuelling rather than with propane fuelling (TVOC 150-170 µg/m^3) in the resurfacer. The recently published results of Guo et al. (2004) agree with our findings. They found a mean TVOC concentration of 800 µg/m^3 and, similarly, higher TVOC values associated with gasoline-fuelled resurfacers than propane-fuelled resurfacers. In addition, Pönkä et al. (1997) measured TVOC concentrations between 350 and 550 µg/m^3 in one ice arena with a gasoline-fuelled resurfacer. Similar or higher TVOC levels (100 to 5000 µg/m^3) have been measured in other indoor environments such as office buildings, homes, and schools (Brown et al. 1994, Batterman and Peng 1995). For comparison, the mean personal 48-h exposure to a sum of 30 VOC species was 200 µg/m^3 among working adults in Helsinki (Edwards et al. 2001). Thus, TVOC levels in ice arenas do not seem to be unusually high as compared with other indoor environments. However, the comparison of results between VOC studies is difficult, because the target compounds and methods used in VOC sampling and analysis are diverse.

6.2 Factors contributing to NO_2 concentrations

It is not surprising that the most important contributing factor to the indoor NO_2 concentration was simply whether the ice arena had a combustion engine-powered or an electric resurfacer. In the multivariate modelling, the other factors (use of ventilation, number of resurfacings, presence of a catalytic converter) showed much weaker contributions. The unescapable conclusion with respect to risk management is that by far the most efficient measure to abate indoor air NO_2 pollution in any ice arena is the replacement of combustion engine-powered resurfacer with an electric machine. The other measures can be expected to provide, at best, only a partial solution to the problem of elevated NO_2 levels.

In the 1970's and 1980's, gasoline-fuelled resurfacer engines were commonly replaced with propane engines because of their generally cleaner exhaust emissions. However, the ice arenas with propane-fuelled resurfacers had the highest indoor NO_2 concentrations in this study, which agrees well with the findings of previous studies from other countries (Brauer and Spengler 1994, Yoon et al. 1996, Brauer et al. 1997, Levy et al. 1998). Generally, the difference between propane- and gasoline-fuelled resurfacers has been small and statistically not significant with only one exception (Levy et al. 1998). Thus, gasoline-fuelled ice resurfacers can produce virtually identical NO_2 levels but, moreover, they usually emit larger quantities of other harmful compounds such as CO, HC, and particles (Clarck 1988).

Arena volume was the second most significant contributor to the I/O-ratio of NO_2 in the present study. This was also an expected result, because approximately similar resurfacer emissions released into a smaller mixing volume should result in higher pollutant concentrations. However, in other studies, the arena volume was not associated with the NO_2 concentration (Brauer et al. 1995 and 1997, Levy et al. 1998). The possible reasons for this contradiction could be, on one hand, that in some studies the seating capacity has been used as a surrogate measure for arena volume and, on the other hand, the relatively modern and possibly more homogeneous, tight construction of Finnish ice arenas. It has also been hypothesised that the actual mixing volume of resurfacer emissions is smaller than the arena volume due to temperature inversion (Garcia 1986, Pelham et al. 2002). Our measurement of the vertical NO_2 distribution in this study does not fully support this view (I). In all, the vertical temperature gradient probably has little effect on the exposure of skaters.

The presence of ECT in the resurfacer made only a small contribution to the NO_2 level in the present multivariate modelling, probably because only six propane engines with modern three-way catalyst technologies were included in our data (II: Table 2). The other four catalysts fitted into the gasoline engines were not likely to effectively decrease NO_x. In individual arenas, an optimally adjusted three-way catalyst technology has very convincingly removed over 90% of the CO, HC and NO_x emissions from a propane-fuelled ice resurfacer as found in this study (III) and by McNabb et al. (1997).

The use of arena ventilation had a small, statistically non-significant contribution to the indoor NO_2 concentration in the present multivariate modelling. The possible reasons for the small contribution include unknown actual air exchange rates, differences between the reported and actual use of ventilation, and misunderstood questions. In other words, the use of a questionnaire for estimation of air exchange rates proved to be inadequate and has given conflicting results also in other studies (Brauer et al. 1997). However, the increased use of mechanical ventilation has been shown to reduce CO and NO_2 levels in individual ice arenas although increased air exchange rate may not alone be sufficient to reduce the pollutant concentrations to acceptable levels (Lee et al. 1993, Yoon et al. 1996). Nonetheless, arenas without ventilation systems have exhibited higher indoor NO_2 concentrations than arenas with ventilation systems (Brauer and Spengler 1994).

6.3 Health risks of CO and NO_2 in users of ice arenas

The health risks in users of ice arenas were examined in three ways: by evaluating the factors that led to epidemic CO poisonings and the health outcomes of the poisonings, by modelling the association of respiratory symptoms with repeated NO_2 exposure in individual arenas, and by estimating the number of arena users that might be exposed to harmful levels of indoor air pollution in ice arenas.

Epidemic CO poisonings

The CO poisonings in the present study can be considered as being quite severe, as headache (86-97%) and dizziness (18-78%) were commonly reported by the affected subjects. The high prevalence of these symptoms and the recorded blood-COHb levels in two cases (8-24%) suggest that the COHb levels were likely to have exceeded 10% in all four cases. Maximal exercise performance deteriorates already at COHb levels of 2-5%, and psychomotor effects (reduced coordination etc.) appear at COHb levels of 5-8% (WHO 1987, EPA 1991). COHb levels exceeding 10% lead to the effects typical of acute CO poisoning (shortness of breath, headache, fatigue, dizziness, nausea, vomiting), when the levels exceed 20% then the effects become very severe (Maynard and Waller 1999, IPCS 1999).

The most important cause of the poisonings in this study was a malfunctioning ice resurfacer. The additional factors common to all four cases were a small arena volume, inadequate ventilation, and very recent opening (less than one year) of the arena. The fact that these arenas were new suggests not only their air-tight construction but also that the arena personnel may have been inexperienced and unaware of the potential air quality hazards, and perhaps not fully familiar with the operation of the resurfacer and ventilation system. This supports the need for adherence to recommendations, instructions and regulations issued by local and national environmental health authorities. It is noteworthy that all four arenas had resurfacers fuelled with propane instead of gasoline. This may indicate not only the prevalence (66-68%) of propane fuelling, but also point to the fact that even slightly malfunctioning propane engines may run apparently well but do not emit any odorous exhaust gases, thus making it more difficult to detect the hazard of increased emissions.

In previous reports on epidemic CO poisonings (Johnson et al. 1975, Coueffin 1981, Russell et al. 1984, André et al. 1988, Miller et al. 1989, Paulozzi et al. 1991, Smith et al. 1992, Hampson 1996), the high CO concentrations ranging from 60 to 400 mg/m^3 were also attributed to a combination of high resurfacer emissions (9 out of 13 cases) and insufficient ventilation (at least 4 cases) in the ice arena. The resurfacer was fuelled with propane in 6 cases and with gasoline in 5 cases (2 unknown). The volume of the arena, when reported, ranged between 8500 and 55 000 m^3. Based on the descriptions of the cases and exposed subjects, it is reasonable to assume that most of the other arenas were small (<30 000 m^3).

On the basis of the existing literature on CO health effects in ice arenas, one might be liable to conclude that adverse effects associated only with epidemic poisonings when more than one unfavourable factor was present simultaneously. However, CO concentrations exceeding the guideline level of 30 mg/m^3 (WHO 2000) have been commonly reported in North America (Kwok 1983, Paulozzi et al. 1993, Lee et al. 1994a). In Finland, the proportion of combustion engine-powered resurfacers (73%), as well as the prevalence of inadequate ventilation (25%) was high, and complaints about indoor air quality were received in 11% of the arenas in 2000. This together with the high minute ventilation of skaters suggests that users of ice arenas may be exposed to CO or other harmful compounds derived from incomplete combustion at levels that are not grossly toxic but may be harmful in a more subtle way, for example impairing their exercise performance and psychomotor functions.

NO_2 exposure and respiratory symptoms

The overall health significance of the NO_2-associated respiratory symptoms in this study seemed to be rather small. The reported symptoms (rhinitis/nasal symptoms, cough, mucus production, sore throat) are also the ordinary symptoms of influenza or common cold, and as such they do not greatly restrict the performance of subjects.

In this study, the odds ratio (OR) of rhinitis corresponding to an increase of 100 µg/m^3 NO_2 was 1.5 (95% CI 1.1-2.3). This is comparable to the odds ratio in nasal symptoms of 1.7 (1.3-2.3) found for the NO_2 difference of approximately 400 µg/m^3 by Thunqvist et al. (2002). However, the plausibility of NO_2 exposure as the direct cause may be questioned since rhinitis is a symptom arising in the upper respiratory tract. When inhaled, NO_2 is preferentially absorbed in the smallest (terminal) bronchioles and the pulmonary region of the lower respiratory tract (Miller et al. 1982, EPA

1993). Cough, on the other hand, can be regarded as a lower respiratory tract symptom that interestingly had a slightly stronger association with NO_2 exposure (OR 1.62, 95% CI 1.1-2.5) than rhinitis in this study.

The potential respiratory outcomes associated with long-term NO_2 exposures in ice arenas include increased asthma symptoms, increased hyperresponsiveness to bronchoconstrictor stimuli, and decreased lung function. In this study, atopy (40%) was rather prevalent among ice hockey players, but asthma (4.4%) was not as prevalent as in some previous studies (15-19%) (Leuppi et al. 1998, Lumme et al. 2003, Thunqvist et al. 2002). Some studies have found about twice as frequent bronchial hyperresponsiveness in ice hockey players (24-35%) as in control subjects (Leuppi et al. 1998, Lumme et al. 2003), and recurrent exercise-induced bronchial symptoms have been reported by as many as 52% of players (Lumme et al. 2003). Moreover, a decrease in lung function was detected in 14 ice hockey players when their site of training was moved from an arena with an electric resurfacer to one with a combustion engine-powered resurfacer (Rundell 2004a).

Since the respiratory outcomes were found at NO_2 levels that may be too low (200-500 $\mu g/m^3$) to cause acute toxicity in healthy subjects (WHO 2000), it has been suggested that fine or ultrafine particles may be the causative agents (Rundell 2003 and 2004a). In that case, NO_2 in this study and in the one by Thunqvist et al. (2002) should be considered more as an indicator of a mixture of resurfacer exhaust emissions rather than a causative agent for health effects. A similar claim has been presented in association with epidemiological research on NO_2 and health in urban environments (WHO 2003).

Users at risk

In 1994, the European 1-h NO_2 guideline value (200 $\mu g/m^3$) (WHO 1995, WHO 2000) was estimated to be exceeded in 65% of the Finnish ice arenas (II). The corresponding estimated number of daily arena users exposed to these high NO_2 levels was 15 000. In 2000, 48% of the arenas did not comply with the recommendations and correspondingly, the approximately 20 000 daily users of these ice arenas were at risk of inhaling poor quality air. The majority of these arenas were small and built especially for training purposes of young ice hockey players and skaters. It is noteworthy that children are thought to be more susceptible than adults to the effects of air pollution including NO_2 (IEH 1996, WHO 1995 and 2000). The prevalence of allergic rhinitis (18%) and asthma (4%) in young ice hockey players in this study may also contribute to their susceptibility to NO_2 (V), since Randell (1997) has shown that repeated short-lasting exposures to NO_2 (500 $\mu g/m^3$) in exercising mild asthmatic subjects cumulatively increased their lower respiratory symptom index (arithmetic mean of dyspnoea, substernal irritation, cough, and sputum production) in a cold environment.

In connection with the occasional cases of very high CO levels leading to acute poisonings, also spectators in these arenas may be at risk. The susceptible groups to CO effects include pregnant women, subjects with ischemic heart disease, and elderly people in general. The highest measured NO_2 values in Finland are comparable to the NO_2 levels of 5000-8000 $\mu g/m^3$ (3-4 ppm) reported in connection with other epidemic NO_2 poisonings (Dewailly et al. 1988, Hedberg et al. 1989, Morgan 1995, Karlson-Stiber et al. 1996). Fortunately, there have been no actual poisonings in Finland, which may suggest that the true NO_2 concentrations during epidemic poisonings may have been higher than those reported, or that no susceptible subjects have played for long enough periods (e.g. a tournament) in arenas with the highest NO_2 levels in Finland.

6.4 Abatement measures and their implementation

The replacement of combustion engine-powered resurfacers with electric ones in Finnish ice arenas has been slower than anticipated. The features that have impaired the popularity of electric resurfacers include their higher price, smaller supply and selection, and some technical problems which occurred in early models. An electric resurfacer costs substantially more than a new combustion-powered resurfacer, and also cheaper, second-hand propane-fuelled resurfacers have become available from other arenas in Finland and Sweden. In 2000, only 32% of arenas with combustion engine-powered resurfacers reported that they intended to purchase an electric resurfacer within the next few years. Consequently, the proportion of electric resurfacers probably will continue to increase slowly, which means that it will be necessary to have effective abatement measures for the long-term use of combustion engine-powered resurfacers.

An ECT in an ice resurfacer can effectively reduce the indoor air pollution, but this requires good adherence to a great many factors. This can be seen in the relative decrements in the various NO_x parameters noted in this study: NO_x emissions from one controlled resurfacer by 96% (III), NO_2 concentration in the corresponding ice arena by 86% (III), and NO_2 levels in eleven arenas applying the same technology by 77% (IV). The decrease in the CO concentration in the single arena was 80% (III). Some of our findings are in agreement with the study of McNabb et al. (1997) reporting 87% and 57% reductions in NO_2 and CO concentrations, respectively. It has been shown that a propane engine is better suited for ECT than a gasoline engine (Nylund and Riikonen 1991, Nylund 1995). The propane engine does not need enrichment with cold-starts, and the exhaust emissions of CO, HC and particles are lower than those from gasoline and diesel-fuelled engines (Clarck 1988). However, the long-term durability of ECT efficiency in the intermittent use of resurfacers has not been studied. In common gasoline-fuelled cars equipped with three-way catalytic converters, the mean NO_x emissions increased moderately from 0.15 to 0.26 g/km (i.e. approximately from 8 to 14 g/h) during 80 000 km of vehicle use (Laurikko 1998). This distance can be estimated to correspond on average to approximately 2-3 years of resurfacer use in Finnish ice arenas.

The number of retrofitted or new ECT in resurfacers increased substantially between 1994 and 2000. In fact, by 2000 the majority (82%) of arenas had either an electric resurfacer or a propane-fuelled resurfacer with ECT. Unfortunately, the other recommendations were not fulfilled in every arena. The ECT was clearly a more favourable abatement option than the purchase of an electric resurfacer, probably due to its much lower price.

The other recommended measures (continuous use of mechanical ventilation, CO monitor and alarm) are complementary to the measures concerning the ice resurfacer, but on their own they are not effective. In the study of Levy et al. (1998), the applied measures (increased ventilation, resurfacer tuning) were effective immediately after intervention, but subsequently the NO_2 concentrations returned towards the original levels. In Finland, the proportion of 25% of ice arenas reporting inadequate ventilation is unacceptably high. Moreover, the actual use of ventilation may differ from the reported average use, e.g. in cases of neglect, difficult (warm and humid) weather conditions, or malfunction. Inadequate ventilation is a common problem also in other countries, as 16% of the ice arenas in nine countries reported an absence of mechanical ventilation units (Brauer et al. 1997).

The installation of CO monitor and alarm system in ice arenas with combustion engine-powered resurfacers is important, because even resurfacers with ECT may fail as occurred in one of our poisoning cases (V). CO monitors became, in fact, rather common by the year 2000 (48%), which may have contributed to the fact that there have been no epidemic CO poisonings since 1997 in Finland.

7 CONCLUSIONS AND RECOMMENDATIONS

The indoor air concentrations of CO and NO_2 in Finnish ice arenas were high when compared with both ambient outdoor air and the national and European air quality guidelines. The pollutant levels in Finnish arenas were comparable to the levels reported from other countries. The NO_2 concentrations were estimated to be continuously high in a large number of arenas, whereas the CO concentrations may be occasionally elevated in some arenas due to abrupt changes in resurfacer or arena operation.

Ice arenas with combustion engine-powered resurfacers had significantly higher NO_2 concentration than arenas using electric resurfacers. Propane and gasoline fuelling were almost the same with respect to NO_2, but gasoline fuelling was associated with a higher CO concentration. Small arenas had higher NO_2 concentrations than larger arenas, and the highest pollutant levels were associated with a combination of a small sized arena and a combustion engine-powered ice resurfacer. The number of resurfacings, the use of ventilation, and the presence of catalytic converter had only minor contributions to NO_2 concentration in our multivariate analysis. Cases of epidemic CO poisonings were characterised by a combination of a malfunctioning resurfacer, small and newly opened arena, and inadequate ventilation.

The best and probably only sustainable abatement solution for indoor air pollution is the replacement of combustion engine-powered resurfacers with electric machines. Retrofitting of ECT in propane-fuelled resurfacers is a feasible option during the transition to electric resurfacers, but this requires careful control of the arena and resurfacer use and maintenance.

A substantial improvement in the overall ice arena air quality was achieved during this study as indicated by the increasing implementation rates of the recommended abatement measures introduced between 1994 and 2000. However, the present non-compulsory recommendations seem to be only partially effective with respect to some ice arenas. Moreover, one unfavourable trend was that most of the new arenas were small and equipped with combustion engine-powered resurfacers which on a long-term basis makes them prone to air quality problems. Consequently, it seems likely that there will be cases where elevated pollutant levels in Finnish ice arenas will exceed the health-based air quality guidelines in the future if no governmental regulatory measures are taken.

A total number of 20 000 daily users of ice arenas were estimated to be at risk of breathing poor quality air. The adverse health effects typical of an acute epidemic CO poisoning were clearly demonstrated in association with infrequent cases, whereas the long-term NO_2 exposure was associated with relatively mild respiratory symptoms.

On the basis of this study and the previously published literature, the following updated list of recommendations can be given to the Finnish ice arenas and similar new arenas all over the world:

1. An electric resurfacer is the best solution to minimize indoor air pollution in ice arenas.
2. Retrofitting of ECT in propane-fuelled resurfacers is an efficient and economical temporary option to reduce engine emissions. However, the use of this technology requires regular (twice per season) service and checks of the engine and the ECT as well as the measurement of exhaust emissions once a year according to regulations given for low-emitting passanger cars. In addition, a CO monitoring and alarm system should be installed in the arena.
3. All other types of combustion engine-powered resurfacers are not acceptable and should no longer be used in ice arenas.
4. Mechanical ventilation should be used at a reasonable air exchange rate (minimum 0.25 h^{-1}) during opening hours in all ice arenas.
5. In arenas where combustion engine-powered resurfacers are used, the personnel should be well trained to understand the risks associated with poor maintenance practices. They should fill in a logbook with information on the resurfacer use, maintenance, and faults as well as the use of ventilation and monitored CO levels.
6. The following immediate measures are advised to be taken on the basis of monitored 1-hour average CO or NO_2 concentrations: a) increase of ventilation at CO concentration above 20 mg/m^3 (17 ppm) or NO_2 concentration above 150 µg/m^3 (0.08 ppm); b) evacuation of ice arena users and spectators at CO concentration above 60 mg/m^3 (50 ppm) or NO_2 concentration above 2000 µg/m^3 (1 ppm), if the elevated pollutant level cannot be effectively reduced within 15-30 min.

Those ice arenas still using combustion engine-powered resurfacers should have an evacuation plan for emergency events due to high CO or NO_2 concentration or epidemic poisonings. Moreover, the arena personnel and ice sports managers should investigate all suspected incidents of adverse health effects in collaboration with local health authorities.

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9 APPENDICES

Appendix 1. Technical questionnaire of ice arenas (in Finnish)

Appendix 2. Health questionnaire in the NO_2 health study among 14 to 21-year-old ice hockey players (in Finnish)