PARTICULATE MATTER AND GASEOUS CONTAMINANTS IN INDOOR ENVIRONMENTS IN AN ISOLATED NORTHERN COMMUNITY

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ABSTRACT

Objectives. Globally, 86% of exposure to particulate matter (PM) occurs indoors. Wood furnaces and smoke curing are known sources of PM in isolated communities in northern Canada.

Study Design. Three homes with wood furnaces, three with oil furnaces, and nine tipis (smoke curing huts) in Deline, Northwest Territories were sampled for carbon monoxide, carbon dioxide, total hydrocarbons, formaldehyde, and for PM of less than 10 microns in diameter (PM_{10}).

Results. All gaseous contaminants were below relevant air quality standards. In contrast, all but one environment had PM_{10} concentrations above standards. The presence of smokers correlated with higher PM_{10} levels within fuel categories. PM_{10} did not differ significantly between heating types (means, 0.12-0.53 mg/m^3). Exposures to PM_{10} in tipis averaged 2.3 mg/m^3.

Conclusion. Residents were exposed to substantial concentrations of PM_{10} from cigarette smoking, wood stoves, and smoke curing. Concentrations were within the range where respiratory symptoms have been observed. Measures to reduce exposure should consider prevention of adverse health effects and preservation of traditional activities.

Key words: Particulate matter, PM_{10}, Indoor air quality, Wood stoves, Smoke curing

INTRODUCTION

Half the world’s population relies on wood and other biomass fuels for cooking and heating. These are predominantly burned in open fires, or simple stoves (1). Concentrations of particulate matter (PM) in poorly ventilated houses can exceed relevant standards (1,2). The
World Health Organization estimated that 86% of global exposure to PM takes place indoors (1). Since most emissions are released into the living area, women and children are at greatest risk (3). Gas- and kerosene-fuelled devices are also sources of indoor pollutants (4).

Ambient air pollution may be responsible for two million excess deaths per year in developing countries (5). Respiratory health effects are also observed at high indoor concentrations of wood smoke (5,6). Recently, the adequacy of current national air quality standards for PM have been questioned, since health effects have been demonstrated at the accepted levels (7,8).

Epstein equated the health status of Aboriginal populations in developed countries with that of developing countries (9). Mortality for respiratory conditions in the Northwest Territories (NWT), where 62% of the population is aboriginal (10), was 34% higher than the national rates (11). Respiratory diseases accounted for >10% of inpatient hospital visits and 25% of visits to community health clinics (10). In an aboriginal community in northwestern Ontario, childhood respiratory infections accounted for almost 50% of all episodes of illness (12).

In the study region, smoke curing of fish and meat is part of the traditional lifestyle. This process is often completed in small huts called tipis. A smoldering fire producing a high smoke density is required (13). Tipis are also used for tanning animal hides. The present study was prompted by concern about the potential for respiratory diseases associated with wood smoke exposures.

MATERIAL AND METHODS

Study location

The study community, Deline (formerly Fort Franklin), is located 544 km northwest of Yellowknife in the NWT. Average January temperatures are –24.0°C and the heating season is from September to May. Access to the community is limited to air services and a winter road. Housing quality in Deline is typical of that in the Western Arctic and below the average for the NWT (14). In 2000, 46% of houses in Deline were classified as having “problems.” Most of these problems related to the suitability of the housing – referring to the number of people in the house relative to the size of the house and the number
of bedrooms. There were six or more people per household in 14.5% of the houses in Deline, compared to 7.8% in the NWT and 11.9% in the Western Arctic. Nearly one-in-five houses (18.5%) in Deline were classified as needing major repairs, compared to 14.3% in the Northwest Territories and 16.5% in the Western Arctic.

In 1994, the population of Deline was 573, with 90% classified as Native Indians. Lifestyles ranged from traditional to modern. Half of the males regularly trapped and hunted, spending up to 10 hours per day outside. Women and children spent most of their time inside during the heating season. Males and females were actively engaged in smoke curing meat and fish, and tanning hides. Ethics approval was obtained from the Ethics Review Board at the University of Alberta.

Housing and tipis
In 1994, 76% of the residents lived in one-family houses (15). Most homes (60%) were built after 1981 and a few (8%) before 1960. More than half of the population (56%) was likely to be exposed to indoor pollutants from oil furnaces and 17% from wood heaters. Only a few (4%) lived in homes heated by electricity. The remaining people used a mixture of these fuels (23%).

The tipis are cone-shaped, with a base diameter of five to seven metres and a height of approximately seven metres. The door is usually open when in operation. Curing of meat and the tanning of hides is usually done from mid-September to mid-October: drying of fish from July to October. Initially, the meat is removed from the hides. The meat is put on a rack located inside the tipi, about 1.5 metres off the ground over the fire, and smoked and dried for 24 hours. Meanwhile, the leather is soaked in a concentration of animal brain tissues to soften the hide, and hung outside to dry. The dry hides are spread over the same rack as the meat and smoked for about a week. For most of this work the occupants take a squatting position, with the head about a metre above ground level. During preparative work, the workers prefer to have the fire pit filled with large quantities of hot coals under light smoke conditions. Later, when the tipis are in full operation, the workers enter the tipi long enough (about 15 minutes every two hours) to ensure that the smoke density is optimal.

Air quality measurements
Sampling was conducted from September 29 to October 3, 1994. Six homes and nine tipis were sampled for carbon dioxide (CO₂), carbon
monoxide (CO), total hydrocarbons (THC), formaldehyde, and for particulate matter of less than 10 microns in diameter (PM<sub>10</sub>).

Three houses with wood furnaces (one with no cigarette smokers and two with smokers) and three houses with oil furnaces (one with cigarette smokers and a five-year old furnace, two with smokers and 25-year-old furnaces) were examined. Standard methods for sampling and analysis were used (16,17). Measurements for gases were taken in the breathing zone at fixed locations. Periodic readings were taken over a 24-hour period using a portable Gastec hand pump (Levitt Safety Limited, Oakville, Ontario) with low-range detector tubes for CO<sub>2</sub> (detection limit: 100 ppm), CO (detection limit: 1 ppm), THC (detection limit: 100 ppm), and very low-range detector tubes for formaldehyde (detection limit: 0.05 ppm). Total suspended particles (TSP; diameter < 25-40 µm) were measured using a 37-mm filter cassette with a PVC filter with 0.8-µm pore size, aspirated for 24 hours at 5 to 10 liters per minute, depending on the dust concentrations (cassette: B30812M, AME, South Dakota; pump: Air-Sample Pump, SKC Inc., Pittsburgh, Pennsylvania). The mass of dust was analyzed gravimetrically (detection limit: 25 µg). Additionally, instantaneous short-term measurements (5-10 minute intervals) of PM<sub>10</sub> were collected using the “Miniram” aerosol sampler (Model PDM3 from MIE Inc., Massachusetts).

The same pollutants were examined in tipis during full operation, using the same devices and procedures described above. Smoke concentrations were measured inside the tipis near the open door and also in the back sections. Breathing zone and general area samples were taken. To obtain vertical smoke density profiles, measurements were made at different heights. For the horizontal profile, samples were taken on the horizontal plane at three feet above the ground, starting five feet outside the door, passing over the smoldering fire and proceeding to the back of the tipi.

Data on tobacco exposure and housing characteristics were obtained by a questionnaire based on an existing instrument (18). Questions on wood smoke exposure were added. Questionnaires were obtained from 78% of the population (15).

Data analysis
Concentrations were expressed as means and standard deviations (SD). Student’s t-test for independent samples was used to compare mean concentrations in different environments. The chi-square test was ap-
plied to test percentages for independence. To measure air exchange rates, PM$_{10}$ concentrations were sampled over time and exchange rates were estimated using the slopes of the decay curves.

**RESULTS**

Houses were generally well heated (temperatures >21°C). Relative humidity was fairly low (35%-40%) (19). Residents often perceived houses as being dry and about one-third periodically used humidifiers (often when someone was ill) (Table I). Environmental tobacco smoke (ETS) was common. Although more than half were non-smokers, most were exposed to ETS. As a proxy for the maintenance status of the houses, the occurrence of drafts during windy weather was assessed. Drafts were more common in oil-heated homes. The occupancy rate (people per heated room) was significantly higher for wood-fuelled residences (1.8) than oil-heated houses (1.5). Air exchange rates for houses were below, or bordered on, recommended standards (i.e., 0.4-0.7 changes per hour (20)). Air exchange rates for tipis averaged 2.4 per hour.

Concentrations of gases in homes and tipis were below standards; concentrations of formaldehyde were below the detection limit (Table II). Levels of CO and CO$_2$ were higher in tipis. Concentrations for THC were moderately elevated in residences.

PM$_{10}$ concentrations were highest in fully operational tipis (2.3 mg/m$^3$), but lower during preparative work (0.43 mg/m$^3$) (Table III).

**Table I.** Characteristics of residents and homes grouped by heating system in Deline, NWT, Canada. All characteristics except ‘air exchange rate’ are from a study described in detail elsewhere (reference 12).

| Characteristics                        | Oil (%) (n=227) | Wood (%) (n=67) |
|-----------------------------------------|-----------------|-----------------|
| **Fuel used for heating**               |                 |                 |
| Oil                                     | 56.0            | 64.2            |
| Wood                                    | 44.0            | 35.8            |
| **Pack-years, mean and SD**             | 7.32 ± 15.64    | 6.93 ± 13.77    |
| **Smoking habit**                       |                 |                 |
| Non-smokers                             |                 |                 |
| Current smokers                         |                 |                 |
| Pack-years, mean and SD                 |                 |                 |
| No exposure                             | 21.0            | 26.2*           |
| < 4 hrs per day                         | 39.7            | 20.0            |
| ≥ 4 hrs per day                         | 39.3            | 53.8            |
| **Environmental tobacco smoke**         |                 |                 |
| No exposure                             |                 |                 |
| < 4 hrs per day                         |                 |                 |
| ≥ 4 hrs per day                         |                 |                 |
| **Use of humidifier**                   |                 |                 |
| Drafts in house                         |                 |                 |
| Number of people sharing a heated room, mean and SD | 1.48 ± 0.82 | 1.82*± 1.01 |
| Number of air exchanges per hour, mean and SD | 0.37 ± 0.10 | 0.17 ± 0.05 |

* p<0.05

a includes ex-smokers and current smokers
Homes with wood furnaces had higher levels of TSP than those with oil furnaces, regardless of the presence of smokers. This was not observed for PM\textsubscript{10}. The presence of smokers correlated with higher mean values within the same fuel category for TSP and PM\textsubscript{10}. Cooking (frying) and a high level of general activity (i.e., walking, cleaning) also increased PM\textsubscript{10} levels. The ratios of ambient particulate levels to their standards were 12.3 for TSP and 1.4 for PM\textsubscript{10} in light, windy conditions.

Concentrations for indoor samples varied substantially (i.e., for houses with old oil furnaces: PM\textsubscript{10} mean: 0.53 mg/m\textsuperscript{3}, SD: 0.81 mg/m\textsuperscript{3}). Mean levels of PM\textsubscript{10} did not differ between housing types. However, 60% of PM\textsubscript{10} readings in residences and 32% of breathing zone samples in tipis were above relevant standards (21,22). Exposures peaked at 2.6 mg/m\textsuperscript{3} in houses and 27.0 mg/m\textsuperscript{3} in tipis.

The horizontal smoke profile of tipis in full operation showed a bimodal distribution (Figure 1). Outdoor concentrations of PM\textsubscript{10} increased near the open tipi door. Above the fire, about a metre in from the door, values peaked for the first time (26.8 mg/m\textsuperscript{3}), and peaked again in the back of the tipi (108.0 mg/m\textsuperscript{3} of PM\textsubscript{10}). Both vertical

| Pollutant | Residential Tipis | Outdoors | Standard |
|-----------|-------------------|----------|----------|
| CO\textsubscript{2} | Oil | Wood | CO\textsubscript{2} |
| 405 ± 137 | 408 ± 58 | 744 ± 627 | 350 | 3500\textsuperscript{a} |
| CO | 2.50 ± 1.38 | 2.83 ± 1.33 | 6.67 ± 6.89 | <1.00 | 11\textsuperscript{a}, 50\textsuperscript{b} |
| Total Hydrocarbons | 374 ± 178 | 292 ± 111 | 172 ± 115 | <100 |
| Formaldehyde | <0.05 | <0.05 | <0.05 | <0.05 | 0.1\textsuperscript{a} |

\textsuperscript{a} 8-hr average for Canadian (8)
\textsuperscript{b} 8-hr, time-weighted average for workplace (18)

Table II. Concentrations of gaseous air pollutants found in residential and occupational environments in Deline, NWT, Canada. Means ± SD are expressed in parts per million (ppm). Some values were below the limit of detection (<).

| Pollutant | Oil-heated Residential | Wood-heated Residential | Tipis | Outdoors | Standard |
|-----------|-------------------------|-------------------------|-------|----------|----------|
| TSP | New furnace Non-smokers | Old furnace Non-smokers | Wood-heated Non-smokers | Smokers |
| 0.16 ± 0.17 | 0.34 ± 0.26 | 0.72 ± 0.35 | 1.14 ± 1.47 | 6.91 ± 4.15 | 0.56 ± 0.65 | 0.15\textsuperscript{a} |
| M/S-Ratio \textsuperscript{b} | 1.1 | 2.3 | 4.8 | 7.6 | 2.0 | 12.3 | 3.5 \textsuperscript{d} |
| I/O-Ratio \textsuperscript{c} | 0.3 | 0.6 | 1.3 | 2.0 | 12.3 | 1.0 | 0.05\textsuperscript{e} |
| PM\textsubscript{10} | 0.12 ± 0.06 | 0.53 ± 0.81 | 0.16 ± 0.06 | 0.32 ± 0.18 | 2.29 ± 3.33 | 0.07 ± 0.01 | 0.15\textsuperscript{a} |
| M/S-Ratio \textsuperscript{b} | 0.8 | 3.5 | 1.1 | 2.1 | 0.7 | 1.4 | 3.5 \textsuperscript{d} |
| I/O-Ratio \textsuperscript{c} | 1.7 | 7.6 | 2.3 | 4.6 | 32.7 | 1.0 | 0.05\textsuperscript{e} |

\textsuperscript{a} Japanese indoor standard for PM\textsubscript{10}(reference 20)
\textsuperscript{b} Measured concentrations divided by referring standard
\textsuperscript{c} Indoor concentrations divided by outdoor level
\textsuperscript{d} Workplace threshold limit value for inorganic carbon particles (reference 22)
\textsuperscript{e} Year-weighted average for ambient PM\textsubscript{10} (reference 23)
profiles showed a maximum concentration at rack-height, about 1.5 metres off the ground: 15.2 mg/m$^3$ near the door and 22.0 mg/m$^3$ in the back (Figure 2). Both concentrations were within, or somewhat above, the adequate smoke concentrations of 9.1-18.2 mg/m$^3$ for curing fish and meat (13). In general, values for the vertical profiles near the door showed lower concentrations than those obtained in the back.

DISCUSSION

All environments were subject to pollution by PM. All except one of the means were above the relevant standards. The concentrations of TSP were lower for houses with oil furnaces than those with wood stoves, regardless of the smoking habits of the occupants. Furnace type did not influence levels of PM$_{10}$. However, smoking resulted in higher mean levels within the same category of furnace. Ambient TSP and PM$_{10}$ were 12.3 and 1.4 times above recommended standards, respectively. For houses without indoor sources of PM, the indoor/outdoor ratio for particulates of outdoor origin were slightly below one, likely due to sedimentation (24). Ratios for PM$_{10}$ and TSP in wood-heated homes were above one, suggesting indoor sources.

Factors that influence indoor air quality are the volume of indoor air space, the sources of air pollutants, the decay rate (i.e., sedimentation, chemical reactions), the air exchange rate, and outdoor concentrations of pollutants (23). Wood stoves are not necessarily a source of indoor
air pollutants. Airtight stoves can be maintained with negligible release of particles (25). Non-airtight stoves, however, are major sources of indoor particulates. Traynor et al. reported indoor concentrations of TSP between 24 and 71 µg/m³ in homes with airtight wood stoves, 28–1500 µg/m³ with non-airtight stoves, and 19–24 µg/m³ in homes without stoves (26).

Many residents of Deline were active smokers, and only about a fourth were unexposed to ETS (15). Burning wood and smoking generate predominantly fine particles (PM$_{2.5}$) (27). After being exhausted or disturbed, fine particles remain airborne for days to weeks, whereas larger particles are suspended for only minutes to days (28). Low air exchange rates prolong the residence time of pollutants inside homes and lead to an accumulation of contaminants from indoor sources. At the same time, low exchange rates prevent infiltration of outdoor pollutants. While most conventional homes have an average air exchange rate of around 1.0 per hour, rates in “tight” homes can be as low as 0.5 per hour during winter and, in “super-tight” homes, between 0.1 and 0.3 per hour (4). The estimated air exchange rates in Deline were similar to those found in “super-tight” homes, with 0.37 exchanges per hour in houses with oil furnaces and 0.17 exchanges per hour for those with wood furnaces. In areas with little industry, ambient PM may primarily consist of earth crustal material and volcanic ash (29), or wind-blown dust (30). In residential areas with a high prevalence of wood-heated houses, wood smoke may account for as much as 90 percent of the particle concentrations during wintertime (31). In Deline, there is no industry and little traffic. Sources of outdoor PM in windy conditions were most likely airborne soil (coarse particles), and exhausts from residential heating systems (fine particles).

The mean smoke density (TSP) for tipis in full operation exceeded the occupational standard for inorganic carbon particles two-fold. The mean PM$_{10}$ value of 2.3 mg/m³, however, was within the accepted levels, yet above the action limit of 1.8 mg/m³. Other studies have shown comparable concentrations of TSP, or respirable particles, for similar locations (32).

In tipis, smoke production depended on the state of the fire. Heat convection and currents of air from the open door dispersed the smoke unevenly. Outside air diluted smoke near the door and allowed smoke to leave. Some smoke was pushed back by heat convection, increasing smoke density at rack level. Lack of fresh air in the back sections resulted in an increased smoke density in these areas.
Although indoor concentrations of gaseous contaminants were higher than the outdoor levels, the values remained below relevant standards throughout. For tipis, this may have been a result of the high air exchange rate.

The reported high occurrence of drafts, and the low air exchange rates in the homes seem incompatible. However, people generally wore light clothing inside. The perception of “draft” may have resulted from temperature differentials between unprotected parts of the body and cold surfaces in homes (i.e. walls and windows) (33). Drafts may also have indicated poor insulation, because homes with oil furnaces reported a higher percentage of draftiness, and had higher air exchange rates than those with wood furnaces.

In summary, the residents of Deline were exposed to concentrations of particulates in residential, occupational, and ambient environments, bordering on, or exceeding, relevant standards and within the range where adverse respiratory health effects have been observed (11, 27). Sources were predominantly furnaces and smoking for indoor pollutants, airborne dust for ambient TSP, and smoldering fires in tipis.

Measures to reduce residential exposure could include: (1) installation of airtight stoves and/or the maintenance of existing stoves; (2) cleaning and humidifying the air; and (3) restricting cigarette smoking. Working in tipis in a squatting position and minimizing time spent in this environment are readily applicable measures to decrease the exposure. Abandoning the practice of smoke curing is impractical given the importance of this activity to the life and culture of the local population. It may be possible, however, to modify the tipis to create relatively safer spaces for maintaining the fires and monitoring the process.

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