INDOOR OZONE AND ELECTRONIC AIR CLEANERS

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ABSTRACT
Plate and wire type Electronic Air Cleaners (EAC) are frequently found in Canadian houses. They are often sold based on their potential to improve respiratory health. EAC's produce ozone, a respiratory irritant, during operation. This project involved experiments with an air-handler and EAC in one house under varying air-change and EAC air-flow conditions. Ozone, EAC device airflow and weather data were measured continuously. Indoor ozone levels were predicted for a variety of air-change rates and outside ozone levels. The continuous operation of the EAC in these experiments could raise indoor ozone levels by up to 9 ppb over that which would be expected without EAC operation. The proposed outdoor guidelines by the Canadian Federal-Provincial Working Group on Air Quality range from 20 to 25 ppb, depending upon susceptibility. An addition of 9 ppb will push many houses to indoor ozone levels higher than proposed outdoor guidelines.

INDEX TERMS
Residential, electronic air cleaner, ozone, field testing, respiratory health

INTRODUCTION
Plate and wire type Electronic Air Cleaners (EAC) are frequently found in the central forced air systems of Canadian houses. They are often sold on the basis of their potential to relieve the symptoms of those who suffer from allergy-related and respiratory conditions. It is known that these devices produce ozone (O_3) during operation, and ozone is known to be a respiratory irritant. Until recently, it has been the conventional view that these devices did not significantly decrease air quality due to their relatively small ozone production rates and the theory that the primary source of indoor ozone is from infiltration of outdoor air.

Recent studies have found:

1) There is a statistically significant rise in wintertime indoor ozone levels in Canadian (Toronto area) homes which are equipped with EAC's. (Liu 1995).

2) Production of ozone from EAC's does not appear to be related to condition of the EAC, rather it appears to be constant, provided that the EAC is functioning. (Bowser 1999, Bowser 2000).

3) Lowest Observable Adverse Effect Levels (LOAEL) for outdoor ozone have been estimated at 20 ppb and 25 ppb for non-accidental mortality and respiratory hospital admissions, respectively. (Burnett 1998) These levels are lower than previously accepted, and are within the range of ozone levels recorded inside homes with EAC devices. (Bowser 1999, Bowser 2000).

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The objective of this study was to determine the degree to which ozone levels inside a house are influenced by the operation of an EAC, changes in house air-change rate and changes in airflow through the EAC.

METHODS

An Electronic Plate & Wire type Air cleaner (EAC) was mounted in a 2-level (basement and upper floor) home located in Brantford, Ontario, Canada. The upper level contained the normal sleeping, living and food preparation rooms and the lower lever contained the furnace/utility/laundry/mechanical room and a home office. The home was normally occupied. No special preparation of the EAC was made except that the pre-filter and collection elements were cleaned prior to test. A total of 185 hours of data were obtained consisting of 14 separate experimental arrangements. The experiments ranged in duration from 3 to 21 hours with the average test period being 13 hours. Sampling occurred at all times of the day and night, and where possible, an effort was made to obtain both day-time and night-time data for each particular experiment. Variables of the experiments were as follows:

- EAC on vs. EAC off
- Air Handler High (339 L/s) vs. Air Handler Low (166 L/s)
- Low Air-Change (0.40 ACH) vs. High Air-Change (0.65 ACH)

At least one experiment was conducted for each of the possible variable combinations. Weather data was measured during the experiment period and a natural air-change value was predicted using the AIM2 model (Walker 1990). The combined effect of natural and exhaust ventilation was predicted using the Keil-Wilson (Wilson 1990) relationship.

Experiments were conducted during November and December 2000 with all of the windows closed, corresponding to typical Canadian "shoulder-season" home operation. Samples were obtained using a Dasibi 1003AH Ambient Ozone Monitor (UV sampling chamber photometer) connected to a sampling apparatus which rotated the sampling flow sequentially through 5 stations as follows: 1) Outside, 2) Upstream of the EAC, 3) Office Area, 4) Downstream of EAC, 5) Bedroom. The time for a each set of 5 samples was 8.75 minutes. The loss of ozone in transit through sampling lines and sampling apparatus was determined by co-location testing over a range of 9 to 28 ppb O_3.

Interior ozone levels are reported as absolute values as well as ratios of indoor vs. outdoor level (I/O Ratio). An I/O ratio of 0.5 would indicate for example, that the inside measurements were 50% of the outdoor levels. A ratio of 1.5 would indicate that indoor levels were 150% of outdoors. When reporting I/O ratios, the bedroom values are used as they were judged as more likely to be representative of personal exposure. A general model (*equation 1*) based on equation 3 from the work of Freijer et al (Freijer 2000) was used to predict the expected indoor ozone concentration for varying conditions of outdoor ozone concentration and air-change rate.

$$Ci = \{Kv(1 + f)Co + S/V\}/(Kv + K_T) \qquad (1)$$

Where: *Ci* = Concentration, indoors, *Kv* = Air exchange, air changes per hour, *f* = Filtration factor for incoming air such that 0 = no filtration. 1= 100% filtration, *Co* = Concentration, outdoors, *S* = Source strength, indoors, *V* = Volume of house/space, K_T = Decay rate, air changes per hour, as follows:

$$K_T=V_D(A/V) \qquad (2)$$

Where: V_D = Deposition velocity, A = Surface area available for deposition. In this case, taken as the total of all interior wall, ceiling and floor surfaces, not including furniture.

The filtration factor in *equation 1* was set to 0 (no filtration) in order to be consistent with assumptions of other authors such as Weschler (Weschler 2000). It was hoped that the experiments would yield sufficient data to allow estimation of a filtration factor, but due to the similarities of the indoor and outdoor ozone levels during the experiments, this was not possible.

Ordinarily, it would be assumed that residential indoor sources of ozone are very small or non-existent (Weschler, 2000), however analysis of experimental data gathered during the EAC "Off period" showed that there was a continuous background source of 57 mg/hr (+/- 2.3) ozone in the home. This ozone source was attributed to operation of equipment such as computers, pumps, solenoid values and other data acquisition equipment. A K_T value of 5.623 ACH, and a V_D value of 0.083 cm/s were identified as having the best fit to measured experimental values. These values are higher than those obtained by other researchers such as Lee et al (Lee 1999) who obtained an average K_T value of 2.80 ACH and a V_D value of 0.049 cm/s for 123 California homes. The K_T and V_D values used in this study probably reflect the increased deposition velocity resulting from the continuous operation of the central air-handling system.

The model was used to predict the levels of ozone which would be experienced in this house with the following conditions:

1) No internal sources of ozone except EAC. (The experiments were carried out in the presence of internal sources of ozone arising from the data-acquisition equipment. The model predicts ozone levels in a "normal" house.)
2) Air change rates of 0.2, 0.7 and 1.0. This approximates the winter (0.69 ACH) and summer (1.04 ACH) air exchange rates reported for Toronto area houses studied by Liu et al (Liu 1995). The 0.2 ACH value represents a newer, more air-tight house with minimal ventilation.
3) Filtration of outdoor infiltrating into the house set to "0" (no filtration.)
4) Ozone production by the EAC of 46 mg/hr, based on the experimental data from this study.

RESULTS

Table 1. Ozone Levels (ppb O_3), Average of all Results

Location	*EAC Off*	*EAC On*
Outside	20 ppb (+/- 4)	22 ppb (+/-4.3)
Office	13 ppb (+/-0.1)	16 ppb (+/-0.9)
Bedroom	12 ppb (+/-0.1)	21 ppb (+/-1.9)
EAC Discharge	13 ppb (+/-0.2)	43 ppb (+/-10.3)

With the EAC off, the inside ozone levels were uniformly lower than outside levels and there was little or no variability between experiments. (See Table 1) The observed baseline of 13 ppb during EAC off conditions is consistent with the continuous internal sources identified earlier. With the EAC operating, the bedroom levels were slightly higher than the office. It is surmised that the bedroom sample point recorded higher values because the sample intake was more directly exposed to airstreams exiting from supply registers, and infiltrating air was more abundant in the basement (office) area during the testing periods. The office area is also physically smaller than the bedroom, resulting in a higher surface to volume ratio and therefore a higher surface deposition rate for ozone could be expected. During one experiment, a bedroom ozone level of 30 ppb was recorded and the experiment was stopped due to the onset of asthma symptoms which required medication for one of the house occupants.

There was no measurable ozone originating from the EAC when it was off. When the EAC was operating, significantly higher ozone concentrations were measured in the downstream air under Low Airflow conditions compared to High Airflow conditions. (See Table 2)

Table 2. Ozone Levels (ppb O_3) and Added Ozone (mg/hr) with EAC On

	Low Airflow (166 L/s)	*High Airflow (339 L/s)*
EAC Discharge	57 ppb (+/-5.6)	37 ppb (+/-1.5)
Added Ozone	48 mg/hr (+/-5)	44 mg/hr (+/-3)
Bedroom	23 ppb (+/-2.8)	21 ppb (+/-1.5)

The change in upstream vs. downstream ozone concentration was used in conjunction with the measured airflow through the filter and expressed as a source strength attributable to the EAC called "*Added Ozone*". With the EAC in operation, a constant ozone source strength of about 46 mg/hr was measured. This value was slightly reduced under higher airflow conditions. (See Table 2) The added ozone measured for this filter agrees well with the source strengths of 37 (+/-20) mg/hr measured by Bowser et al (Bowser 2000) for both dirty and clean filters and 42 mg/hr recorded by Hanley et al (Hanley 1993) under laboratory conditions. There was no significant change in house ozone levels attributable to change in airflow through the EAC, although slightly lower absolute bedroom levels were recorded at the higher airflow setting (see Table 2).

Table 3. Ozone Levels (ppb O_3) with EAC On at High and Low Ventilation Rates

	Low Air Change (0.40 ACH)	*High Air Change (0.68 ACH)*
Outdoor	23 ppb (+/-5.0)	20 ppb (+/-6.8)
Bedroom	22 ppb (+/-2.6)	21 ppb (+/-0.2)

With the EAC operating, slightly lower ozone levels were measured at higher air change rates, however the difference was not statistically significant. (See Table 3) The lack of result was attributed to the fact that outdoor levels were very similar to indoor levels during the test so that increased or decreased air-change rates did not have a measurable effect. Similarly, it was not possible to derive a filtration factor that could be reliably assigned to the incoming air.

Predicted rise of ozone concentration due to EAC operation is shown in Tables 4 and 5 for winter and summer conditions respectively. A rise of 9.2 to 8.1 ppb for low through high air change cases respectively is predicted. Table 4 shows the predicted I/O ratio at 15 ppb outdoors (winter) and Table 5 shows the predicted I/O ratio at 20 ppb outside (summer). 15 ppb was chosen for winter conditions based on the measurements of Liu et al (Liu 1995) who found the mean Toronto-area wintertime outdoor level of ozone to be 15.4 ppb (+/-6.0). 20 ppb was chosen for summer conditions based on the same study which found the mean summertime outdoor level of ozone to be 19.1 ppb (+/-10.0).

Table 4. Predicted Changes Due to EAC Operation, Wintertime, House Closed

ACH	*Rise in Indoor Ozone due to EAC*	*I/O ratio (15 ppb Outside)*	
		EAC off	*EAC On*
0.2	9.2 ppb	0.03	0.65
0.7	8.5 ppb	0.11	0.68
1.0	8.1 ppb	0.15	0.69

Table 5. Predicted Changes Due to EAC Operation, Summertime, House Closed

ACH	*Rise in Indoor Ozone due to EAC*	*I/O ratio (20 ppb Outside)*	
		EAC off	*EAC On*
0.2	9.2 ppb	0.03	0.49
0.7	8.5 ppb	0.11	0.53
1.0	8.1 ppb	0.15	0.56

DISCUSSION

I/O ratios of indoor vs. outdoor ozone are widely used in predictive exposure studies where the primary variable is outdoor ozone. Personal exposure can be substantively affected by the I/O ratio assumption as time spent indoors is often estimated to be as high as 80%. Liu et al (Liu 1995) found that the I/O ratio for homes without an EAC during the winter was 0.05. The Liu study predicts that the I/O ratio will vary between 0.03 and 0.15, depending on the rate of air-change. Liu et al also found that a sub-group of houses with EAC's experienced higher I/O ratios 0.13 (+/-0.12) during the winter. This change is not as great as predicted by our model, however it is likely that not all of the houses tested by Liu et al had EAC devices which operated continuously. Intermittent operation of the air-handling system could reduce the discharge of ozone from the EAC by a factor of up to 80%.

Liu et al (Liu 1995) found that the I/O ratio for homes without EAC was 0.45 during the summer. The model used in our study predicts that the I/O ratio will vary between 0.03 and 0.15 for a home with closed windows and no operating EAC. For summer operation, our predictive model does not agree with the measurements of Liu et al. This disagreement is probably due to the opening of windows during the summer by the houses included in the Liu study.

A 1-hour Reference Level value for non-accidental morbidity (20 ppb ozone outdoor air) has been proposed by the Canadian Federal-Provincial Working Group on Air Quality Objectives and Guidelines (WGAQOG, Health Canada 1999). An addition of 9 ppb to winter-time indoor air ozone levels would result in the 20 ppb threshold being exceeded in 5% of the houses studied by Liu et al (Liu 1995). An addition of 9 ppb during the summer would result in the 20 ppb threshold being exceeded in 25% of the houses studied by Liu et al. It is therefore possible that in houses with continuously operating EAC's and with "closed window" operation, the indoor air ozone concentration will exceed the proposed Canadian Reference Levels for outdoor air.

CONCLUSIONS

1) The operation of an Electronic Air Cleaner (EAC) can result in a rise of indoor ozone levels by 8 to 9 ppb higher than that which would be expected without EAC operation.
2) The airflow through the filter does not appear to influence ozone generation rate nor the eventual rise of interior ozone concentrations.

3) EAC operation may have a significant effect on personal exposure models. Indoor absolute ozone levels may be substantially higher inside a home equipped with an EAC than one without, particularly if the air handling system and EAC are operated continuously. Winter-time I/O ratios used for predictive population studies may be substantially incorrect for houses with continuously operating EAC's. Summer-time I/O ratios for air-conditioned houses may also be incorrect if the house contains an EAC.
4) EAC devices are sold on the basis of their potential to improve the health of a person with respiratory challenges. Such a person currently receives advice from public agencies to remain indoors on days with high outdoor ozone. In homes equipped with an EAC and a continuously operating air-handling system, it is possible that the indoor air will exceed the 1 hour Reference Level values for outdoor air proposed by the WGAQOG, (Health Canada 1999). In these situations, a susceptible individual would not have a sanctuary from the effects of ozone.

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