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Authors

Dobbin, Nina A
Sun, Liu
Wallace, Lance
et al.

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The benefit of kitchen exhaust fan use after cooking - An experimental assessment

Nina A. Dobbin[a,*], Liu Sun[a], Lance Wallace[b], Ryan Kulka[a], Hongyu You[a], Tim Shin[a], Daniel Aubin[c], Melissa St-Jean[a], Brett C. Singer[d]

[a] Healthy Environments and Consumer Safety Branch, Health Canada, Canada
[b] Health Canada, Canada
[c] National Research Council Canada, Canada
[d] Indoor Environment Group, Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

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ABSTRACT

Cooking is one of the main sources of indoor air pollutants, and may even exceed the contribution from outdoor sources. This pilot study examines the use of different flow-rate fans during cooking and tests whether continuing to run the fan after cooking significantly improves pollutant removal rates and integrated exposures. Tests were carried out in the Canadian Centre for Housing Technology's twin research houses, in Ottawa, Ontario. We completed the same cooking protocol 60 times on a gas stove, testing 6 different flow rates on three different over-the-range exhaust fans, while continuously measuring UFP, $PM_{2.5}$, NO_2, and NO. The fan was operated during cooking for all tests and then either turned off or left on after cooking for the duration of the three hour test. We estimated decay rates, source emission rates, and integrated exposures to measured pollutants following the cooking test. The results showed that while leaving the fan on after cooking generally increased decay rates, it had a relatively small effect on integrated exposures compared to the effects of fan flow rate and the specific fan used during cooking. For $PM_{2.5}$, the effect of running an exhaust fan for 15 min after cooking was similar in magnitude to the impact of a 100 cfm increase in the flow rate used while cooking: both were associated with a decrease in 15-min integrated exposure of roughly 3 $\mu g\,m^{-3}$. This suggests that one can partially compensate for a low flow rate exhaust fan by continuing to run the fan after cooking.

1. Introduction

Cooking is a significant source of indoor pollutants. High emissions of particles from cooking activities have been reported in many studies [1–9]. Kearney et al. [5] found that about two-thirds of the 100 Canadian homes studied had higher contributions of ultrafine particles (UFPs) from indoor sources (mainly cooking) than from the entry of outdoor UFPs. Wallace et al. [10] found that cooking was associated with an increase of a factor of ten in the concentration of UFPs and an increase of a factor of three in fine $PM_{2.5}$. Wheelet et al. [8] reported that during the dinnertime cooking period, indoor UFP and $PM_{2.5}$ concentrations exceeded their daily mean values by, on average, 160% and 60%, respectively.

For homes with natural gas cooking stoves, higher residential levels of nitrogen dioxide (NO_2) are an additional concern [11,12]. A recent simulation study [13] found that gas burner use may routinely lead to NO_2 concentrations that exceed the 1 h U.S. ambient air quality standard of 100 ppb and follow-up measurements found that the threshold was exceeded by moderate burner use in four of nine homes in which experiments were conducted [14].

Many studies, both experimental and simulation, have demonstrated that kitchen exhaust fans can reduce cooking-related air pollutants [14–21]. However, the efficiency of exhaust fans to capture cooking-related pollutants can vary widely based on a number of factors, including equipment type, size and location, exhaust flow rate, exhaust ducting, installation details and use behavior [15,19,22,23]. Use behavior is an important factor to maximize effectiveness, especially for those who are not able to purchase a higher performance unit or make improvements to the installations, such as renters.

Kitchen exhaust fans reduce cooking emission in two ways: 1) by removing emissions directly at the stove before they mix into the surrounding air and 2) by increasing overall air exchange in the home to remove pollutants from the indoor environment. A number of studies have measured the fraction of emissions captured by kitchen fans at the source, which is referred to as capture efficiency [15,17,19]. Capture efficiencies during cooking can vary widely but are typically below 75%

* Corresponding author. 420 – 757 West Hastings Street, Vancouver, BC, V6C 1A1, Canada.
E-mail address: Nina.dobbin@canada.ca (N.A. Dobbin).

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[19].

After cooking, when the emission source has stopped, the kitchen fan can continue to reduce pollutant concentrations by increasing air exchange. To our knowledge, the impact of leaving a fan running after cooking has not previously been studied experimentally. Our goal was to evaluate the impact of different fan flow rates and of leaving a fan running for 15 min after cooking on cooking-related pollutant concentrations.

2. Methods

2.1. Measurements

The cooking experiments were conducted in the Canadian Centre for Housing Technology's (CCHT's) twin research houses, in Ottawa, Ontario. They are identical two-story, four-bedroom, three-bathroom, detached houses with a floor area of 2260 ft^2, and are unfurnished with tiled floors in the kitchen and family rooms, and carpets in the other areas (see supplemental information Figure S1 for floor plan). There is a standard 30-inch gas stove, over which we installed the 30-inch under-cabinet exhaust fans. Fan A had a depth of 18 inches, while fans B and C each had a depth of 20 inches, over a standard 25-inch deep cooktop (See supplemental Table S1 for fan details and Figure S2 for diagrams).

Three kitchen exhaust fans were selected for the study. Fan A was a Broan-Nutone, model RL6100F (existing fan in the home, no current price available, comparable current models are $100-$120 retail). It is a single-speed fan with a stated exhaust airflow rate of 180 cfm. Fan B was a Broan-Allure, model QS1 30SSN ($211 retail). It has two speed settings and the unit specifications state exhaust airflow rates of 110 and 220 cfm. Fan C was a BOSCH model DUH30252UC ($550 retail). It is a higher performance model that has four fan speeds; the unit specifications stated exhaust airflow rates were between 150 and 400 cfm, of which the low, high, and maximum settings were tested. The high speed setting did not have a manufacturer specified flow rate.

The duct was the same size for all fans (7 inches) and all were installed with the duct positioned vertically. As the airflow for installed exhaust fans has been found to be less than manufacturer's specification [15,18,19], the actual airflow rate inside the duct was measured for use in the analysis. The fans exhausted directly to the outside. Fan A was the existing fan in one of the test houses, while fan B and C were purchased for the study. Fan A and B were tested in one house and fan C was tested in the other house.

The protocol for each cooking test was as follows. First, the gas stovetop burner was started simultaneously with the exhaust fan. The next step was boiling four cups of water on the rear burner and once boiling, adding frozen broccoli to cook for five minutes. The pot was covered with a lid throughout. After this step, the rear burner was turned off. The next step was frying four beef hamburger patties on a frying pan on the front burner, using four tablespoons of vegetable oil to coat the pan initially. The patties were fried for five minutes on each side. After the stove was turned off at the end of cooking, the exhaust fan was either turned off (off condition) or left on for an additional three hours (on condition). Each set of test conditions (six total fan speeds, on/off condition) was repeated five times, for a total of 60 cooking tests. Air pollutant monitoring started 15 min before cooking and continued for approximately three hours following cooking. Two tests were completed in each house per day, one in the morning starting at 9:30 a.m. and one in the afternoon starting at 3 p.m.

Field work was completed in September and October 2015. During the tests, the furnace, hot water tank, and other ventilation systems in the home were turned off. Windows were closed and ventilation ducts were sealed off to minimize air exchange in the home aside from the kitchen exhaust fan. The air exchange rate in the homes was measured before the start of the experiments using the decay of the tracer gas sulfur-hexafluoride (SF_6) according to ASTM test method E 741-00 (ASTM, 2006) using an Innova Model 1312 photoacoustic field gas monitor.

Localized air exchange in the kitchen was measured during each test using the same tracer gas method. One deviation from the usual air exchange test method was not using mixing fans in the space, as this would interfere with the cooking test. The tracer gas was injected at three locations on the first floor of the research house one hour before each test and measured every 30 s thereafter until three hours following cooking. The AER was estimated based on decay from approximately 15 min to one hour following cooking. This measurement gives the integrated estimate of the AER during this period, but does not allow us to estimate the AER specifically during cooking.

Air quality monitoring instrumentation was placed next to the kitchen island, approximately 2–3 m from the stove. This location was chosen to approximate the exposure of people in the kitchen. $PM_{2.5}$, NO, and NO_2 were monitored continuously during the sampling period. Data was collected at one minute averages using an Airpointer ($PM_{2.5}$: Nephelometry, NO_2/NO: Chemiluminescence) (MLU-Recordum, Austria). The sampling inlet was at a fixed height of 1.7 m. UFP were measured continuously using condensation particle counters (CPC) model 3007s (TSI, St Paul, MN), collected at one minute averages. This model does not have a size selective inlet and counts particles from 10 nm to 1 μm in size; however, for freshly created particles from indoor sources the vast majority are UFPs [24]. The CPC was placed on a table, with the inlet at a height of 1.2 m. This sampling height was in the breathing zone of someone sitting at a table in the kitchen/dining room. The Airpointer has a fixed inlet height that is 50 cm above the CPC inlet, but the equipment was located centrally in the room in a well-mixed area, so this height difference is not expected to cause any appreciable difference for monitored concentrations. Temperature and relative humidity were recorded continuously during the sampling period at 1 min intervals using a Hobo Data logger U12-013 (Onset, Bourne, MN).

The flow rate for each kitchen exhaust fan was compared against the manufacturer's specifications for each fan speed setting. This was accomplished by measuring the exhaust flow rate downstream of the installed exhaust fan. Nailor Industries model 36FMS flow stations were installed in the exhaust ducting in both experimental homes, and the pressure differential across the flow station was measured using a TSI Model 9565-P multifunction ventilation meter.

All instruments were calibrated before the fieldwork. The CPC was calibrated by the manufacturer before the study. The manufacturer estimates accuracy within about 20% for the instrument. Inter-comparisons were made between instruments at the same location before and after the monitoring period to assess any problems between instruments. All continuous instruments were assessed for drift and zeroed daily. All data collected from continuous instruments were visually assessed for bias, instrument malfunction or abnormal peaks.

2.2. Statistical analysis

All pollutant concentrations were visually assessed in individual plots of each cooking test. The background concentration may vary over the course of the test due to changes in outdoor concentration so we used both the beginning and end concentrations to estimate it. Specifically, we calculated the average concentration during the 15 min before cooking and the average during the 15 min at the end of the test (three hours after cooking). For the majority of tests, the concentration at the end of the test was higher than at the beginning, likely because the cooking peak had yet to fully decay; for these tests we used the beginning concentration as the background. In cases where the end concentration was lower, we used a linear interpolation between the beginning and ending concentrations as the background. In both cases, the estimated background concentration was subtracted from all the readings for subsequent analyses [14].

Each unique set of fan conditions was tested five times. As the duration of cooking varied slightly from test to test, we used the end of cooking as a reference point to line up the tests, and calculated the minute-by-minute mean and 95% confidence interval (CI) to get an overall concentration curve for each set of fan conditions. These means and CIs were plotted to compare the effects of different fan conditions.

We estimated the source strength for each pollutant during cooking by multiplying the asymptotic concentration of each pollutant by the airflow rate in the room, as described by Ott [37]. The asymptotic concentration is the equilibrium between the pollutant generation rate and removal rate, calculated as follows:

$$x_\infty = \frac{C_{max}}{(1 - e^{-\varnothing t_{max}})} \tag{1}$$

where C_{max} is the estimated particle peak concentration (particles/cm^3) with no fan running, t is the length of time (in minutes) of the source being emitted, and $\varnothing$ is the decay rate (min^{-1}). We estimated C_{max} by taking the intercept of a regression of peak concentrations against cfm. The source duration was estimated as the entire length of gas stove use for NO_2 and NO (25 min) and as the length of the frying period for UFP and $PM_{2.5}$ (13 min), as the plots indicated that this is when the bulk of particle emissions occurred. The source strength (S) was then calculated as follows:

$$S = x_\infty \varnothing v \tag{2}$$

where v is the mixing volume of the first floor of the home (244 m^3).

A decay rate was estimated for every test where a clear rise and fall in pollutant concentration could be observed in the plot. It was estimated by fitting a linear regression of the natural logarithm of measured background-corrected pollutant concentration versus time. The decay rate was calculated from the peak to one hour following the end of cooking. This time frame was chosen because we observed frequent deviations from linearity when extending to longer time scales, which, had they been included in the regression, would have led to inaccurate estimates of the initial decay rate. The initial decay rate was likely faster because it included dispersion of the pollutants throughout the open-concept kitchen and dining area, and after this dispersion was complete the decay rate slowed down. For our study, it was important to accurately estimate the initial decay rate because the primary goal was to characterize the effects of fan use in the immediate period following cooking when pollutant concentrations are highest and when a user may most benefit from running the fan for an additional time period. Only decay rates where the linear regression R^2 value was at least 0.9 were retained for analysis. In order to estimate the potential benefits of leaving a fan running for 15 min after cooking versus turning it off immediately, we modelled integrated exposure (IE_{1h}) for the first hour after cooking in two portions as follows:

$$IE_{1h} = IE_{15min} + IE_{15min-1h} \tag{3}$$

$$IE_{15min} = \int_0^{0.25} c(t)dt \tag{4}$$

where $c(t)$ is the measured pollutant concentration at time t (hours) with the background concentration removed; we estimated the area under the concentration curve using the proc expand function in SAS EG 5.1 (Cary, North Carolina, USA) with the spline method. The next portion of the integrated exposure was modelled as follows:

$$IE_{15min-1h} = \int_{0.25}^{1} c_{0.25}\, e^{-decay \times t}\, dt \tag{5}$$

where $c_{0.25}$ is the background-corrected concentration at 15 min after cooking, *decay* is the average decay rate estimated for that pollutant with the fan off, and t is the time in hours. We estimated the confidence intervals for IE_{1h} by taking the square root of the sum of squares of the error terms associated with each segment ($IE_{15min} + IE_{15min–1h}$). The confidence intervals for the modelled term ($IE_{15min–1h}$) were calculated by calculating an upper and lower bound for the concentration curve using the confidence intervals for $c_{0.25}$ and the decay rate.

We examined the effect of fan use characteristics on decay rates and integrated exposures using linear regression models of the following form:

$$y = \beta_0 + \sum \beta_i x_i + \epsilon \tag{6}$$

where y is the outcome variable (either decay rate or integrated exposure for a specific pollutant), β_0 is the intercept, x_i are the predictor variables, β_i are the associated regression coefficients, and ε is the error term. The following variables were examined as predictors: outdoor pollutant level, fan status after cooking, fan flow rate, fan model, kitchen air exchange, humidity, and temperature. Final regression models included the following predictors that were found to have significant effects on the outcomes: fan flow rate (cfm as a continuous variable), fan status (indicator term for fan being left on after cooking), and indicator variables for fan type. Fan type (a categorical variable with three levels) was dummy coded and entered in the models as two indicator variables for fan A and fan B, with fan C as the reference case. Variance inflation factors for these variables in a combined model were all below 2, indicating that multicollinearity was minor.

We used dominance analysis to evaluate the relative importance of these test characteristics in predicting decay rates and integrated exposures [25,26]. Dominance analysis evaluates the importance of different predictors in a regression model by averaging the change in R^2 that occurs across all possible subsets of the model, including a model with the variable alone as well as in all combinations with the other predictors. This approach overcomes the potential problems with correlated predictors that are an issue with other measures of importance [27]. The dominance analysis reported here was carried out using the SAS Dominance Analysis macro developed by Razia Azen and available at [https://pantherfile.uwm.edu/azen/www/damacro.html].

We also examined the impact of adding an interaction term (flow rate * fan status), because the fan flow rate would be expected to have a larger impact on the tests where the fan was left on after cooking as compared to the tests where the fan was turned off immediately after cooking. Traditional dominance analysis is not appropriate for higher order terms because it examines every possible subset of predictors, and higher order terms require the lower order terms to be present. We therefore evaluated the impact of this higher order term by calculating the difference between the R^2 of the first-order model (flow rate + fan type + fan status) with the full model [flow rate + fan type + fan status + (flow rate * fan status)], an approach described by LeBreton et al. [28].

3. Results and discussion

3.1. Cooking tests

A total of 60 cooking tests were performed. There was one cooking test for which NO and NO_2 data were not collected and a separate test where no UFP data were collected due to instrument failure. $PM_{2.5}$ data from three cooking tests were excluded from analysis because they showed unexpected patterns that indicated possible instrument malfunction.

The house infiltration rate was 0.08 h^{-1} (SE: 0.01 h^{-1}). This indicates the test homes were very airtight as compared with typical Canadian housing stock built in the same time period. Other cities in Ontario with similar climate and housing stock have found a mean air exchange of 0.22 ± 0.15h^{-1} in Toronto [29] and median air exchanges ranging from 0.14h^{-1} to 0.30h^{-1} in Windsor [30].

Measured flow rates of the fans ranged from 76 to 309 cfm, and were 12–31% lower than the flow rates specified in product literature (supplemental Table S1). These differences could have resulted from mechanical wear due to age in the case of the Broan-Nutone fan as it was not new, differences in measurement method/conditions between

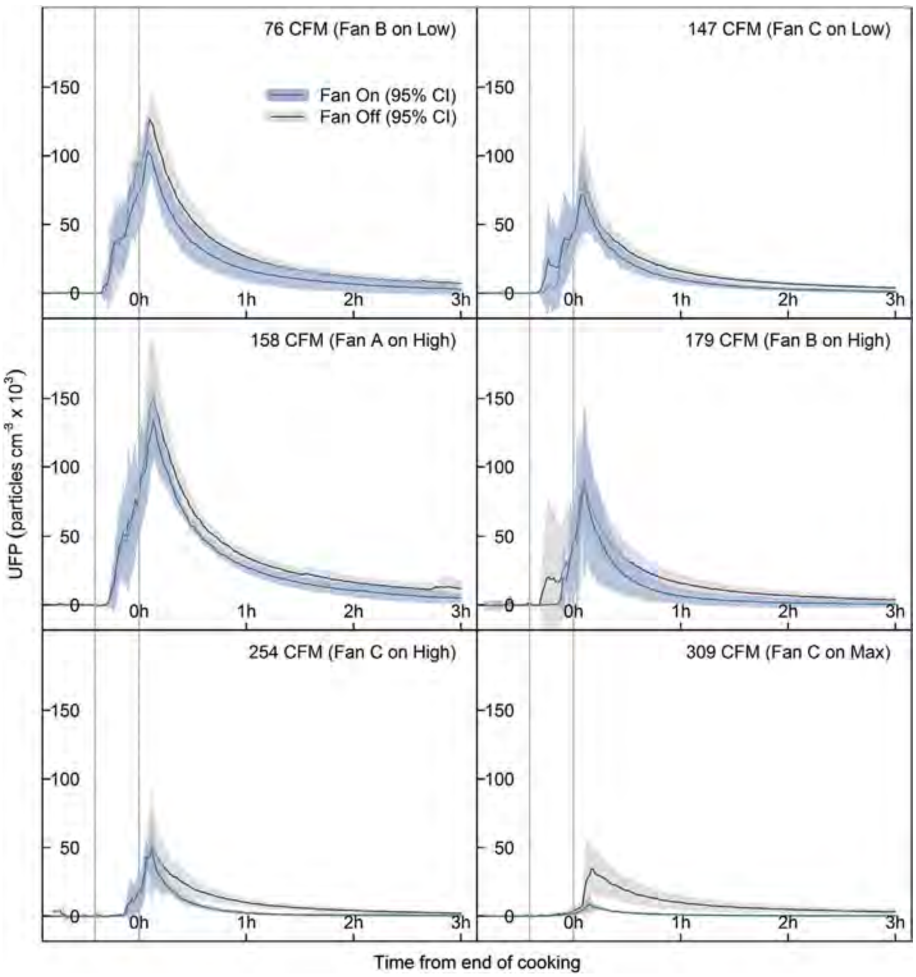

Fig. 1. Mean UFP concentrations across all tests and fan conditions, after subtracting the background concentration. Solid lines are the mean of 5 repeated tests performed under the same set of conditions and the shaded areas show 95% confidence intervals. The fan was on during cooking for all tests – this period is indicated by the dashed vertical lines. At the end of cooking the fan was either turned off (grey line) or left on (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that reported in this study and that used by the manufacturer, and resistance to airflow caused by an excessively tight building envelope and the lack of make-up air normally being provided by the HRV (which was not operating and sealed shut in this case). Air exchange rates associated with fan use were estimated to range from 0.72 h^{-1} with the 76 cfm fan to 2.30 h^{-1} with the 309 cfm fan. Full air exchange results for each fan flow rate are provided in supplemental Table S2.

The cooking test used in this study was intended to simulate a typical family meal. The first stage of cooking was boiling broccoli on the rear burner and this stage was observable in many of the concentration plots (Figs. 1–4) as a slight peak, which was most distinct in the UFP plots. We would expect boiling to produce NO, NO_2, and UFP in line with fuel use, and minimal $PM_{2.5}$. The use of the rear burner for this stage also affected observed concentrations; capture efficiencies are higher for rear burners than front burners because they are fully covered by the exhaust fan [19].

The second stage of the cooking protocol, frying of hamburger patties, generated the primary peak observed in the concentration plots. The particle production rate during the frying of fatty foods is at the upper-end of cooking activities and skews towards UFPs. Wallace et al. [10] estimated that the number of particles emitted from frying may be 6–10 times higher than other typical forms of cooking. In addition, in our cooking test the hamburgers were fried on the front burner, and none of the tested fans fully covered this portion of the cooktop. This is typical of most fans on the market [31].

We estimated the UFP source strength to be 4×10^{12} particlesmin^{-1} during frying; previous studies of cooking on gas stoves have also found rates of roughly 10^{12} particlesmin^{-1} [10,32]. We estimated $PM_{2.5}$ source strength to be 1300 μgmin^{-1} during frying. As shown by Figs. 3 and 4, NO_2 and NO were emitted at a steady rate throughout the cooking period (boiling broccoli followed by frying) and their source strengths were estimated to be 6×10^5 ngmin^{-1} and 15×10^5 ngmin^{-1} during this period, respectively.

We made significant efforts to ensure consistency across cooking tests, but still observed a fair amount of variation in emissions, as evidenced in the confidence intervals on the concentration plots, as well as the end-of-cooking concentrations reported in Supplemental Table S3. The fan was on during cooking for all tests, so we would expect the concentrations throughout cooking to be the same for a given fan flow rate; indeed, t-tests comparing end of cooking concentrations for tests where the fan was turned off after cooking versus left on showed that the means were not significantly different ($p > 0.05$) in almost all cases (Supplemental Table S3). The exceptions were observed with the $PM_{2.5}$ concentrations at the end of cooking, especially while using fan A at 158 cfm. It was found to be significantly higher for tests where the fan was turned off immediately after cooking versus left on (28.0 μg m^{-3} versus 16.6 μg m^{-3}, $p = 0.03$). A similar trend of higher cooking emissions for tests where the fan was turned off immediately after cooking was also observed while using fan B at 76 cfm, though in this case it did not reach statistical significance. It is unclear what

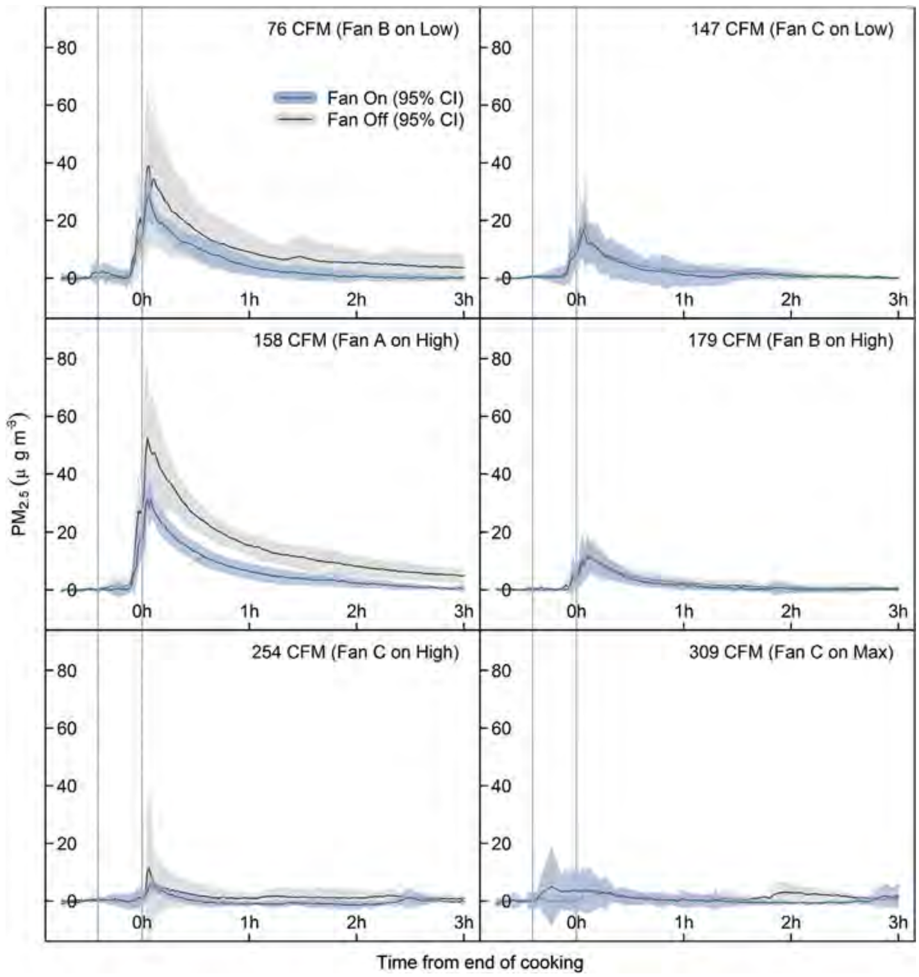

Fig. 2. Mean $PM_{2.5}$ concentrations across all tests and fan conditions, after subtracting the background concentration. Solid lines are the mean of 5 repeated tests performed under the same set of conditions and the shaded areas show 95% confidence intervals. The fan was on during cooking for all tests – this period is indicated by the dashed vertical lines. At the end of cooking the fan was either turned off (grey line) or left on (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

caused this difference in emissions and $PM_{2.5}$ results for these two fan speeds should be interpreted with caution.

In general, the largest relative differences between fan off and fan on tests were observed for high fan speeds, where the end of cooking concentrations were low and thus represented small absolute differences (e.g. 1800 cm^{-3} difference in UFP concentrations for fan C at 309 cfm).

The cooking peaks show the most variability by fan flow rate (Figs. 1–4). Guidance from the Home Ventilation Institute (HVI) states that an exhaust fan placed over a standard 30 inch stove and against a wall (as in the current tests) should have a minimum flow of 100 cfm and they recommend a flow of 250 cfm (HVI) [38]. All of the fans we tested had manufacturer-specified airflows that exceeded the HVI minimum of 100 cfm. However, fan B on the lowest setting had a measured flow rate of 76 cfm, despite a manufacturer specified flow rate of 110 cfm. This fan speed, as well as fan A on its single setting (with a specified airflow of 180 cfm and a measured airflow of 158 cfm), performed significantly worse than the other tested fan speeds. Average cooking peaks with these fan speeds were at least 100% higher for particles and at least 25% higher for NO_2 and NO than the other tested fan speeds, including fan C on low with a measured airflow of 147 cfm. We did not test a sufficient number of fans to make broad recommendations on flow rates, but our results suggest that manufacturer specified flow rates alone may not provide sufficient information to ensure adequate removal of cooking emissions.

NO_2 concentrations are of particular concern when using gas stoves. The NO_2 cooking peak observed with the least effective fan (fan A on 158 cfm) was roughly 15 ppb, while with the more effective fans (fans B and C on higher settings, starting at 179 cfm) the peaks were much smaller at 1–4 ppb. Health Canada's proposed indoor air quality guideline for NO_2 is a maximum short-term exposure limit of 90 ppb, and the peaks measured in the current study are well below this value. In general, indoor air measurements of homes in various Canadian cities have found median levels of NO_2 between 2 and 5 ppb, while in homes with gas ranges levels were generally between 5 and 12 ppb, in some cases exceeding the proposed maximum long-term exposure limit of 11 ppb [33]. Levels of NO_2 in homes with gas stoves are a health concern because studies have linked them to increased respiratory symptoms in children [34,35]. The current results suggest that the use of effective ventilation during cooking may reduce NO_2 exposures in homes with gas stoves.

3.2. Decay rates

The decay rate of the pollutant peaks is governed by deposition and air exchange, as well as coagulation at high concentrations of UFP [7]. We measured concentrations in the kitchen of a home with an open floor-plan, so part of the initial decay rate also includes mixing of the air through the rest of the living space. As the background air exchange in the home is low and held constant for all the cooking tests, the main

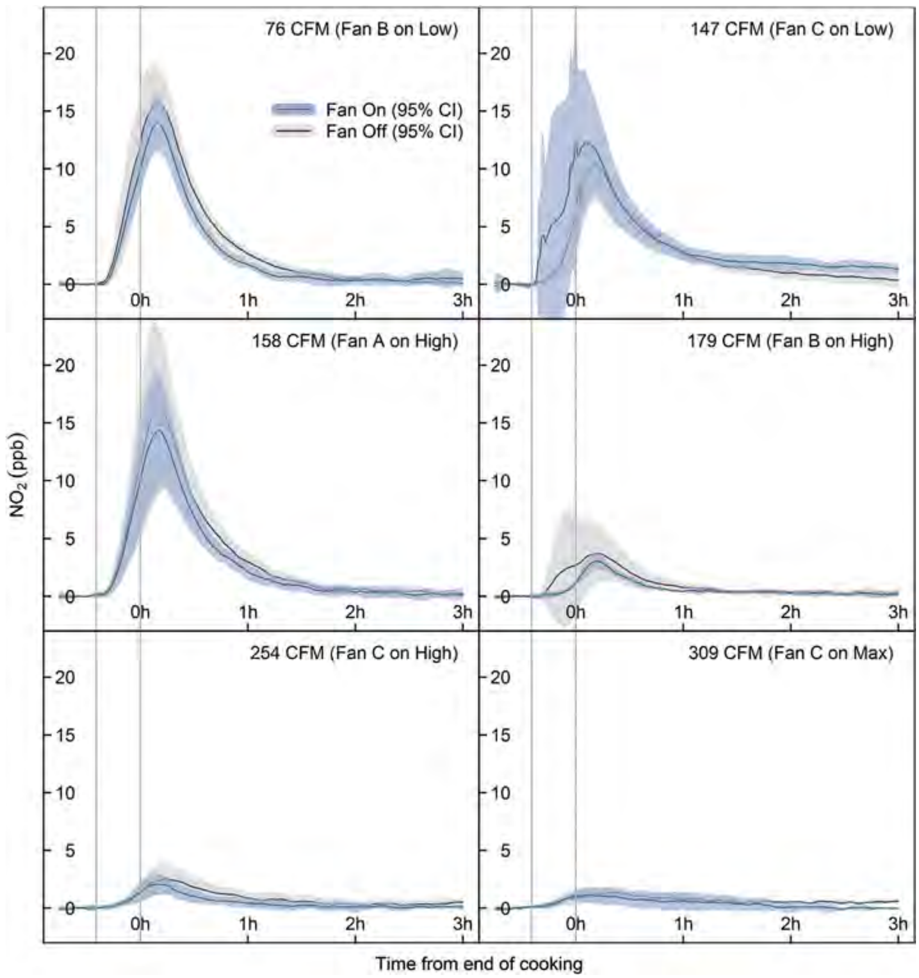

Fig. 3. Mean NO_2 concentrations across all tests and fan conditions, after subtracting the background concentration. Solid lines are the mean of 5 repeated tests performed under the same set of conditions and the shaded areas show 95% confidence intervals. The fan was on during cooking for all tests – this period is indicated by the dashed vertical lines. At the end of cooking the fan was either turned off (grey line) or left on (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

variable between tests was the air exchange provided by the kitchen fan. Deposition, which is also expected to stay roughly constant between tests, contributes to the decay rates of UFP, $PM_{2.5}$ and NO_2; the mean difference in decay rates between these pollutants and NO was 0.9 h^{-1} (Table 1), which is a rough estimate of the deposition rate.

For a number of the tests of fan C on 309 cfm, no cooking peak was evident and therefore no decay rate was calculated. This affected one test for UFP, four tests for $PM_{2.5}$, and all ten tests of fan C on 309 cfm for NO and NO_2. Modelled decay rates with R^2 values less than 90% were also excluded, which affected UFP during one test, $PM_{2.5}$ during 17 tests, NO_2 during three tests, and NO during one test. Due to the large number of excluded decay rates for $PM_{2.5}$, the $PM_{2.5}$ decay model results should be interpreted with caution.

Modelled decay rates were significantly different ($p < 0.05$) by fan status for a number of tested flow rates, most consistently for UFP (Table 1). For other pollutants, the faster decay rates were primarily evident with higher flow rate fans. Bhangar et al. [36] estimated the UFP decay rate for peaks emitted from the gas stove at 1.9 ± 0.7 hr^{-1}, which is very similar to our measured decay rate of 1.7 hr^{-1} (CI: 1.6–1.8 hr^{-1}) with the fan turned off. The air exchange rate in the home without a fun running was 0.08 h^{-1}.

The decay rate is mainly governed by post-cooking factors, namely whether the fan was left on after cooking, and at what flow rate. This was especially apparent in the regression results for UFP, where flow rate and its interaction term with 'fan on' together accounted for half the variability in decay rate (Fig. 5). Although we observed relatively high R^2 values for these terms in predicting decay rate, most of the effect size estimates did not reach statistical significance (Table 2). Fan type generally did not affect the decay rate, as would be expected since the decay occurs after cooking, when the pollutants have distributed into the room air and their removal becomes governed by the air exchange rate and deposition rather than physical capture by the fan. The exceptions were apparently lower removal rate of $PM_{2.5}$ by fan A and higher removal rate of NO_2 by fan B, as compared with fan C as the reference case. It is unclear what caused these differences.

3.3. *Integrated exposures*

The most consistent predictor of 15 min integrated exposures after cooking was the fan flow rate used during cooking. Multiple regression models and associated dominance analysis showed that the fan flow rate predicted 27–56% of the variability in (post-cooking) 15 min integrated exposure (Fig. 5). The difference in 15 min integrated exposure between the lowest and highest flow rates tested was 80–94% for UPF, 84–90% for $PM_{2.5}$, 91–93% for NO_2 and 97% for NO (Table 3). This was especially important for the gaseous pollutants we measured (NO and NO_2), where flow rate of the fan used during cooking predicted roughly half of its variability in the 15 min following. For a 100 cfm increase in the flow rate of the fan used during cooking, exposures during the 15 min following cooking were reduced by 7900 cm^{-3} h for UFP, by

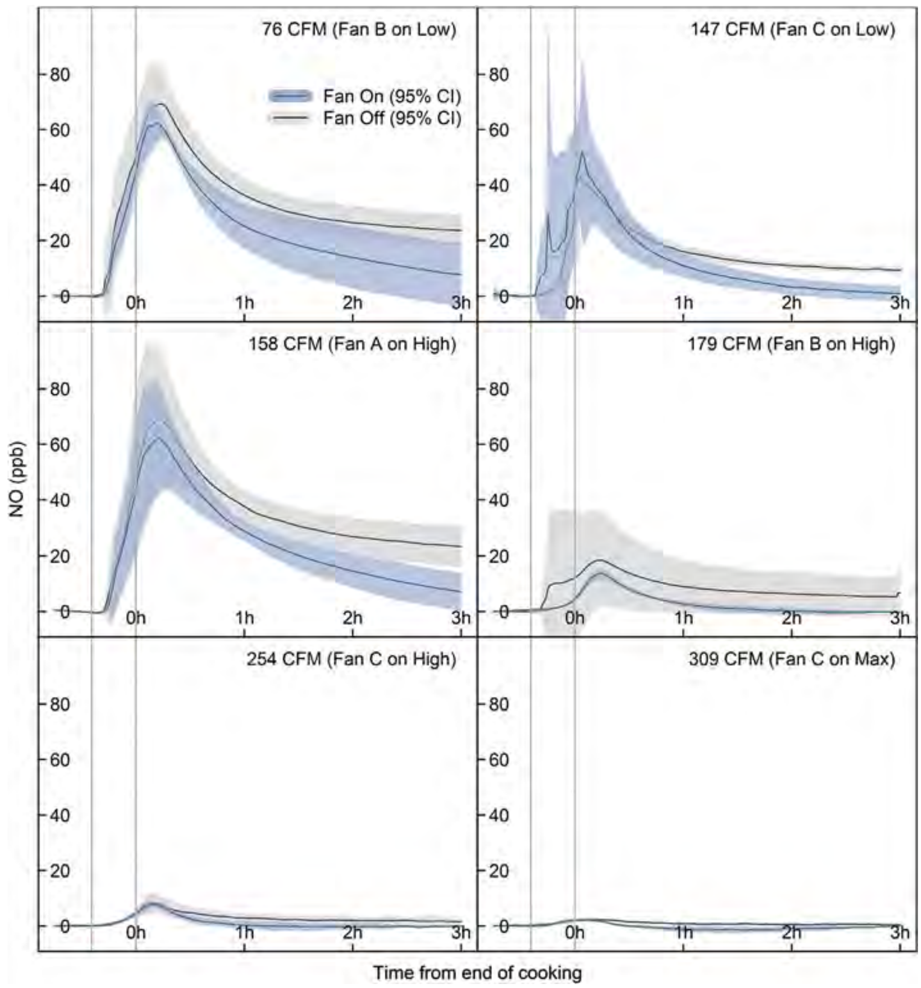

Fig. 4. Mean NO concentrations across all tests and fan conditions, after subtracting the background concentration. Solid lines are the mean of 5 repeated tests performed under the same set of conditions and the shaded areas show 95% confidence intervals. The fan was on during cooking for all tests – this period is indicated by the dashed vertical lines. At the end of cooking the fan was either turned off (grey line) or left on (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Modelled decay rates (h^{-1}) of pollutant concentrations in kitchen over the period from the observed peak to one hour after cooking ended [95% confidence interval]. Bold results indicate where the decay rate with fan on is significantly different ($p < 0.05$) from the fan off condition.

Fan Flow Rate	Fan status after cooking	UFP		$PM_{2.5}$		NO_2		NO	
		N	Mean [95% CI]	N	Mean [95% CI]	N	Mean [95% CI]	N	Mean [95% CI]
All	Off	30	1.7 [1.6, 1.8]	19	1.9 [1.5, 2.2]	24	2.0 [1.8, 2.1]	24	1.0 [0.9, 1.1]
76 (fan B)	On	5	**2.0 [1.7, 2.4]**	4	2.4 [0.9, 3.8]	5	**2.7 [2.5, 3.0]**	5	1.2 [0.8, 1.7]
147 (fan C)	On	5	**2.1 [1.8, 2.5]**	2	3.4 [-0.7, 7.4]	5	1.8 [1.6, 2.0]	5	**1.6 [1.1, 2.0]**
158 (fan A)	On	5	1.8 [1.4, 2.2]	5	1.7 [1.3, 2.1]	5	**2.4 [2.2, 2.6]**	5	1.0 [0.6, 1.3]
179 (fan B)	On	4	**2.9 [2.4, 3.3]**	3	3.7 [-0.3, 7.7]	5	**2.7 [2.3, 3.0]**	5	**2.2 [1.7, 2.8]**
254 (fan C)	On	5	**3.3 [2.8, 3.8]**	2	7.3 [-34.7, 49.3]	3	2.1 [0.6, 3.6]	5	**4.5 [1.4, 7.5]**
309 (fan C)	On	3	2.6 [0.6, 4.6]	1	1.8	0	–	0	–

2.8 $\mu g\,m^{-3}$ h for $PM_{2.5}$, by 2.0 ppb h for NO_2, and by 8.5 ppb h for NO (Table 2).

Integrated exposures over the first 15 min following cooking were generally lower with the fan kept running versus turned off immediately after cooking, but the difference only reached statistical significance for fan C at 309 cfm for UFP (Table 3). We did also observe a statistically significant difference for $PM_{2.5}$ at 158 cfm; however, as noted earlier, this set of tests was biased towards lower emissions from the fan "on" tests even during cooking, and thus should be interpreted with caution. Leaving the fan on after cooking did not show any predictive value in multiple regression models of the 15 min integrated exposure. This demonstrates that the immediate post-cooking 15 min integrated exposure is primarily impacted by capture efficiency during cooking, and continuing to run the fan during this period does not produce substantial pollutant removal in the short term, because the pollutants have already entered the wider room air. For $PM_{2.5}$, the effect of running an exhaust fan for 15 min after cooking was similar in magnitude to the impact of a 100 cfm increase in the flow rate used while cooking: both were associated with a decrease in integrated exposure of roughly 3 $\mu g\,m^{-3}$. For UFP, keeping the fan running for

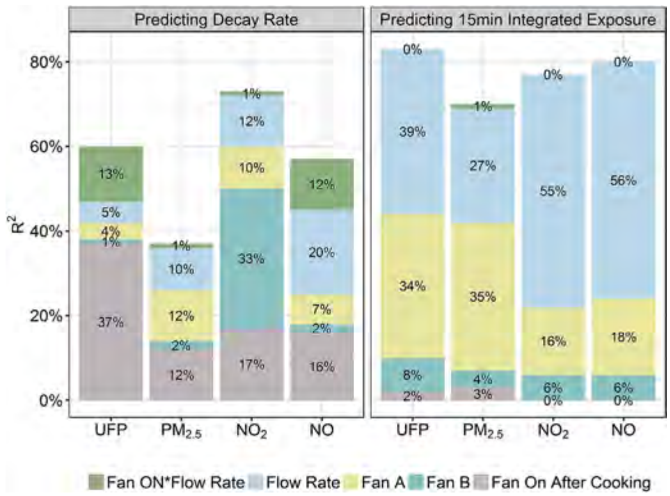

Fig. 5. The predictive contributions of predictors in multiple regression models predicting decay rate (left) and the 15 min integrated exposure following cooking (right). The predictive contributions of first order predictors were determined using dominance analysis. The predictive power of the second-order interaction term (fan status * flow rate) was calculated as the difference between the R^2 of the full first-order model with and without the interaction term.

15 min after cooking had roughly half the impact of a 100 cfm increase in fan speed used during cooking. In other words, to reduce integrated exposure to particulate matter from cooking, one can partially compensate for a low flow rate by continuing to run the fan after cooking. However, the magnitude of this benefit remains small compared to the significant increase in exposure from using a fan that is inefficient at capturing emissions during cooking. Based on the regression models, the 15 min integrated exposures when using fan A were more than 16,000 cm^{-3} h higher for UFP and 5.5 $\mu g\,m^{-3}$ h higher for $PM_{2.5}$ as compared with using fan C (adjusted for flow rate) (Table 2).

Fan characteristics other than flow rate were also influential of the 15 min integrated exposures. The use of fan A was associated with significantly higher integrated exposures compared to use of fan C for all pollutants, while the effect of using fan B was less consistent. This difference likely arises from the cooking period, as different fans vary in their effectiveness to capture the cooking plume. Previous studies evaluating capture efficiencies for a number of fan types have found that with a given cooking plume and fan flow, capture efficiency is lower with fans that do not fully cover the front burner [15,18,19]. Fan A had 2 inches less coverage over the burners than fans B and C, and this may have significantly reduced its capture efficiency in comparison. This would increase the quantity of pollutants released to the room during cooking, and would therefore lead to higher concentrations throughout the post-cooking period. This additional cooktop coverage of fans B and C appears to have been more important than the presence of an open capture hood on fan A, which generally improves emission capture as compared to fans with a flat profile [15,19]. Fans B and C both had flat profiles covered in grease screens and despite this, captured significantly more pollutants. The area covered by grease screens in fan A was smaller (95 in^2) than in fans B and C (327 in^2 for fan B, and 336 in^2 for fan C). See Figure S2 in the supplemental information for diagrammatic pictures of the fans. These differences in fan characteristics may account for their significantly different performance in removing pollutants during cooking; however, further testing is necessary to confirm these findings. Continuing to run fan A for 15 min after cooking reduced integrated exposures, but they still remained higher than when using the more effective fans (B and C, starting at 147 cfm) and turning them off immediately after cooking.

The primary goal of this study was to examine whether continuing to run an exhaust fan after cooking could significantly reduce exposure to cooking emissions. The added air exchange of a cooking fan is expected over time to lead to decreases in concentrations; however, there are tradeoffs to long-term use of a fan. One of the main reasons people state for not using a kitchen fan is the noise it generates, which can often be loud enough to impede ordinary conversation [15,31]. Although kitchen fans generally impose a small energy cost and are a very energy efficient means of improving indoor air quality, this cost does increase in extreme climates where the replacement air must be heated or cooled [13]. In these climates, the diminishing indoor air quality benefits of extended fan use must be balanced against energy costs. Due to these considerations, it is impractical to suggest home cooks use their exhaust fans for long periods after cooking. Our analysis therefore focused on estimating the effects of running the fan for an additional 15 min following cooking, and then turning it off.

Our modelled 1-h integrated exposures were consistently lower with the fan kept running for an extra 15 min, but due to the wide confidence intervals from propagating errors, these differences did not reach statistical significance in most cases. The condition for which the difference was statistically significant was fan C at 309 cfm, which showed 80% lower UFP levels with the fan kept running for an extra 15 min

Table 2
Results of multiple regression models predicting decay rates and integrated exposures after cooking. The following predictors were included in all models: fan on after cooking (as an indicator variable), the fan flow rate (a continuous variable in 100 cfm intervals), fan type (a categorical variable with three levels, dummy coded and entered in the model as two indicator variables, fan A and fan B, with fan C serving as the baseline case), and an interaction variable of flow rate and fan ON (a continuous variable in 100 cfm intervals for all tests where the fan was left on after cooking).

Outcome variable	Pollutant Modelled	N	Multiple Regression Coefficient [95% CI]				
			Fan On After Cooking	Fan flow rate (100 cfm intervals)	Fan A	Fan B	Flow rate * Fan On After Cooking
0 to 15 Min Integrated Exposure (from end of cooking)	UFP (cm^{-3} x10^3 h)	59	−4.30 [-10.6, 2.02]	−7.94 [-10.6, −5.30]	15.79 [12.06, 19.52]	3.40 [-0.18, 6.97]	0.75 [-2.38, 3.87]
	$PM_{2.5}$ ($\mu g\,m^{-3}$ h)	57	−3.19 [-6.19, −0.19]	−2.81 [-4.02, −1.59]	5.52 [3.80, 7.25]	0.41 [-1.21, 2.03]	0.98 [-0.55, 2.52]
	NO_2 (ppb h)	60	−0.39 [-1.49, 0.72]	−2.03 [-2.49, −1.57]	0.99 [0.33, 1.64]	−1.12 [-1.73, −0.50]	0.14 [-0.41, 0.69]
	NO (ppb h)	59	−1.62 [-6.30, 3.06]	−8.54 [-10.5, −6.59]	5.23 [2.47, 8.00]	−3.52 [-6.12, −0.93]	0.52 [-1.80, 2.84]
Decay Rate (from peak to one hour after cooking)	UFP (hr^{-1})	57	−0.34 [-0.91, 0.22]	−0.03 [-0.26, 0.20]	−0.25 [-0.58, 0.07]	0.21 [-0.10, 0.52]	0.60 [0.31, 0.89]
	$PM_{2.5}$ (hr^{-1})	33	0.19 [-2.78, 3.16]	0.42 [-1.11, 1.94]	−1.63 [-3.06, −0.20]	−0.45 [-1.84, 0.95]	0.64 [-1.21, 2.48]
	NO_2 (hr^{-1})	46	0.08 [-0.37, 0.54]	−0.18 [-0.39, 0.02]	0.53 [0.32, 0.74]	0.67 [0.47, 0.87]	0.18 [-0.09, 0.46]
	NO (hr^{-1})	45	−1.59 [-3.16, −0.03]	0.20 [-0.53, 0.94]	−0.79 [-1.53, −0.05]	−0.02 [-0.72, 0.68]	1.63 [0.71, 2.55]

Table 3
Fifteen-minute integrated cooking exposures in the kitchen area [95% confidence interval] calculated as the area under the curve from the end of cooking to 15 min following. The background concentration has been removed prior to calculations. Results in bold indicate statistically significant differences, as determined by the Student's t-test with p-level less than 0.05).

Fan Flow Rate (cfm)	Fan status after cooking	UFP (cm^{-3} x 10^3 h)		$PM_{2.5}$ (μg m^{-3} h)		NO_2 (ppb h)		NO (ppb h)	
		N	Mean [95% CI]	N	Mean [95% CI]	N	Mean [95% CI]	N	Mean [95% CI]
76 (fan B)	Off	5	28.2 [23.1, 33.3]	5	7.9 [2.5, 13.3]	5	4.0 [3.0, 4.9]	5	17.2 [13.1, 21.2]
	On	5	22.4 [17.2, 27.6]	5	5.6 [4.7, 6.4]	5	3.4 [2.8, 4.0]	5	15.6 [13.7, 17.4]
147 (fan C)	Off	5	16.5 [10.8, 22.2]	5	3.3 [1.6, 5.1]	5	2.5 [1.9, 3.1]	5	10.3 [7.9, 12.8]
	On	5	15.0 [11.0, 18.9]	5	3.0 [1.3, 4.7]	5	3.1 [1.7, 4.5]	5	11.4 [6.4, 16.5]
158 (fan A)	Off	5	33.3 [23.8, 42.8]	5	**11.4 [7.1, 15.7]**	5	4.0 [2.1, 5.8]	5	17.0 [9.3, 24.7]
	On	5	29.1 [22.6, 35.7]	5	**6.7 [5.7, 7.6]**	5	3.5 [2.2, 4.8]	5	15.4 [9.6, 21.1]
179 (fan B)	Off	5	17.3 [9.0, 25.5]	5	2.5 [1.3, 3.7]	5	0.9 [0.1, 1.7]	5	4.3 [-0.9, 9.5]
	On	4	16.8 [6.5, 27.2]	5	2.5 [1.1, 3.9]	5	0.7 [0.5, 0.8]	5	2.8 [2.3, 3.2]
254 (fan C)	Off	5	9.7 [4.2, 15.1]	4	1.4 [-1.6, 4.4]	5	0.6 [0.3, 0.9]	5	1.9 [1.2, 2.7]
	On	5	8.6 [6.1, 11.1]	5	0.9 [0.5, 1.4]	5	0.5 [0.3, 0.7]	5	1.8 [1.5, 2.1]
309 (fan C)	Off	5	**5.6 [2.3, 8.9]**	5	0.8 [0.1, 1.5]	5	0.3 [0.2, 0.4]	5	0.6 [0.5, 0.7]
	On	5	**1.4 [0.7, 2.1]**	3	0.9 [-0.9, 2.6]	5	0.3 [0.1, 0.5]	5	0.5 [0.4, 0.7]

Table 4
One-hour integrated exposures in the kitchen area [95% confidence interval] comparing exposures when the fan is immediately turned off after cooking, versus leaving the fan on for 15 min after cooking and then turning it off. The first 15 min of the time period are calculated directly from the data. The remainder of the period is modelled using the average decay rate observed for that pollutant with the fan off. The background concentration has been removed prior to all calculations.

Fan Flow Rate (cfm)	Fan status after cooking	UFP (cm^{-3} x 10^3 h)		PM2.5 (μg m-3 h)		NO2 (ppb h)		NO (ppb h)	
		N	Mean [95% CI]	N	Mean [95% CI]	N	Mean [95% CI]	N	Mean [95% CI]
76 (fan B)	Off immediately	5	64.0 [54.3, 74.1]	5	17.3 [8.4, 27.9]	5	9.6 [8.1, 11.2]	5	50.2 [42.1, 58.9]
	On for 15 min then off	5	49.6 [40.4, 59.2]	5	11.8 [9.8, 14.4]	5	8.3 [7.1, 9.5]	5	44.6 [41.4, 47.9]
147 (fan C)	Off immediately	5	36.6 [29.3, 44.1]	5	6.5 [4.2, 9.1]	5	6.3 [5.4, 7.2]	5	26.9 [22.7, 31.3]
	On for 15 min then off	5	32.4 [26.8, 38.2]	5	6.0 [2.9, 9.9]	5	7.1 [5.0, 9.2]	5	29.0 [20.5, 37.9]
158 (fan A)	Off immediately	5	80.9 [66.4, 95.9]	5	25.4 [18.8, 33.0]	5	9.8 [6.8, 12.9]	5	49.7 [35.6, 64.5]
	On for 15 min then off	5	70.0 [60.3, 80.0]	5	14.3 [11.8, 17.4]	5	8.6 [6.4, 10.8]	5	44.5 [33.9, 55.6]
179 (fan B)	Off immediately	5	40.5 [27.6, 53.8]	5	5.7 [3.8, 7.8]	5	2.3 [1.1, 3.5]	5	13.1 [3.5, 23.3]
	On for 15 min then off	5	32.9 [16.0, 50.3]	5	5.6 [3.2, 8.5]	5	1.8 [1.5, 2.1]	5	9.3 [8.1, 10.6]
254 (fan C)	Off immediately	5	23.8 [14.8, 33.2]	5	2.6 [-1.1, 6.7]	5	1.5 [0.9, 2.2]	5	5.4 [3.7, 7.3]
	On for 15 min then off	5	18.1 [13.4, 23.0]	5	1.8 [1.0, 2.8]	5	1.3 [0.9, 1.7]	5	5.0 [4.3, 5.8]
309 (fan C)	Off immediately	5	17.7 [10.3, 25.4]	5	1.9 [0.7, 3.4]	5	0.8 [0.5, 1.1]	5	1.7 [1.4, 2.0]
	On for 15 min then off	5	3.7 [2.7, 4.7]	5	1.6 [-1.0, 4.7]	5	0.7 [0.4, 1.0]	5	1.3 [1.1, 1.6]

after cooking (Table 4). The majority of the error in the analysis originates from modeling $IE_{15min–1h}$ (Equation (5)). The differences we observed were larger for UFP and $PM_{2.5}$ than for NO_2 and NO. Overall, running a fan for 15 min following cooking may offer reductions in exposure to particulate matter, but fan flow rate and other physical characteristics that influence capture efficiency during cooking are the primary determinants of integrated exposures.

3.4. Limitations

The main limitation of this work is the relatively small number of cooking tests we performed that limited our ability to find statistically significant differences across test conditions. Although we made significant efforts to ensure consistency across cooking tests, we still observed significant variability in cooking emissions between tests of the same fan conditions. This variability propagated through our calculations, and resulted in broad confidence intervals.

We also tested a limited number of fans, which limits our ability to make broader conclusions about the effect of different fan characteristics. Specifically, it became clear that fan A performed significantly worse than fans B and C. Potentially this was due to lower coverage of the front burners or smaller air intake area, but our sample size was too small to definitively conclude this. We also did not perform cooking tests without any fan running, which limits our ability to comment on the full emissions of the cooking test and calculation of the capture efficiency. It should also be noted that the tests were conducted in airtight test homes with the windows closed, and the pollutant distribution we observed in these conditions may not apply in homes with other ventilation conditions.

4. Conclusions

Regression models demonstrated that running an exhaust fan for 15 min after cooking offered similar reductions in $PM_{2.5}$ to that achieved by a 100cfm increase in the flow rate of the fan used while cooking, demonstrating that one can partially compensate for a low flow rate by continuing to run the fan after cooking. However, for the majority of tested flow rates and pollutants, the reductions observed from continuing to run a fan after cooking did not reach statistical significance. The flow rate and physical characteristics of the exhaust fan used during cooking were the most important determinants of integrated exposures following cooking. Running Fan C at 309 cfm during cooking compared to running Fan B at 76 cfm during cooking reduced the 1-h integrated exposures to UFP by 72% (95% CI: 53–86%), to $PM_{2.5}$ by 89% (95% CI: 60–97%), to NO_2 by 92% (95% CI: 86–96%), and to NO by 97% (95% CI: 95–98%). Using the back burner when feasible will also significantly reduce emissions, especially if the fan does not have good coverage of the front burners.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2018.02.039.

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