ASHRAE®
Fall 2006
IAQ Applications
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Vol. 7, No. 4

Can Displacement Ventilation Control Secondhand ETS?

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Various hospitality organizations and the tobacco industry have promoted displacement ventilation as a solution to controlling secondhand tobacco smoke (SHS) exposure by citing it in presentations to city councils and public meetings concerning smoking restrictions.[1]

This article examines these claims with research on displacement ventilation's effectiveness at hospitality venues.

Displacement Ventilation

ASHRAE[2] has unequivocally ruled out dilution ventilation as a control for SHS (also known as environmental tobacco smoke, or ETS), stating in part:

> *…although complete separation and isolation of smoking rooms can control ETS exposure in nonsmoking spaces, in the same building, adverse health effects for the occupants of the smoking room cannot be controlled by ventilation. No other engineering approaches, including current and advanced dilution ventilation or air cleaning technologies, have been demonstrated or should be relied upon to control health risks from ETS exposure in spaces where smoking occurs.*

A Canadian experimental study purported to show that the unidirectional airflow of a displacement system can be used to control SHS in upstream nonsmoking areas contiguous to downstream smoking areas despite open connecting passageways. Ontario and Toronto hospitality associations opposed smoke-free proposals, asserting a demonstration study[3] they sponsored that used unrecirculated displacement ventilation in the Black Dog Pub actually achieved nonsmoking area SHS concentrations comparable to venues with total smoking bans.[4] However, this study was flawed because its control venues had measurable nicotine contamination and employee exposure in the smoking bar area was ignored. The Black Dog Pub permitted smoking in its bar area until 2004, when it went smoke-free.

In Mesa, Ariz., TGI Friday's (TGIF), and Macaroni Grill (MacGrill) both had smoking-permitted bar areas contiguous to nonsmoking dining areas, connected by large open passageways. Both used unrecirculated displacement ventilation technology, claiming that this new technology would satisfy Mesa's smokefree restaurant ordinance.

To experimentally test the claims made by proponents of displacement technology, we made concealed air quality measurements in both the smoking and nonsmoking areas of the Black Dog Pub in 2002 and in the TGIF and Macaroni Grill in 2003. We remeasured the Black Dog Pub in 2004 after it had banned smoking. We also performed control measurements in six nonsmoking pubs with dilution ventilation in Ottawa in 2002.

The Toronto study. Located near Toronto, the Black Dog Pub has a smoking bar area with a seating capacity of 45 persons, with 15 seats at the bar and eight tables. An adjacent nonsmoking dining room seats 99 persons at 20 tables, and is separated from the bar by a wall with two pass-through windows and two open doorways. Ventilation is provided by a 3,100 cfm (1463 L/s) energy/heat recovery ventilation system (HRV) tied into two rooftop HVAC units, with a capacity of 5 tons

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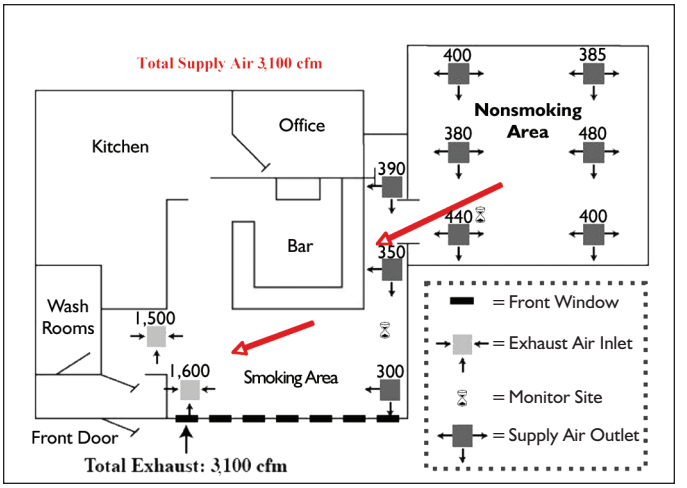
Inside

A substantial reduction to the required ventilation rate for homes is proposed. See Pages 12–15.



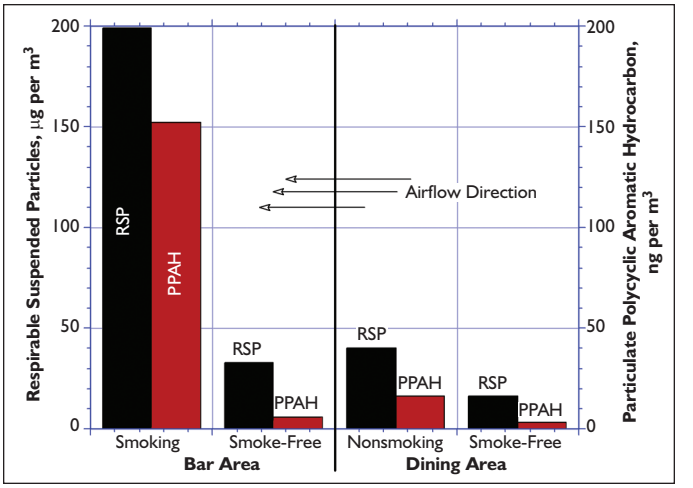


***Figure 1 (at left): General layout of the Black Dog Pub, with airflow rates in cfm/occupant. Arrows show direction of airflow from supplies to returns.[3,8] Figure 2 (at right): Respirable suspended particles (RSP) and particulate polycyclic aromatic hydrocarbon (PPAH) pollutant concentrations in the smoking and nonsmoking sections of the Black Dog Pub. A smoking ban decreased PPAH carcinogens by 96% in the smoking bar room, and by 80% in the nonsmoking dining room. Fine particles decreased by 83% in the bar, and by 60% in the dining room. Post-ban dining area RSP levels exceeded outdoor background, while PPAH levels were lower than outdoors, as shown in* Table 1.**

Smoke, From Page 1

(17.5 kW) each. The system creates directional flow of air from the nonsmoking dining area to the smoking bar area, where it is exhausted without recirculation (*Figure 1*), while energy (heating and cooling) is recovered by the HRV desiccant wheel on the exhaust side. The ventilation system introduces 1,600 cfm (755 L/s) of fresh air from the west side into the nonsmoking dining area and 1,500 cfm (708 L/s) at the borderline between smoking and nonsmoking.[3] To ensure optimal performance, after installation, smoke tests were carried out in the smoking and nonsmoking sections, and a purge unit and filters were added following initial sampling.[3]

We measured smoking and nonsmoking areas simultaneously with real-time monitors for respirable suspended particles (RSP) ($PM_{3.5}$) and carcinogenic particulate polycyclic aromatic hydrocarbons (PPAH). We assessed temperature, relative humidity, and ventilation from CO_2. The methods and instrument calibration are described in detail in a previous study.[5]

Toronto Results. We first visited the Black Dog Pub on Friday evening, Dec. 13, 2002, when smoking was permitted. Nonsmoking volunteers occupied the tables in each area where the monitors were located throughout the sampling period, as shown in *Figure 1*, rotating in and out after their drinks and meals were finished, so that the tables were occupied throughout the evening. Real-time measurements of RSP, PPAH, and CO_2 were made simultaneously indoors for 4.35 hours, and outdoors before and after the indoor measurements, for a total of 0.6 hours. The Black Dog's nonsmoking dining room area measured 690 ft2 (64 m^2), with a volume of 7,204 ft^3 (204 m^3), and the smoking bar area measured 1,089 ft^2 (101 m^2), with a volume of 10,418 ft^3 (295 m^3). An average of 50 occupants were present in the bar area, measured 11 times during the sampling period, with an average of 6.94 active smokers, measured 16 times during the sampling period. This equates to an estimated smoking prevalence of 3 × 6.94/50 = 41.6%, using the method of Repace and Lowrey,[5] which estimates the number of smokers present from the average number of burning cigarettes by multiplying by 3. An average of 50.6 persons were also present in the nonsmoking dining room during the same period. CO_2 levels were measured the following Sunday due to a malfunction in the monitor on Friday, and were also estimated from data provided by Jenkins[3] with similar results: 29 cfm/occupant (14.5 L/s per occupant). This complied with Standard 62-2001's recommendation of 30 cfm/occupant (15 L/s per occupant) for bars.

The Black Dog study was repeated on Friday, Dec. 10, 2004, after the pub went smoke-free. Real-time measurements of RSP, PPAH, and CO_2 were made simultaneously indoors for 4.8 hours, and outdoors, before and after the indoor measurements, for a total of 0.9 hours. CO_2 levels showed a decline in outdoor air supply to 5 L/s per occupant, in compliance with the Standard 62.1-2004 recommendation for nonsmoking bars. However, the air quality felt stuffy. *Table 1* summarizes the Black Dog measurements.

Despite a ventilation rate of 30 cfm/occupant (15 L/s per occupant), pre-ban measurements in the Black Dog's smoking section in 2002 showed RSP levels of 199 µg/m^3 (standard deviation [SD] of 92 µg/m^3), 10 times outdoors. Post-ban Black Dog smoking area RSP levels in 2004 declined 83%. Black Dog pre-ban nonsmoking area RSP levels averaged 40 µg/m^3 (SD 13 µg/m^3). Black Dog

Area	Date	RSP	PPAH	CO_2	Person Count	Avg. No. Smokers Of Active Smokers	Est. OA Flow Rate Per Person, V_o
Bar, Smoking Section	12/13/02	199 μg/m³ (SD 92) [*n* = 266]	152 ng/m³ (SD 82) [*n* = 262]	—	50 (SD 12) [*n* = 11]	6.94 (SD 2.44) [*n* = 16]	—
Restaurant, Nonsmoking Section	12/13/02	40 μg/m³ (SD 13) [*n* = 259]	16 ng/m³ (SD = 20) [*n* = 259]	—	50.6 (SD 14.2) [*n* = 7]	0	—
Combined Bar/Rest.	12/13/02				100.6 [*n* = 18]	—	14.5 L/s[a,b] 12.7 L/s[f]
Outdoors	12/13/02	21 μg/m³ (SD 9.9) [*n* = 38]	4.4 ng/m³ (SD 3.9) [*n* = 30]	—	—	0	—
Bar, Smoking Section	12/15/02	—	—	760 ppm (SD 95) [*n* = 65]	31.8 (SD 4.27) [*n* = 5]	2.8 (SD 1.8) [*n* = 5]	23 L/s[c]
Restaurant, Nonsmoking Section	12/15/02	—	—	701 ppm (SD 68) [*n* = 65]	24 (SD 13.5) [*n* = 6]	0	32 L/s[c]
Combined Bar/Rest. 4:40–5:45 p.m.	12/15/02	—	—	730.5 ppm (avg.)	54.4 (SD 12.3) [*n* = 11]	—	26.8 L/s[c]
Outdoors	12/15/02	—	—	544[d] ppm 532[e] ppm	—	0	—
Bar, Smoke-Free	12/10/04	33 μg/m³ (SD = 22) [*n* = 296]	5.7 ng/m³ (SD = 4.1) [*n* = 290]		34 (SD = 6.0) [*n* = 10]	0	—
Restaurant, Smoke-Free	12/10/04	16 μg/m³ (SD 11) [*n* = 281]	3.1 ng/m³ (SD 2.2) [*n* = 278]	1518 ppm (SD 132) [*n* = 279]	37 (SD 7.0) [*n* = 10]	0	5 L/s
Outdoors	12/10/04	0.96 μg/m³ (SD 1.3) [*n* = 54]	5.1 ng/m³ (SD 2.8) [*n* = 49]	469 ppm (SD 11) [*n* = 11]	—	0	—

[a] Value obtained from design flow rate,[3] divided by observed occupants. [b] Value obtained from scaling Dec. 15 V_o by ratio of combined occupancy on Dec. 15 to combined occupancy Dec. 13. [c] Estimated using equation from ASHRAE Standard 62-1999, Appendix D. [d] Estimated by dividing total airflow[3] by total average persons (Dec. 15, 2002, Table entry), and applying equation from ASHRAE Standard 62-1999, Appendix D. [e] Lowest observed value. [f] Equivalent V_o to 9.6 air changes per hour, derived from habitual smoker mass-balance model, and 100.6 occupants.

Table 1: Black Dog Pub ventilation parameters, pre- and post-voluntary smoking ban.

post-ban nonsmoking area RSP levels declined 60%, and were higher than outdoors. Pre-ban Black Dog smoking area PPAH levels averaged 152 ng/m³ (SD 82 ng/m³), 35 times outdoors. Post-ban Black Dog smoking area PPAH levels averaged 5.7 ng/m³ (SD 4.1 ng/m³), a decline of 96%, and were comparable to outdoors. Pre-ban Black Dog nonsmoking area PPAH levels averaged 16 ng/m³ (SD 20 ng/m³), about four times outdoors. Post-ban Black Dog nonsmoking area PPAH levels in 2004 declined by 80% to 3.1 ng/m³ (SD 2.2 ng/m³) and were lower than outdoors. These results are plotted in *Figure 2*.

Despite proper design, operation and ventilation rate, the measurements in the Black Dog Pub's smoking section in 2002 showed RSP levels 25% higher than our U.S. controls, six smoking bars with dilution ventilation measured pre-ban in Wilmington, Del., while Black Dog Pub pre-ban nonsmoking area RSP levels averaged 40 μg/m³ (SD 13 μg/m³), 3.5 times higher than the six smoke-free Wilmington bars post-ban.[6,7] Pre-ban Black Dog Pub smoking area PPAH levels averaged 40% higher than the pre-ban mean for the six smoking Wilmington bars, while Black Dog Pub nonsmoking area post-ban PPAH levels were only 14% higher than for the six Wilmington bars post-ban. The Black Dog's post-ban dining room still had levels of RSP much higher than outdoors (*Table 1*), likely due to infiltration of smoke from the kitchen; however PPAH levels reduced to 60% of outdoor values.

The Mesa Study. The air quality measurements described for the Black Dog Pub were repeated in two Mesa, Arizona, pubs: TGI Fridays (TGIF) and Macaroni Grill (MacGrill), both of which also provided unrecirculated displacement ventilation with smoking bars and contiguous nonsmoking dining rooms.

Representatives of these two pubs asserted that the proposed displacement ventilation systems would satisfy Mesa's smoke-free restaurant ordinance despite open doorways from the bar areas to the restaurants.

Our measurements were conducted to test this assertion, with assistance from nonsmoking volunteers, who occupied the tables in each area where the monitors were located throughout the sampling period, so that monitoring sites were occupied throughout each evening.

Mesa Results. A researcher visited TGIF on Thursday evening, March 6, 2003, and the MacGrill on the next evening. Real-time measurements of RSP, PPAH, and CO_2 were made simultaneously indoors in TGIF for three hours, and outdoors, which included travel from Tempe to Mesa before and after the indoor measurements, for a total of 5.75 hours. As shown in *Table 2*, the TGIF's nonsmoking dining room area measured 2,592 ft² (240 m²), with a volume of 28,499 ft³ (807 m³), and the smoking bar area measured 1,458 ft² (135 m²), with a volume of 16,033 ft³ (454 m³). An average of 39 persons were present in the bar area, measured seven times during the sampling period, with an

Location, Volume	Date	RSP [n = no. min.]	PPAH	CO_2	Person Count [n = no. counts]	Avg. No. Smokers Of Active Smokers (Cigarettes) [n = no. counts]	Est. OA Flow Rate Per Person, V_o
MacGrill Bar, (161 m^3 Smoking Section)	3/7/03	80 µg/m^3 (SD 42) [n = 320]	304 ng/m^3 (SD 82) [n = 305]	975 ppm	32.5 (SD 11.7) [n = 8]	0.43 (SD 0.68) [n = 21]	9.43 L/s[a] 5.2 L/s[b]
MacGrill Rest., (1545 m^3 Non-Smoking Section)	3/7/03	229 µg/m^3 (SD 288) [n = 320]	451 ng/m^3 (SD = 288) [n = 305]	—	175 (SD 24.5) [n = 6]	0	—
Combined Bar/Rest. (1706 m^3)	3/7/03	—	—	—	207.5 [n = 14]	—	—
Outdoors, In Transit	3/7/03	7 µg/m^3 (SD 11) [n = 269]	11 ng/m^3 (SD 11) [n = 269]	445 ppm		0	—
TGIF Bar, 454 m^3 Smoking Section	3/6/03	205 µg/m^3 (SD 250) [n = 180]	13 ng/m^3 (SD 14) [n = 181]	900 ppm	39 (SD 6) [n = 7]	2.04 (SD 0.93) [n = 25]	14.3 L/s[a] 9.4 L/s[b]
TGIF Rest., 807 m^3 Nonsmoking Section	3/6/03	306 µg/m^3 (SD 246) [n = 180]	2 ng/m^3 (SD 4) [n = 182]	—	110 (SD 43) [n = 5]	0	—
Combined Bar/Rest., 1261 m^3	3/6/03	—	—	—	149 [n = 12]	—	—
Outdoors, In Transit	3/6/03	7.5 µg/m^3 (SD 3.9) [n = 345]	15 ng/m^3 (SD 16) [n = 313]	550 ppm	—	0	—

[a] Estimated from CO_2 differences. [b] Estimated from active smoker model.

Table 2: Two Mesa displacement ventilation pubs. One minute average ventilation parameters.

average of 2.04 active smokers, measured 16 times during the sampling period, and equating to an estimated smoking prevalence of $3 \times 2.04/39 = 15.7\%$. The active smoker density averaged $100 \times 2.04/161 = 1.27$ burning cigarettes per 3,530 ft^3(100 m^3). An average of 110 persons were present in the dining room during the same period. CO_2 levels corresponded to 29 cfm/occupant (14.5 L/s per occupant), equivalent to 6.7 air changes per hour (h^{-1}), in compliance with ASHRAE 62-2001's recommendation of 15 L/s per occupant for bars. However, the air exchange rate calculated using the active smoker model was lower, at 4.4 h^{-1}.

Bar smoking area RSP and PPAH levels were, respectively, 205 µg/m^3 and 13 ng/m^3, 27 and 0.87 times outdoor levels. Dining room nonsmoking area RSP and PPAH levels averaged, respectively, 306 µg/m^3 and 2 ng/m^3, 27 and 0.13 times outdoor levels. However, the real-time PPAH data (not given) shows two periods: two hours while an outside door to the bar was propped open when the PPAH levels averaged 0.16 ng/m^3, and an hour when that door was closed, when PPAH averaged 4.7 ng/m^3, or 36% of the smoking section value. A strong odor of disinfectant permeated the lobby, indicating that restroom air was not being properly exhausted. Kitchen odors were also noticed in the dining area, suggesting that the HVAC system may have been improperly balanced.

Similarly, real-time measurements of RSP, PPAH, and CO_2 were made simultaneously indoors in the MacGrill for a period of 5.3 hours, plus outdoors, which included travel from Tempe to Mesa before and after the indoor measurements, for a total of 4.5 hours. As shown in *Table 2*, MacGrill's nonsmoking dining room area measured 3,762 ft^2 (350 m^2), with a volume of 54,562 ft^3 (1545 m^3), and the smoking bar area measured 567 ft^2 (53 m^2), with a volume of 5,721 ft^3 (162 m^3). An average of 32.5 persons were present in the bar area, measured eight times during the sampling period, with an average of 0.43 active smokers, measured 21 times during the sampling period, and equating to an estimated smoking prevalence of $3 \times 0.43/32.5 = 4\%$. The active smoker density averaged $100 \times 0.43/161 = 0.27$ burning cigarettes per 3,530 ft^3 (100 m^3). An average of 175 persons occupied the dining room during the same period. CO_2 levels yielded 19 cfm/occupant (9.6 L/s per occupant), out of compliance with the Standard 62-2001 recommendation of 30 cfm/occupant (15 L/s per occupant) for bars, but in compliance with 20 cfm/occupant (10 L/s per occupant) for restaurant dining rooms. The CO_2-estimated air exchange rate is equivalent to 6.9 h^{-1}. However, the air exchange rate calculated by the active smoker model was lower, at 3.8 h^{-1}. Bar smoking area RSP and PPAH levels were, respectively, 80 µg/m^3 and 304 ng/m^3, 11 and 28 times outdoor levels. Restaurant nonsmoking area RSP and PPAH levels were respectively 229 µg/m^3 and 451 ng/m^3, 33 and 41 times outdoor levels.

The kitchen area was broadly open to the nonsmoking dining room, and the aroma of roasting meats penetrated into the dining area, suggesting that the ventilation system may have been improperly balanced.

Mesa Discussion. For TGIF, the RSP and PPAH levels were high, similar in smoking and nonsmoking areas, and pollutants were apparently exhausted from kitchens and restrooms, suggesting ventilation systems improperly balanced. Although the TGIF had apparently ASHRAE-specified amounts of outdoor air supply as derived from the CO_2 measurements, the HVAC system was seriously

out of balance, such that levels of RSP were higher in the nonsmoking section than the smoking section, a phenomenon observed in four hospitality venues with dilution ventilation in a Finnish study.[8] PPAH carcinogen levels were lower on average in nonsmoking than smoking in the TGIF, but were a substantial fraction of those in smoking during one-third of the monitoring period.

Similarly, PPAH carcinogen levels in the MacGrill were higher in nonsmoking than in smoking. The MacGrill had a CO_2-derived ventilation rate measured in the bar area smoking section that was appropriate for a restaurant, but only 64% of that appropriate for a bar. Air-exchange rates estimated using the active smoker model were lower, and may be more accurate than CO_2 methods. Clearly, both of these pubs had ventilation systems that were improperly designed, installed, operated, or maintained.

The Ottawa Study. Ottawa, Canada's capital, adopted a 100% smoke-free bylaw for all public places and all workplaces including bars and restaurants on Aug. 1, 2001. Canadian control measurements were performed over six hours, from 6 p.m. to midnight on Thursday, Dec. 12, 2002, by way of a "pub crawl" through six busy smoke-free Ottawa bars with dilution ventilation.

These pubs ranged in volume from 7805 ft^3 to 30,795 ft^3 (221 m^3 to 872 m^3), and averaged 19,034 ft^3 (539 m^3), SD 7,381 ft^3 (SD 209 m^3); the occupancy ranged 32–198 persons and averaged 76 (SD 62) persons. The monitoring yielded indoor levels of PPAH and RSP in most cases comparable to outdoors; however, outdoor air was more polluted in Ottawa than Toronto due to outdoor wood smoke from fireplaces, which could be smelled widely in Ottawa's streets.

Notably, two of the Ottawa pubs had elevated contaminant levels from IAQ problems. The first apparently was caused by backdrafting of a fireplace in one venue, thereby producing elevated PPAH. The other venue had oil-burning candles, producing both elevated RSP and PPAH.

Averaging the data for the five venues with no evident RSP sources yielded 25 $\mu g/m^3$ (SD 7.5), and for the four venues with no evident PPAH sources yielded 27 ng/m^3 (SD 11). All six venues, including those with IAQ problems, averaged 34 $\mu g/m^3$ (SD 23) RSP, and 66 ng/m^3 (SD 75) PPAH. By comparison, time-weighted outdoor RSP and PPAH levels averaged 33 $\mu g/m^3$, and 44 ng/m^3, respectively for 55 and 50 min. averages in the busy downtown locations.

Conclusions

The displacement (directed flow) ventilation systems in the two Mesa pubs were improperly designed, implemented, or operated, resulting in high levels of respirable particles and carcinogens in the nonsmoking dining room as well as the smoking bar. In contrast, the Black Dog Pub's displacement ventilation system appears to have been properly designed, implemented, and operated; yet the pre-ban levels of respirable particles and carcinogens in the nonsmoking dining room measured 60%–65% higher than after a smoking ban, despite a post-ban decrease in ventilation rate by two-thirds. The levels of smoke pollution in the Black Dog's bar area were higher than the average of six smoking bars with dilution ventilation studied in Wilmington, Del.

Displacement ventilation is not a viable substitute for smoking bans in controlling ETS exposure in either designated smoking areas or in contiguous designated nonsmoking areas sharing the same space volume.

Acknowledgments

J.L. Repace was supported by the Innovator Award of the Robert Wood Johnson Foundation. We are grateful to Ms. Nina Jones, Ms. Ali Kamen, and Dr. Lee Fairbanks in the Mesa Study, and Dr. Roberta Ferrence, Ms. Jacqui Drope, and Mr. Garfield Mahood in the Black Dog study for arranging for nonsmoking volunteers to assist with these field experiments. The authors thank the Toronto volunteers from the Ontario Tobacco Control Unit and the Nonsmokers' Rights Association, and the Mesa volunteers from the Coalition for a Tobacco Free Arizona, Arizona Clearing the Air, the Arizona Department of Health Services, Smoke-Free Chandler, and Arizonans Concerned About Smoking.

The views presented here represent those of the authors and do not necessarily represent those of the Public Health Agency of Canada.

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