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Accuracy and practicality of a portable ozone monitor for personal exposure estimates

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Abstract

Accurate measurements of personal exposure to atmospheric pollutants such as ozone are important for understanding health risks. We tested a new personal ozone monitor (POM; 2B Technologies) for accuracy, precision, and ease of use. The POM's measurements were compared to simultaneous ozone measurements from a 2B Model 205 monitor and a ThermoScientific 49i monitor, and multiple POMs were placed side-by-side to check precision. Tests were undertaken in a controlled environmental facility, outdoors, and in a private residence. Additionally, ten volunteers wore a POM for five days and answered a questionnaire about its ease of use.

The POM measured ozone accurately compared to the 49i ozone monitor, with average relative differences of less than 8%. In the controlled environment tests, the POM's ozone measurements did not change in the presence of additional atmospheric constituents with similar absorption lines to ozone, though there may have been a small decrease in precision and accuracy. Precision between POMs varied by environment ($r^2 = 0.98$ outdoors; $r^2 = 0.3$ to 0.9 in controlled lab conditions). Volunteers reported that the POM was reasonably comfortable to wear, although all reported that they felt that it was too noisy. Overall, the POM is a viable option for personal ozone monitoring.

1. Introduction

Ozone (O_3) is one of the Environmental Protection Agency's criteria pollutants. Increased concentrations of ozone are associated with decreased lung function (Brauer and Brook, 1997) and an increase in daily morbidity and mortality (Bell et al., 2014; Ito et al., 2005; Sunyer et al., 2002; Weisel et al., 2002) at elevated levels. However, characterization of the level and pattern of personal ozone exposure with a resolution of minutes has been limited due to lack of personal ozone monitors. Rather, integrated ozone measurements, ambient ozone concentration and model approaches have been used as a surrogate for personal exposure in health studies (Bell, 2006; Jerrett et al., 2009). Quantifying personal exposure to ozone is thus important for understanding health effects, which may be a result of peak

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concentration, short term excursions or repetitive average daily exposures measured as an integrated concentration, which has led to changes in the ozone standard in the United States (Rombout et al., 1986). Exposure to ozone changes throughout a day due to its production, removal processes and transport in ambient air, its losses when transported indoors and people's movement between indoor and outdoor locations (Weschler et al., 1989). These changes will not be identified from a long term integrated sample. Personal sampling, in which a person wears sampling equipment for a period of time, provides a more accurate representation of the amount of a pollutant that is inhaled than stationary or central point ambient air monitoring, since peak values differ over small spatial regions (Monn, 2001) and there are losses of ozone when it is transported indoors (Liu et al., 1993; Weschler, 2006). Furthermore, central point ambient air monitoring does not account for indoor ozone concentrations, which have been measured to be 3 to 60% of the ambient concentration depending upon the ventilation system and air exchange rate (Lee et al., 2004; Liu et al., 1995; Zhang and Li, 1994). Ozone personal samplers based on passive badges have been successfully used in exposure studies (Demirel et al., 2014; Koutrakis et al., 1994; Liard et al., 1999; Liu et al., 1995) but only provide average concentrations over extended time periods and require chemical laboratories to analyze the badge. Recently, several small continuous ozone monitors have been proposed or developed for incorporation into personal samplers based on: semi-conductions sensors (Cao and Thompson, 2016; Piedrahita et al., 2014), electrochemical cells (Cho, 2015; Pang et al., 2017), dispersive surface acoustic wave (SAW) (Westafer et al., 2014) and ultraviolet light adsorption (Andersen et al., 2010). Several strengths and weaknesses of these systems have been reviewed (e.g., McKercher et al., 2017; Snyder et al., 2013).

The Personal Ozone Monitor (POM; http://www.twobtech.com/model_POM.htm) was developed by 2B Technologies to address the need for a lightweight, portable, battery operated, and moderately-price (\$4,500) way to measure personal exposure to ozone using a similar premise to the 2B Technology 205 ozone monitor (Andersen et al., 2010). In this study, we evaluate POM precision and accuracy 1) within a controlled environmental of ozone alone and in the presence of additional compounds, 2) outdoors in the ambient environment, and 3) indoors in a private residence. Additionally, the POM was evaluated by volunteers for practicality for everyday personal use. The study design is summarized in Table 1.

2. Methods

2.1 Instrument description

Similar to 2B's 205 ozone monitor, the POM uses the absorption of UV light at 254 nm to determine ozone concentrations, but with a curved optical path, thus reducing the size of the instrument (10cm×7.6cm×3.8cm, 0.45kg, power requirements of 2.9W supplied by a Lithium Ion 7.4V battery which operates up to 8 hours on a charge). The POM operates at a flow rate of 0.8 L/min and records ozone concentrations at a resolution of 10 seconds, with the option to store data as one-minute, five-minute, or one-hour averages. We operated the POM with a one-minute average. The limit of detection is 4 ppb, which is below the ozone concentration typically encountered in ambient air. Two POMs (subsequently referred to as

POM 1 and POM 2) were received from 2B Technologies during their evaluation phase of the POM development and were used for evaluation tests in the Controlled Environment Facility (CEF; see additional details below) at Rutgers University, indoors and subject evaluation. The outdoor tests were done on POMs that were purchased once they became commercially available.

2.2 Experimental design

To evaluate the accuracy of the POM, we compared its measurements to a 2B Technology Model 205 ozone monitor and a ThermoScientific 49i ozone monitor. The ThermoScientific monitor and the 2B Technology Model 205 are Federal Equivalent Methods (FEM) for ozone measurement (# EQOA-0410-190). These comparisons were carried out in three different settings: the CEF, in which concentrations, temperature ($21\pm2^{\circ}\text{C}$), and relative humidity ($45\pm10\%$) were closely controlled; outdoors; and inside a private residence (Table 1). Two POMs were also run simultaneously in these settings to assess inter-unit precision.

One set of experiments took place in the CEF at Rutgers University in Piscataway, New Jersey. The CEF is a 25 m^3 steel-walled chamber in which atmospheric constituents can be closely monitored and controlled. The CEF has a single-pass through ventilation system with inlet air filtered through a HEPA filter and a charcoal filter. Ozone and other test compounds can be added to the air stream in a baffle system to facilitate mixing and released into the CEF through a series of diffusers. Further air mixing in the CEF is accomplished using a series of 6 small fans located near the ceiling at corners/wall edges of the CEF. The air exchange rate was set to 45 ACH. Each instrument was placed inside the CEF with their inlets within one meter of each other. Ozone was produced using an Ozone Research and Equipment Corporation (OREC) generator to create a concentration range of 50 to 170 ppb in the CEF. It was introduced into the CEF to provide both steady-concentration periods and periods with rapid increase or decrease in ozone concentration.

Potential interferences from other compounds on ozone measurements were evaluated by introducing a series of “challenge” compounds in the CEF while ozone was held constant at 65 to 90 ppb. This allowed investigation of whether the POM would deviate from its response to ozone in the presence of other chemical compounds that might be found in indoor or outdoor settings and/or have similar UV absorption lines to ozone. The challenge compounds studied included a mixture of toluene, ethyl benzene, and xylenes (“TEX” mixture). A group of aldehydes (formaldehyde, acetaldehyde, and benzaldehyde) and two common food additives, anisole and vanillin, were released into the CEF with each compound’s concentration at approximately 50 ppb, equivalent to the higher end of concentrations that might be seen indoors (Gilbert et al., 2006; Yagi et al., 2004). The compound mixtures were injected into a heated flask, where they were completely volatilized into the CEF by using a constant flow syringe pump system. The contents of the flask were flushed into the inlet air stream of the CEF through a heated transfer line to avoid condensation and losses. The syringe pump flow rate was set to achieve the desired air concentration for the flow conditions and volume of the CEF. The air concentration of these compounds in the CEF was verified by sampling the air onto adsorbent traps which were analyzed by GCMS for volatile organic compounds and onto 2,4-dinitrophenylhydrazine

(DNPH) Sep Pak cartridges which were analyzed by high-performance liquid chromatography (HPLC) with a UV detector for aldehydes. The TEX mixture and aldehydes are common constituents of both indoor and outdoor air that would typically be found along with ozone. Anisole and vanillin are present as food additives in indoor settings and, like ozone, absorb radiation at 254 nm and thus could potentially interfere with the measurement of ozone.

A second set of experiments took place outdoors in the summer of 2014. One POM and one Model 205 monitor were placed outside on the roof the Rutgers School of Public Health Building, which is a 3-floor building located on Rutgers' Busch campus, Piscataway, NJ. The instruments were sited at least 3 meters away from walls and were operated under a shelf to avoid rain and direct exposure under the sun, with measurements recorded as one-minute averages. On a different day, two POMs were placed outside in the same location, with ozone measurements recorded as five-minute averages.

A third set of experiments took place in a private residence over a 6 hour time period while the participant followed his normal daily routine. The Model 205 monitor was placed on a table in the dining room, which connected to the kitchen through an opened doorway. The two POMs were worn on a belt by the volunteer with the inlets on different sides of the body. It is recognized that this height is lower than the breathing zone but should provide a comparison of the personal ozone exposure to indoor levels while an individual performed typical activities at home. It should also provide an indication of the variability in air concentrations measured by the POM next to a person. During some parts of the experiment, one POM was placed on top of the Model 205 monitor for a direct comparison of POM readings for indoor air and personal air. One activity done by the participant was to stir-fry food with the oven ventilation fan.

Finally, POMs were given to ten volunteers who were each asked to wear the monitors for eight hours on five days and provide feedback on the usability of the instrument. IRB approval was obtained prior to conducting the human subject portion of the study. Subjects were recruited by posting and distributing flyers at Rutgers University requesting participants. All subjects signed an informed consent prior to participation. Each was given a written instruction sheet, and the use of the POM and how to charge it was demonstrated by a field technician. A phone number was provided if any questions about its operation arose during its use. The subjects were asked to follow their normal activities throughout the day while wearing the POM. The volunteers charged the POM's battery overnight and were given a spare battery as well.

2.3 Statistical methods for evaluation

Recorded ozone measurements were reviewed for all instruments in each set of experiments and only complete pairs of valid measurements were retained for analysis. For tests involving precision between two POMs or a POM and 205 monitor, the correlation of ozone measurements were plotted and the Pearson r-value and equation of line of best fit were calculated. Outliers, defined as points more than 3.29 times the standard deviation away from the mean, were found and removed from only one experiment (POM vs. 205 monitor during in-home testing); additional details may be found in Section 3.2.3 in the text.

Statistical differences were determined using pair t-tests or ANOVA with an alpha value <0.05 denoting significance.

3. Results and Discussion

3.1 Precision of POMs

3.1.1 CEF tests—We tested the precision of the POM by placing two identical POMs in the same setting. In the CEF, the two POMs were placed adjacent to each other, with their inlets approximately 10 centimeters apart. A summary of all evaluations are given in Table 2. Figure 1 shows the results of the POMs when ozone was introduced into the CEF. The two POMs are highly correlated ($r^2 = 0.90$). However, POM 2 consistently measured approximately 5 to 10 ppb higher than POM 1 (mean absolute difference of 5.2 ppb). The average relative difference was 7.3%. This likely represents a calibration bias that could be corrected by more frequent calibration of the POMs. These two instruments were calibrated at the beginning of the study and used for more than 12 months without being recalibrated; 2B Technologies recommends annual calibration by the manufacturer. It should be noted that the ozone concentrations reported here for the CEF studies (50 to 170 ppb) are on the higher end of typical ozone air concentrations (Fadeyi, 2015). Similar results obtained at lower ozone concentrations (20 – 40ppb) may be found in the supplementary materials.

When the TEX mixture was introduced in the CEF, the two POMs measurements show more scatter than in the ozone only experiment (r value = 0.552; Table 2). As in the ozone-only test in the CEF, POM 2 continued to measure higher than POM 1 by an average of 10.5 ppb, or a relative difference of 14%. Additional scatter was seen between the two POMs during the aldehyde challenge experiment; however, the average absolute difference between POM 2 and POM 1 was 4.1 ppb, or about 3.6%, indicating better agreement between the two instruments when aldehydes were present than when ozone alone was present. This is likely due to the fact that the ozone concentrations were changing by design during the ozone-only experiment, while ozone was relatively constant during the aldehyde experiment and that there were slight differences in the time for the mixed air to reach each POM in the ozone-only experiment.

The precision of the two POMs when vanillin and anisole were introduced did not appear to be affected by the presence of vanillin and anisole; the two POMs were correlated with an r value of 0.85 and a slope of 0.90 for the line of best fit, suggesting strong absolute agreement between the two POMs.

3.1.2 Outdoor test—Outdoor testing of POM precision took place in July 2014. The two POMs were placed side-by-side for 24 hours as described in the methods section, with ozone measurements recorded as 5-minute averages. Figure 2 shows the correlation between the POMs.

The ozone concentrations measured by the two POMs are highly correlated ($r = 0.99$). Slightly more scatter was seen in the 20–30 ppb range; which occurred on the sampling day that saw over 2 inches of rain and ozone values varying rapidly between 0 and 30 ppb from 2:30pm into the next morning.

3.1.3 Personal air sampling—To test precision during personal sampling in a volunteer's home, we extracted the two subsets of the time periods, designated Phase 1 and Phase 2, when two POMs were worn simultaneously. These data are shown in Figure 3, along with a one-to-one line. The largest scatter is seen during the third subset when the volunteer cooked stir-fry while wearing the POMs. The ventilation fan on the stove was on during this period, which likely caused turbulence near the POM resulting in the two POMs sampling different air. The absolute differences are quite large. It is possible that there was scavenging of ozone while the POM was worn or the particles from the cooking resulted in high false readings from POM 1. This underscores the importance of using caution when interpreting absolute ozone concentrations in situation involving highly turbulent air.

3.2 Accuracy of POM

3.2.1 Controlled environmental facility (CEF) tests—The POM was first tested in the controlled environmental facility (CEF) against the Model 205 ozone monitor and the Model 49i ozone monitor. As in the precision tests, two POMs were used in each experiment, designated POM 1 and POM 2, except for the ozone only test, which only used one POM. To account for systematic differences between the two POMs, the average difference between the two POMs over each sampling period was subtracted from POM 2's values to create the adjusted POM 2 values shown in the following plots and in Table 3.

Measurements from the period with only ozone present in the CEF are presented in Figure 4. Only one POM (POM 2, chosen arbitrarily) was used in this test, and its ozone measurements were found to be systematically about 7 ppb higher than the measurements from the 49i and 205 monitors; thus, this difference was subtracted from the POM values in Figure 4. Additionally, the POM reacted more quickly to the changes in ozone concentration at 20 and 180 minutes, which may be a result of shorter tubing that was used on the POM than on the 49i and 205 monitors in this experiment. Otherwise, all three monitors show strong agreement throughout the sampling period; the POM's adjusted measurements remained within 8 ppb (approximately 10%) of the 49i monitor's measurements. Regular calibration and adjustment of the POM may be necessary to achieve such agreement.

Ozone measurements from the period with the TEX mixture (toluene, ethyl benzene, and xylenes) was introduced are shown in Figure 5. All four monitors follow the same general shape during the sampling period. The two POMs match closely, with average absolute differences of 9.5 ppb or 7.4% (POM 1) and 5.9 ppb or 4.6% (adjusted POM 2) compared to the 49i monitor, respectively. POM 1 and POM 2 had average absolute differences of 9.5 ppb (7%) and 2.5 ppb (2%) from the 49i's ozone measurements, respectively.

Figure 6 shows the ozone concentrations measured when aldehydes were introduced. POM 1 stayed within $\pm 6.1\%$ of its mean concentration during the period when the aldehydes were present, which was slightly more stable than the Models 205 and 49i monitors (each with a range of approximately $\pm 9\%$ from the mean). POM 1 had an average absolute difference of 4.2 ppb (3.3%) from the 49i monitor. POM 2 tended to drift downward during the second half of the sampling period; the reason for this may be related to the POM battery, which needed to be recharged after these sets of experiments were completed. After the adjustment

for systematic bias, POM 2 had an average absolute difference of 9.7 ppb (8.3%) from the 49i monitor.

Figure 7 shows the ozone concentration measured when vanillin was present. After adjusting POM 2 for the systematic bias, the two POMs tracked each other closely throughout the sampling period. None of the four monitors showed a clear trend upward or downward during the sampling period, suggesting that there was no interference in the ozone measurements. POM 1 had a mean absolute difference, calculated pair-wise, of 8.5 ppb (9%) from the 49i monitor, while the adjusted POM 2 had a mean absolute difference of 9.6 ppb (10%) from the 49i monitor. Both POMs were statistically different from the 49i monitor ($p < 0.05$). The two FRM monitors were generally within ± 5 ppb of each other for all readings, which is slightly larger than combined uncertainty of the two instruments of 1 to 2% full scale which would translate to 3 to 4 ppb. The 49i instrument had a longer tube from the CEF intake so had a slightly longer lag time for response which could cause some differences when the ozone concentration changed rapidly. There appears to be more variation in the 205 monitor when aldehydes were present than for the 49i. This variation was not evident for the POMs which also detects the ozone using essentially the same detector premise.

3.2.2. Outdoor testing—Outdoor tests (and in-home tests described below in Section 3.2.3) were performed with different POMs and Model 205 monitor from the CEF experiments. The 49i instrument was not used as it is not easily portable. The results generally show good agreement between the POM and the Model 205 monitor (Figure 8; slope of line of best fit = 0.922; $r = 0.98$). The POM tended to measure ozone values that were approximately 33% higher than the Model 205's values when the Model 205 monitor was measuring values less than 15 ppb; however, this bias was not evident at higher values. Additionally, the two instruments showed relatively fewer points, and more scatter among these points, when the Model 205 was measuring ozone concentrations of 15 to 25 ppb. These readings occurred between 11:30 pm and midnight on the sampling day, when ozone concentrations were rapidly decreasing.

3.2.3 In-home testing—Figure 9 compares the POM 2 ozone measurements to those from the Model 205 ozone monitor during in-home testing. The figure includes only those measurements taken when POM 2 was placed on top of the Model 205 monitor (POM 1 was worn by a resident of the home for the entire sampling period). Approximately 50 readings were removed when the POM 2 battery was dying, causing spurious readings. An additional 4 outlying readings (one or both measurements more than 3.29 standard deviations away from the mean) were removed. The difference between POM 2 and the Model 205 monitor was larger during the periods when POM 2 was worn by the volunteer, with POM 2 generally measuring lower ozone concentrations. This difference was likely caused by the reaction of ambient ozone with skin oil and clothing (Weschler, 2016), representing a true difference in ozone concentration near a person in an indoor setting. While this is just a single set experiment, it underscores the value of personal monitoring to better reflect the ozone exposure than area monitoring.

3.3 Practicality of use

To assess practicality of use, volunteers were asked to wear the POM for five days while going about their daily activities and respond to a series of questions at the end about the ease and comfort of wearing the POM, charging the battery, and whether it drew attention and comments in public from others. Several volunteers recognized the value of knowing real-time exposure to ozone and found the study interesting to participate in, but all ten volunteers complained about the noise produced, and eight complained about the weight and bulkiness of the POM. Two volunteers also commented that it was difficult to keep the inlet uncovered while wearing a jacket, thus indicating a potential source of error in measurement. Eight of the ten volunteers indicated reluctance to spend time in public while wearing the POM due to receiving questions about the noise, which was measured at 55.6 dBA at one foot away. Based on this feedback, 2B Technologies introduced a muffler to reduce the noise made on subsequent versions of the POM by approximately 75% to 50.7 dBA at one foot away.

4. Conclusions

The POM showed strong inter-unit precision and measured ozone values that were on average within 8% of those measured by the 49i and Model 205 (FEM) units in the controlled environmental facility tests as well as the outdoor tests. The POM generally did not appear to deviate from its ozone measurements when the challenge compounds were introduced, giving confidence to the user that ozone is being measured reliably though there may have been a decrease in their precision and accuracy for TEX and aldehydes levels above those typically encountered in the ambient environment. In tests involving the TEX mixture and vanillins as challenge compounds, the POM measured consistently lower ozone concentrations than the 49i monitor, which suggested a bias in the response of one of the POMs we were using. Thus, the POM should be calibrated when needed following the manufacturer's suggestion of annual calibration and maintenance to assure the validity of the readings. Comparison to the Model 205 values and precision estimates were poorer in the limited in-home test conducted. Ozone levels indoors and near a person are a result of complex sources and sinks and air mixing encountered there and ozone interactions with skin and clothing. These results suggest that a personal sampler would reflect exposures better than area samples. Though the comments from volunteer users indicated that some small changes could be made for ease of use, the POM is shown to be a reliable new instrument for measuring ozone.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- Andersen PC, Williford CJ, Birks JW. Miniature Personal Ozone Monitor Based on UV Absorbance. *Analytical Chemistry*. 2010; 82:7924–7928. [PubMed: 21461365]
- Bell ML. The use of ambient air quality modeling to estimate individual and population exposure for human health research: A case study of ozone in the Northern Georgia Region of the United States. *Environ Int*. 2006; 32:586–593. [PubMed: 16516968]
- Bell ML, Zanobetti A, Dominici F. Who is more affected by ozone pollution? A systematic review and meta-analysis. *American journal of epidemiology*. 2014; 180:15–28. [PubMed: 24872350]
- Brauer M, Brook JR. Ozone personal exposures and health effects for selected groups residing in the Fraser Valley. *Atmospheric Environment*. 1997; 31:2113–2121.
- Cao T, Thompson JE. Personal monitoring of ozone exposure: A fully portable device for under \$150 USD cost. *Sensors and Actuators B: Chemical*. 2016; 224:936–943.
- Cho, H. Personal Environmental Monitoring System and network platform. 2015 9th International Conference on Sensing Technology (ICST); 2015. p. 751-756.
- Demirel G, Özden Ö, Döneroğlu T, Gaga EO. Personal exposure of primary school children to BTEX, NO₂ and ozone in Eskişehir, Turkey: Relationship with indoor/outdoor concentrations and risk assessment. *Science of The Total Environment*. 2014; 473:537–548. [PubMed: 24388904]
- Fadeyi MO. Ozone in indoor environments: Research progress in the past 15 years. *Sustainable Cities and Society*. 2015; 18:78–94.
- Gilbert NL, Gauvin D, Guay M, Heroux ME, Dupuis G, Legris M, Chan CC, Dietz RN, Levesque B. Housing characteristics and indoor concentrations of nitrogen dioxide and formaldehyde in Quebec City, Canada. *Environmental Research*. 2006; 102:1–8. [PubMed: 16620807]
- Ito K, De Leon SF, Lippmann M. Associations between ozone and daily mortality - Analysis and meta-analysis. *Epidemiology*. 2005; 16:446–457. [PubMed: 15951662]
- Jerrett M, Burnett RT, Pope CA, Ito K, Thurston G, Krewski D, Shi YL, Calle E, Thun M. Long-Term Ozone Exposure and Mortality. *New England Journal of Medicine*. 2009; 360:1085–1095. [PubMed: 19279340]
- Koutrakis, P., Wolfson, JM., Bunyaviroch, A., Froehlich, S. Research report. Health Effects Institute; 1994. A passive ozone sampler based on a reaction with nitrite; p. 19-47. discussion 67–82
- Lee K, Parkhurst WJ, Xue JP, Ozkaynak AH, Neuberg D, Spengler JD. Outdoor/indoor/personal ozone exposures of children in Nashville, Tennessee. *Journal of the Air & Waste Management Association*. 2004; 54:352–359. [PubMed: 15061616]
- Liard R, Zureik M, Le Moullec Y, Soussan D, Glorian M, Grimfeld A, Neukirch F. Use of Personal Passive Samplers for Measurement of NO₂, NO, and O₃ Levels in Panel Studies. *Environmental Research*. 1999; 81:339–348. [PubMed: 10581112]
- Liu LJ, Koutrakis P, Leech J, Broder I. Assessment of ozone exposures in the greater metropolitan Toronto area. *Journal of the Air & Waste Management Association* (1995). 1995; 45:223–234.
- Liu LJS, Koutrakis P, Suh HH, Mulik JD, Burton RM. USE OF PERSONAL MEASUREMENTS FOR OZONE EXPOSURE ASSESSMENT - A PILOT-STUDY. *Environmental Health Perspectives*. 1993; 101:318–324. [PubMed: 8275989]
- McKercher GR, Salmond JA, Vanos JK. Characteristics and applications of small, portable gaseous air pollution monitors. *Environmental Pollution*. 2017; 223:102–110. [PubMed: 28162801]
- Monn C. Exposure assessment of air pollutants: a review on spatial heterogeneity and indoor/outdoor/personal exposure to suspended particulate matter, nitrogen dioxide and ozone. *Atmospheric Environment*. 2001; 35:1–32.
- Pang X, Shaw MD, Lewis AC, Carpenter LJ, Batchellier T. Electrochemical ozone sensors: A miniaturised alternative for ozone measurements in laboratory experiments and air-quality monitoring. *Sensors and Actuators B: Chemical*. 2017; 240:829–837.
- Piedrahita R, Xiang Y, Masson N, Ortega J, Collier A, Jiang Y, Li K, Dick RP, Lv Q, Hannigan M, Shang L. The next generation of low-cost personal air quality sensors for quantitative exposure monitoring. *Atmos Meas Tech*. 2014; 7:3325–3336.

- Rombout PJA, Lioy PJ, Goldstein BD. Rationale for an Eight-Hour Ozone Standard. JAPCA. 1986; 36:913–917.
- Snyder EG, Watkins TH, Solomon PA, Thoma ED, Williams RW, Hagler GSW, Shelow D, Hindin DA, Kilaru VJ, Preuss PW. The Changing Paradigm of Air Pollution Monitoring. Environmental Science & Technology. 2013; 47:11369–11377. [PubMed: 23980922]
- Sunyer J, Basagana X, Belmonte J, Anto JM. Effect of nitrogen dioxide and ozone on the risk of dying in patients with severe asthma. Thorax. 2002; 57:687–693. [PubMed: 12149528]
- Weisel CP, Cody RP, Georgopoulos PG, Purushothaman V, Weiss SH, Bielory L, Gregory P, Stern AH. Concepts in developing health-based indicators for ozone. International Archives of Occupational and Environmental Health. 2002; 75:415–422. [PubMed: 12070638]
- Weschler CJ. Ozone's impact on public health: contributions from indoor exposures to ozone and products of ozone-initiated chemistry. Environ Health Perspect. 2006; 114:1489–1496. [PubMed: 17035131]
- Weschler CJ. Roles of the human occupant in indoor chemistry. Indoor Air. 2016; 26:6–24. [PubMed: 25607256]
- Weschler CJ, Shields HC, Naik DV. Indoor Ozone Exposures. JAPCA. 1989; 39:1562–1568. [PubMed: 2607364]
- Westafer RS, Levitin G, Hess DW, Bergin MH, Hunt WD. Detection of ppb ozone using a dispersive surface acoustic wave reflective delay line with integrated reference signal. Sensors and Actuators B: Chemical. 2014; 192:406–413.
- Yagi S, Matsuda S, Teramura A, Yoshida H. Acetaldehyde concentration of indoor air in newly constructed wood-framed residential structures. Mokuzai Gakkaishi. 2004; 50:83–90.
- Zhang JF, Lioy PJ. Ozone in Residential Air - Concentrations, I/O Ratios, Indoor Chemistry, and Exposures. Indoor Air-International Journal of Indoor Air Quality and Climate. 1994; 4:95–105.

Figure 1. One-minute average ozone measurements from POM 1 (x-axis) and POM 2 (y-axis) while ozone was generated in the CEF.

Figure 2.
Correlation of 5-minute average ozone concentrations from two POMs during 24-hour outdoor testing period with line of best fit.

Figure 3. One-minute average ozone concentrations [ppb] from POM 1 (x-axis) and POM 2 (y-axis) when both were worn indoors by a volunteer. During the third period, the volunteer cooked stir-fry.

Figure 4. One-minute average ozone measurements [ppb] in CEF. See text for explanation of adjusted POM values.

Figure 5. One-minute average ozone measurements [ppb] in CEF with TEX mixture present. See text for explanation of adjusted POM 2 values.

Figure 6. One-minute average ozone measurements [ppb] in CEF with aldehydes present. See text for explanation of adjusted POM 2 values.

Figure 7.
One-minute average ozone concentration in the CEF with vanillin and anisole present.

Figure 8.
One-minute average outdoor ozone measurements from 205 instrument (x-axis) and POM (y-axis).

Figure 9.

One-minute average ozone concentrations during in-home testing. For the plotted points, the POM 2 was placed directly on top of the 205 monitor.

Table 1

Summary of Study Design

Test purpose	Location	Ozone source	Additional variables	POM(s) used	Comparison instruments used	Averaging Time for Measurement	Duration of full test(s)	Section in paper
Precision between POMs	Controlled Environmental Facility (CEF)	Corona Discharge Ozone Generator; see text	Challenge compounds	1 and 2	None	1 minute averages	30 minutes to 6 hours	3.1.1
Precision between POMs	Outdoors (rooftop)	Ambient Air	Rain	Commercial	None	5 minute averages	24 hours	3.1.2
Precision between POMs	Indoors (private residence)	Ambient Air Penetration Indoors	Stir-fry cooking, worn by person	1 and 2	None	1 minute averages	8 hours	3.1.3
Accuracy of POM	Controlled Environmental Facility (CEF)	Corona Discharge Ozone Generator; see text	Challenge compounds	1 for ozone only; 1 and 2 for tests with challenge compounds	205 Monitor, 49i	1 minute averages	30 minutes to 6 hours	3.2.1
Accuracy of POM	Outdoors (rooftop)	Ambient Air	Rain	Commercial	205 Monitor	1 minute averages	24 hours	3.2.2
Accuracy of POM	Indoors (private residence)	Ambient Air Penetration Indoors	Stir-fry cooking, worn by person	2	205 Monitor	1 minute averages	8 hours	3.2.3
Practical use of POMs	Various (POMs worn by volunteers)	n/a	None	1 and 2	None	n/a	5 days	3.3

Summary of Precision of the Data Based on Comparison of two POMs Operated Simultaneously

Table 2

Test and location	Slope	Intercept	Correlation (Pearson r value)	Average absolute difference [ppb]	Section in paper
CEF, ozone only	0.82	26.8	0.95	5.0	3.1.1
CEF, ozone + TEX mixture			0.55	10.5	3.1.1
CEF, ozone +aldehydes		123	< 0.1	4.1	3.1.1
CEF, ozone + vanillins	0.90	7.32	0.85		3.1.1
Outdoors	1.08	-4.70	0.99		3.1.2
Indoors					3.1.3

Summary of Estimated Accuracy of the Data Based on Comparison of POMs to Other Ozone Monitors Operated Simultaneously

Table 3

Test and location	Average absolute difference [ppb]		Average absolute difference [ppb]		Section in paper
	POM1 and 49i	adjusted POM2 and 49i	POM1 and 205	adjusted POM2 and 205	
CEF, ozone only	---	---	---	---	3.2.1
CEF, ozone + TEX mixture	9.5 *	5.9 *	4.4 *	2.4	3.2.1
CEF, ozone + aldehydes	4.2 *	9.7 *	4.8 *	10.8 *	3.2.1
CEF, ozone + vanillins	8.5 *	9.6 *	5.4 *	4.9 *	3.2.1
Outdoors	---	---	---	---	3.2.2
Indoors	---	---	---	---	3.2.3

* Significant difference, pair-wise, at alpha = 0.05 level