

AirPen: A Wearable Monitor for Characterizing Exposures to Particulate Matter and Volatile Organic Compounds

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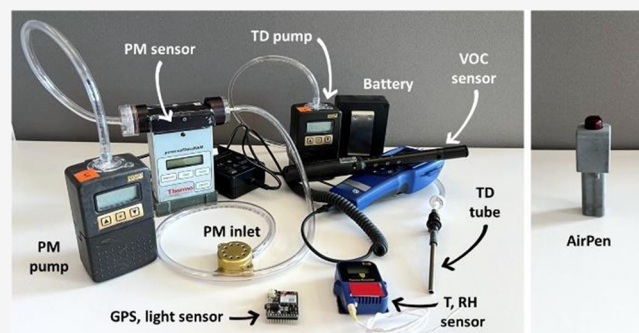
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ABSTRACT: Exposure to air pollution is a leading risk factor for disease and premature death, but technologies for assessing personal exposure to particulate and gaseous air pollutants, including the timing and location of such exposures, are limited. We developed a small, quiet, wearable monitor, called the AirPen, to quantify personal exposures to fine particulate matter (PM_{2.5}) and volatile organic compounds (VOCs). The AirPen combines physical sample collection (PM onto a filter and VOCs onto a sorbent tube) with a suite of low-cost sensors (for PM, VOCs, temperature, pressure, humidity, light intensity, location, and motion). We validated the AirPen against conventional personal sampling equipment in the laboratory and then conducted a field study to measure at-work and away-from-work exposures to PM_{2.5} and VOCs among employees at an agricultural facility in Colorado, USA. The resultant sampling and sensor data indicated that personal exposures to benzene, toluene, ethylbenzene, and xylenes were dominated by a specific workplace location. These results illustrate how the AirPen can be used to advance our understanding of personal exposure to air pollution as a function of time, location, source, and activity, even in the absence of detailed activity diary data.

KEYWORDS: *exposome, personal exposure assessment, occupational health, industrial hygiene, low-cost sensors*



1. INTRODUCTION

Air pollution is the leading environmental health risk on the planet and a top-10 risk factor for premature disease and death,¹ yet only a small fraction of the thousands of chemicals that contribute to air pollution exposure [e.g., volatile organic and inorganic chemicals, semi-volatile and persistent organic compounds, and the many components that make up airborne particulate matter (PM)] have been studied in detail (e.g., formaldehyde, benzene, benzo(a)pyrene, PM_{2.5}, and lead).^{2,3} Although recent technological advances have allowed us to define an individual’s genome, transcriptome, and proteome with high fidelity, our ability to define one’s exposome,⁴ which constitutes the entirety of exposure to all forms of pollution across an individual lifespan, remains out of reach. Exposome measurement is challenging for several reasons: (1) human activity and the microenvironments in which we spend our lives are dynamic and varied;⁵ (2) the pollutant species and concentrations to which we are exposed vary across time, space, and by source;^{6–8} and (3) technologies used to assess exposure have typically been designed for a single sample type

(e.g., particle- vs gas-phase and sometimes even a single gas-phase species).^{9–17}

An emerging body of the literature sets a precedent for pairing human time-activity data with air pollution data to elucidate exposure sources and pathways. For example, when data on people’s movement across microenvironments and their physical activity level have been combined with outdoor air quality modeling¹⁸ or monitoring^{19–21} data, exposure patterns have been highlighted and exposure measurement error has been reduced. To date, the primary approaches have required individuals to keep time-activity diaries or have paired data from mobile devices (like smartphones, which record location and motion data ubiquitously) with air quality data that are external to those mobile devices,^{22–25} however, recent

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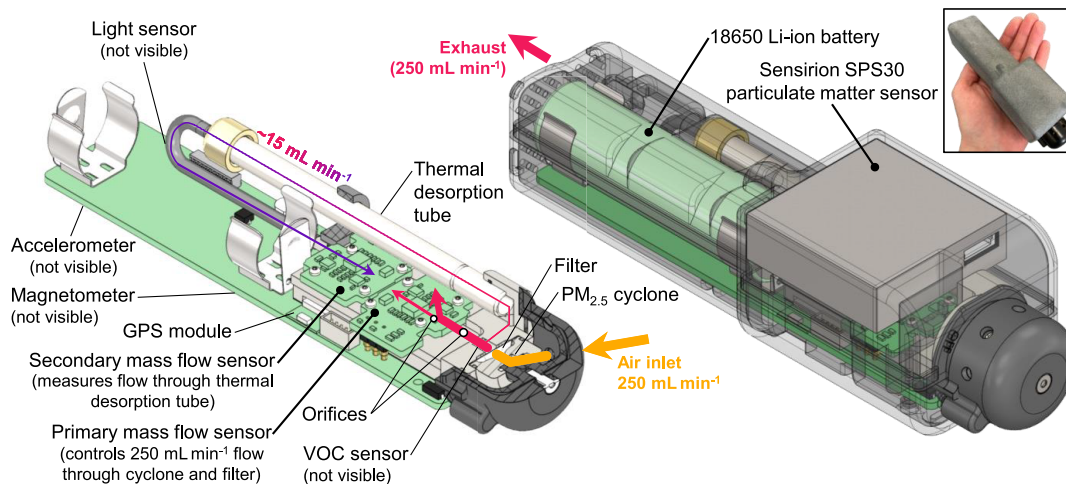


Figure 1. Left: a cut-away view illustrating the sample flow path inside the AirPen. Air containing particulate matter (PM) and VOCs (yellow) enters the AirPen inlet. Particles $\leq 2.5 \mu\text{m}$ pass through the cyclone and are collected on the filter. Downstream of the filter, particle-free air (pink) passes over a total VOC sensor. Approximately 15 mL min^{-1} of this air passes through a thermal desorption tube and then the secondary mass flow sensor (purple). An orifice limits the amount of air that is allowed to bypass the thermal desorption tube, and a second orifice limits the amount of air that passes through the primary mass flow sensor used to control the flow rate through the cyclone and filter. Right: a view of the fully assembled AirPen, with the housing shown as transparent so that the low-cost PM sensor and Li-ion battery are visible. The exhaust flow exits the housing at the end opposite the inlet as shown. Top right: a photograph of the AirPen in the palm of a person's hand for scale.

advances in sensor technology make possible the development of mobile platforms that collect both time-location-activity and pollution data to provide insight into the “personal exposome”.¹⁰

We developed a small, quiet, self-contained wearable monitor that combines a multitude of sensors with the sampling technology needed to quantify personal exposures to particle- and gas-phase air pollutants simultaneously. This monitor, called the “AirPen”, samples PM onto a filter and volatile organic compounds (VOCs) onto a thermal desorption tube while logging time-resolved data on PM concentration, total VOC (TVOC) concentration, temperature, humidity, light intensity, location, and motion. Below, we demonstrate—using data from a field study with a panel of five workers at an agricultural research facility—how these features can be leveraged to identify locations, sources, and activities across multiple microenvironments associated with the largest personal exposures to PM_{2.5} and VOCs.

2. MATERIALS AND METHODS

2.1. Design. The AirPen actively samples PM onto a filter and VOCs onto a thermal desorption tube (Figure 1). The AirPen uses an ultrasonic piezoelectric pump (MZB1001T02, Murata, Nagaokakyo, Japan) to draw air into the inlet at a flow rate of 250 mL min^{-1} . That air passes through a PM_{2.5} cyclone²⁶ and then a 15 mm filter. Downstream of the filter, particle-free air passes over a metal oxide TVOC sensor (SGP30, Sensirion, Stäfa, Switzerland).²⁷ The flow path then splits in two. Approximately, 235 mL min^{-1} bypasses the thermal desorption tube; of this flow, approximately 35 mL min^{-1} passes through the primary mass flow sensor (D6F-P0010A1, Omron, Kyoto, Japan) before being exhausted, while the other 200 mL min^{-1} is exhausted immediately to avoid saturating this sensor. The other 15 mL min^{-1} of air flows through the thermal desorption tube (6.35 mm diameter, 89 mm long), followed by a secondary mass flow sensor (D6F-P0010A1, Omron), before being exhausted. A PM sensor (SPS30, Sensirion) connected to the AirPen samples ambient

air (i.e., air that was not drawn into the cyclone inlet). The AirPen has exterior dimensions of $150 \times 45 \times 38 \text{ mm}$, weighs 200 g, and is powered by a lithium-ion 18650 battery.

Data from the primary mass flow and temperature/humidity/pressure (BME680, Bosch Sensortec, Reutlingen, Germany) sensors are used to actively maintain a constant volumetric flow rate through the size-selective inlet and filter as ambient conditions and the pressure drop across the filter change. The flow rate through the thermal desorption tube is passively controlled by an orifice downstream of the VOC sensor and monitored using the secondary mass flow sensor. See Supporting Information (SI) Section 1 for additional information on the procedure used to calibrate the mass flow sensors.

In addition to PM, TVOC, temperature, relative humidity, atmospheric pressure, and sample flow rate data, the AirPen measures and records time-resolved GPS (CAM-M8Q, Ublox, Thalwil, Switzerland), accelerometer (LSM6DSOX, STMicroelectronics), magnetometer (LIS2MDLTR, STMicroelectronics), and ambient light (Si1133, Silicon Labs, Austin, TX, USA) data.

The AirPen is designed to be deployed as follows: A laboratory technician loads a sample filter, thermal desorption tube, and battery into the monitor before programming the AirPen to sample for the desired duration. The AirPen is then delivered to the individual to undergo exposure assessment. The AirPen begins sampling when the individual switches on the device and stops sampling automatically once the programmed sample duration is completed. Once the AirPen is returned to the laboratory, a technician unloads the sample filter, removes the thermal desorption tube, and downloads the time-resolved sensor data. Then, the technician post-weighs the filter, performs additional analyses on the PM sample as needed (e.g., for black carbon and/or metals), and analyzes the thermal desorption tube for specific VOCs using gas chromatography–mass spectrometry (GC–MS).

2.2. Laboratory PM Sampling Experiment. To assess our ability to quantify PM_{2.5} concentrations, we used (a) three

AirPens equipped with 15 mm diameter PTFE membrane filters (PT15P-PF03, Measurement Technology Laboratories [MTL], Minneapolis, MN, USA) and (b) three conventional personal PM_{2.5} samplers equipped with 37 mm diameter PTFE membrane filters (PT37P-PF03, MTL) to sample five different time-averaged ammonium sulfate concentrations, ranging from approximately 120 to 1300 $\mu\text{g m}^{-3}$, from the inside of a 0.75 m³ laboratory chamber for 4–23 h (depending on the concentration; we aimed to collect at least 30 μg of PM_{2.5} on each filter). Each conventional sampler consisted of an SCC1.062 Triplex cyclone (Mesa Laboratories, Lakewood, CO, USA) connected to a conductive black polypropylene 37 mm filter cassette (Part no. 225-308, SKC, Eighty Four, PA, USA) and an AirChek XR5000 pump (SKC). Each AirChek XR5000 pump sampled air at a flow rate of 1.5 L min⁻¹. Each filter was pre- and post-weighed to the nearest 1 μg (XS3DU, Mettler Toledo, Columbus, OH, USA).

2.3. Laboratory VOC Sampling Experiment. To assess our ability to quantify gas-phase air pollutant concentrations using the AirPen, we sampled benzene concentrations of 0, 10, 50, 100, and 200 ppb (0, 0.1 $\times$, 0.5 $\times$, 1.0 $\times$, and 2.0 $\times$ the National Institute for Occupational Safety and Health [NIOSH] time-weighted average [TWA] recommended exposure limit [REL]) from the inside of a stainless steel enclosure (SA-41, Polycase, Avon, OH, USA) for 1 h each using three AirPens and three conventional personal VOC samplers. Each AirPen was equipped with a PTFE membrane filter and a Carbopack X^{28,29} thermal desorption tube (28686-U, Sigma-Aldrich, St. Louis, MO, USA). Each conventional VOC sampler consisted of a Carbopack X thermal desorption tube that was connected to a low-flow adapter (SKC) and an AirChek 2000 pump (SKC) to draw air through the thermal desorption tube at a flow rate of 20 mL min⁻¹. The 30 samples collected during this experiment (5 unique benzene concentrations $\times$ 6 samples/concentration) were thermally desorbed and then analyzed using GC–MS as described in SI Section 2.2.

2.4. Field Study. We conducted a personal sampling campaign with five participants who were employed at an agricultural research facility in Colorado, USA. This campaign spanned one full work week. We measured each employee's personal exposure to PM_{2.5} and VOCs at work (Monday through Thursday or Friday, depending on the employee's schedule) and "at home" (i.e., anywhere away from work Monday afternoon into Tuesday morning, Tuesday afternoon to Wednesday morning, Wednesday afternoon to Thursday morning, and Thursday afternoon to Friday morning).

While at work, each participant wore a small backpack containing: (1) an AirPen, (2) a conventional personal PM_{2.5} sampler, and (3) a conventional personal VOC sampler (Figure S9). Conventional PM_{2.5} and VOC samples were collected using the equipment described in Sections 2.2 and 2.3. While away from work, each participant wore only the AirPen. Each participant kept a written diary of their daily activities. Over the course of the week, we collected one "at-work" PM_{2.5} sample per participant, one "at-home" PM_{2.5} sample per participant, eight to ten at-work VOC samples per participant (one AirPen and one conventional sample per day for 4 or 5 days), and four at-home VOC samples per participant. All personal PM_{2.5} and VOC samples were collected on PTFE membrane filters and Carbopack X tubes, respectively.

We also sampled PM_{2.5} and VOCs at three stationary locations throughout the facility: (1) in the "shop" (which included a workshop area and garage bays where motorized equipment was stored), (2) in the main office building, and (3) outside in the "field" (at the edge of an orchard near a gravel road that provided access to growing fields across the facility). Stationary samples were collected using Home Health Boxes.³⁰ Over the course of the work week, we collected one PM_{2.5} sample on a PTFE membrane filter, one PM_{2.5} sample on a quartz filter (TISSUQUARTZ, 2500QAT-UP, Pall Life Sciences, Port Washington, NY, USA), and five VOC samples (one per day; on a Carbopack X thermal desorption tube) in each location. Each stationary sampler was started at approximately 06:30 each day and shut down at approximately 17:30 each day.

PTFE filter samples were analyzed for PM_{2.5} mass, black carbon, and elemental composition; quartz filter samples were analyzed for elemental carbon (SI Section 2.1). Data from these analyses were used to estimate the masses of black carbon, ammonium sulfate, fine soil, non-soil potassium, salts (CaCO₃, MgCO₃, Na₂SO₄), and other metals in the samples (SI Section 4.2.2).^{31,32}

Fine PM concentrations reported by the Sensirion SPS30 sensors were corrected by scaling the sensor-reported values linearly so that the time-averaged PM_{2.5} concentration matched that derived from the corresponding AirPen filter sample (see eq S15). Filter-corrected, time-resolved PM_{2.5} concentrations were then averaged over 10 min intervals and matched to 12 different categories of activities that were obtained from participants' diaries.

VOC samples were analyzed for 39 different compounds—including benzene, toluene, ethylbenzene, and xylenes (BTEX)—using thermal desorption GC–MS as described in SI Section 2.2. We analyzed samples for BTEX compounds, which are present in liquid hydrocarbon fuels, so that we could investigate whether and how participants' use of motorized farm equipment influenced their exposure to air toxics. We also used data from the VOC samples, AirPen sensors, and time-activity diaries to assess how much of participants' exposures to VOCs might be occurring in the shop. We tested six different methods for estimating how much time each participant spent working in the shop each day: (1) the "activity diary" method relied on participant time-activity diaries alone; (2) the "light data + activity diary + GPS" method used data from the light sensor and GPS on the AirPen to supplement the time-activity diaries; (3) the "light data + job + GPS" method used data from the light sensor and GPS on the AirPen along with general knowledge of each participant's job duties (but no time-activity diaries); (4) the "light data + job + GPS + motion data" method was similar to the "light data + job + GPS" method but also used data from the accelerometer and magnetometer on the AirPen to help estimate participant location; (5) the "light data + GPS" method used only data from the light sensor and GPS on the AirPen (but no knowledge of participant job duties or activities); finally, (6) the "light data + GPS + motion data" method was similar to the "light data + GPS" method but also used data from the accelerometer and magnetometer to help estimate participant location. These methods are described in SI Section 4.2.5. For each method, we compared each participant's work-shift average personal exposure to each of four VOCs (BTEX) to the work-day average concentration of that VOC in the shop multiplied by the fraction of the work shift that the participant

spent in the shop. All data analyses were completed using R version 4.1.1 (R Foundation for Statistical Computing, Vienna, Austria).

Field sampling protocols were approved by the Institutional Review Board at Colorado State University (protocol #2364), and all participants provided informed consent.

3. RESULTS AND DISCUSSION

$PM_{2.5}$ and benzene concentrations derived from filter and thermal desorption tube samples collected in laboratory settings using AirPens were strongly correlated with (Pearson's $r > 0.99$), but slightly lower than, $PM_{2.5}$ and benzene concentrations derived from filter and thermal desorption tube samples collected using conventional personal samplers (Tables S3–S4 and Figures S5–S8). The linear models fit to the laboratory data using Deming regression were $PM_{2.5, \text{AirPen}} = 0.87 PM_{2.5, \text{conventional}} - 15 \mu\text{g m}^{-3}$ and $c_{C_6H_6, \text{AirPen}} = 0.82 c_{C_6H_6, \text{conventional}} - 1.4 \text{ ppb}$. The lower concentrations measured using the AirPens might be due to challenges associated with controlling the low sample flow rate (0.25 L min^{-1} at the inlet). In the future, we will reevaluate the procedures used to calibrate the flow rates through the filter and thermal desorption tube.

Study participants at the agricultural facility were exposed to work-week average filter-derived $PM_{2.5}$ concentrations of up to $82 \mu\text{g m}^{-3}$ and much of this $PM_{2.5}$ was attributed to soil (Figure 2). The PM sensors in the AirPens recorded the highest concentrations when employees completed tasks that disturbed the soil using motorized equipment (e.g., mowing; Figures 3 and 4). Based on this result, we suggested workers at this facility consider voluntary use of respiratory protection during mowing and tilling tasks to reduce their exposure to

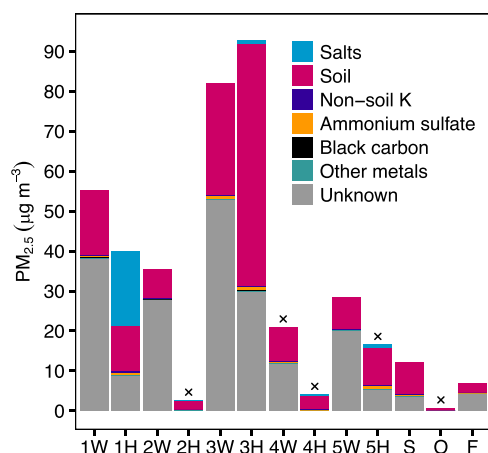


Figure 2. Time-averaged concentration and composition of $PM_{2.5}$ pollution to which participants were exposed while at work, to which participants were exposed while away from work, in the shop (S), in the office building (O), and outside in the field (F) over the course of one work week. On the x axis, numbers 1–5 denote the five participants, “W” denotes samples that were collected at work, and “H” denotes samples that were collected away from work (e.g., 1 W = the $PM_{2.5}$ sample collected for Participant 1 at work). Samples S, O, and F were collected during working hours only. The overall height of each bar indicates the total $PM_{2.5}$ concentration derived from the filter sample. An “x” above the bar indicates that the $PM_{2.5}$ mass was below the gravimetric LOD (see Table S5). Samples 1W–5W and 1H–5H were collected with AirPens; samples S, O, and F were collected with Home Health Boxes.

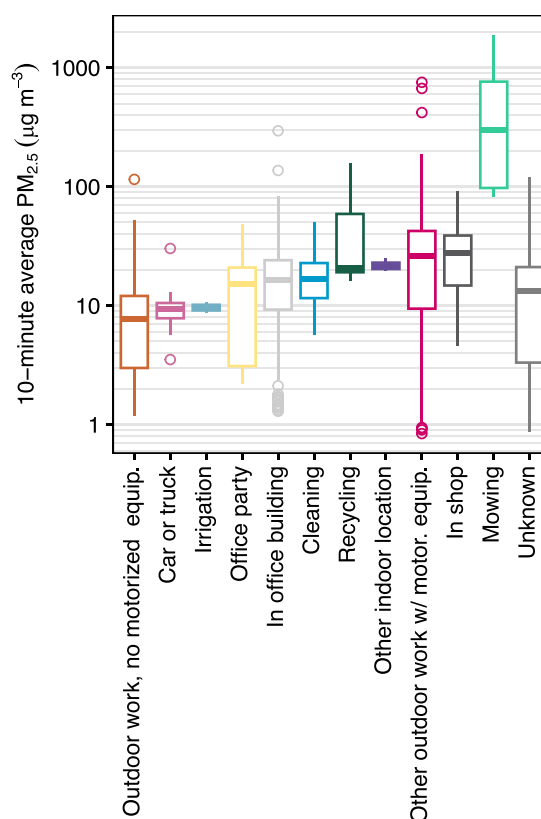


Figure 3. Apportionment of at-work $PM_{2.5}$ exposure by activity. All 10-minute average filter-corrected personal $PM_{2.5}$ exposure data were matched to 12 activity categories. “Other outdoor work with motorized equipment” refers to an activity that was not mowing or tilling but involved operation of motorized farm equipment. “Car or truck” refers to the operation of an on-road vehicle. Times when participants were in the shop were identified using the “light data + activity diary + GPS” method; times associated with other activities were obtained from participants’ diaries.

PM. Work-week average $PM_{2.5}$ concentrations of 12 and $6.9 \mu\text{g m}^{-3}$ were measured in the shop and outside by the orchard, respectively. The average $PM_{2.5}$ concentration in the office building was below our $4.1 \mu\text{g m}^{-3}$ limit of detection (LOD) for that filter sample (see SI Section S4.2.1 for more information).

Most (4 of 5) participants were exposed to lower work-week averaged $PM_{2.5}$ concentrations while away from work. Participant 1 was exposed to an average $PM_{2.5}$ concentration of $40 \mu\text{g m}^{-3}$ away from work, and 50% of this exposure was attributed to salt aerosol emitted by an ultrasonic humidifier used at Participant 1’s home. The $PM_{2.5}$ concentration in Participant 1’s home sometimes reached a steady-state level of approximately $130 \mu\text{g m}^{-3}$ in the early morning hours (Figure S15). Prior studies demonstrated that the use of ultrasonic humidifiers can result in similarly elevated $PM_{2.5}$ concentrations in residences.^{32,33} Participant 3 was the only participant exposed to a higher work-week averaged $PM_{2.5}$ concentration while away from work. This exposure was mostly attributed to soil and might have occurred when Participant 3 completed a mowing task at home.

The SPS30 PM sensor underestimated the filter-derived work-week average $PM_{2.5}$ concentration for all samples for which paired filter-sensor data were available and the mass collected on the filter was above the gravimetric LOD (Table

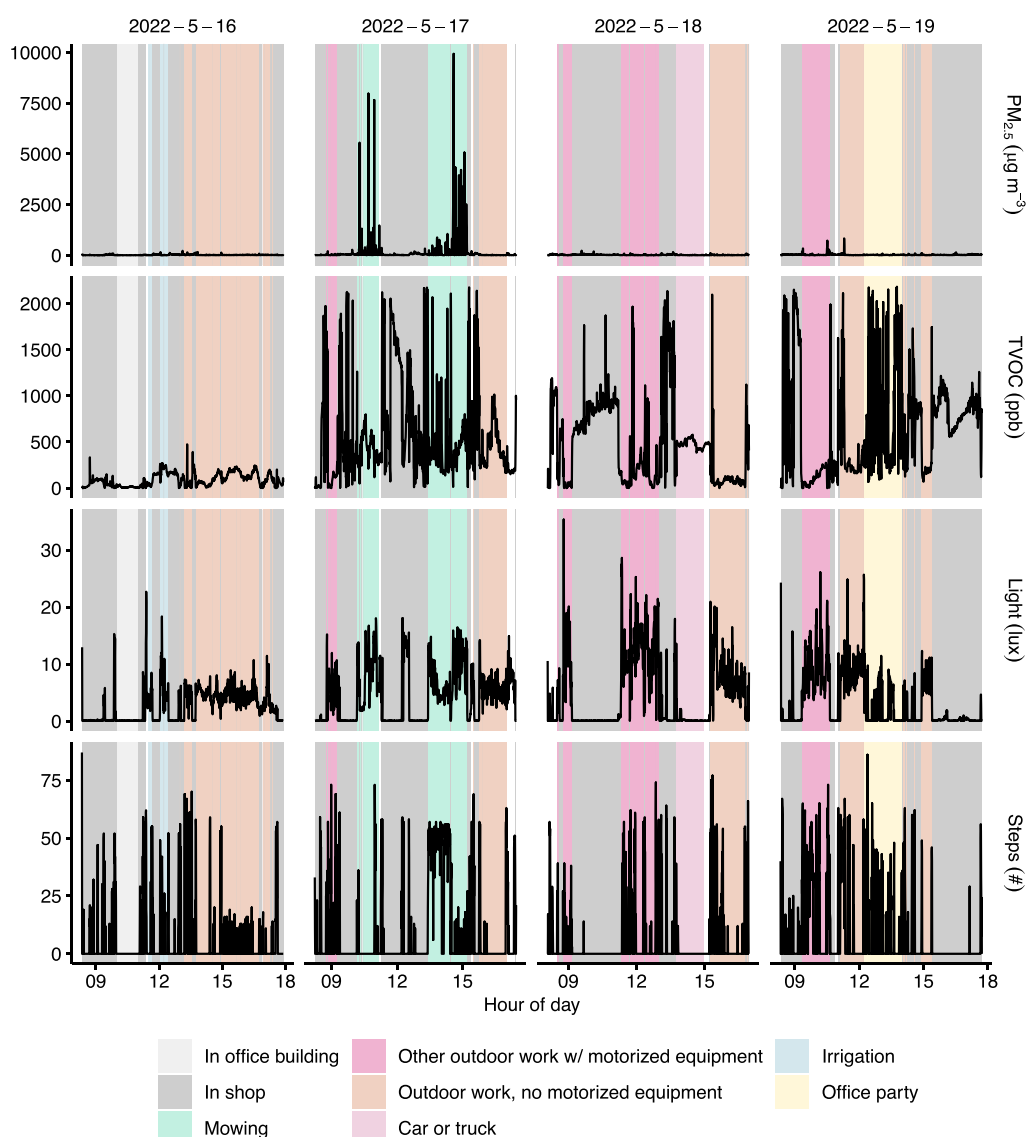


Figure 4. Data obtained at 30 s intervals using the particulate matter (PM) sensor, total volatile organic compound (TVOC) sensor, light sensor, and accelerometer in the AirPen worn by Participant 1. These 30 s $PM_{2.5}$ concentrations have been scaled so that the work-week averaged concentration matches the concentration derived from the at-work filter sample. The shaded areas in the background of each panel indicate the location where the participant was working or the activity in which the participant was engaged. Periods when the participant was in the shop were identified using the “light data + activity diary + GPS” method; the timing of all other activities was obtained from the participant’s diary.

S6). The ratio of filter-derived to sensor-reported personal $PM_{2.5}$ exposure that Participant 1 experienced away from work, where much of the $PM_{2.5}$ to which Participant 1 was exposed consisted of salt from an ultrasonic humidifier (Figure 2), was 1.6. This ratio was identical to the ratio from a prior laboratory experiment in which SPS30 sensors measured nebulized salt aerosol.³⁴ SPS30 sensors underestimated several other work-week average $PM_{2.5}$ concentrations more severely (e.g., Participant 1’s at-work exposure, the concentration measured outside by the orchard). This underestimation is consistent with the presence of particles larger than $1.0\ \mu m$ (e.g., windblown or mechanically generated dust), which most low-cost PM sensors do a poor job of detecting.³⁵

No personal exposures to the VOCs that we quantified exceeded a TWA REL published by NIOSH or a TWA permissible exposure limit set by the Occupational Safety and Health Administration (OSHA). Work-shift averaged (i.e., 8–10 h average) personal VOC exposures measured using AirPen

thermal desorption tube samples were strongly correlated with (Pearson’s $r = 0.92$ for benzene and 0.99 for toluene), but slightly lower than, work-shift averaged VOC exposures measured using conventional personal thermal desorption tube samples (Figure S16), which was consistent with our laboratory results (Figure S8). The linear models fit to the benzene and toluene data, using Deming regression, were $c_{C6H6, AirPen} = 0.79c_{C6H6, conventional} - 0.62$ and $c_{C7H8, AirPen} = 0.77c_{C7H8, conventional} - 0.31$ ppb, respectively.

Six VOCs were detected in the at-work samples at a mean concentration that was (a) at least 15% higher than the mean ambient concentration measured outside in the field and (b) greater than 0.1 ppb: benzene, toluene, ethylbenzene, xylenes, 1,2,4-trimethylbenzene, and chloromethane. The highest concentrations of BTEX and 1,2,4-trimethylbenzene were measured in the shop (Figure 5). Participants 1 and 3—who had offices in the shop—had higher at-work exposures to these compounds than participants 2, 4, and 5. Participants were

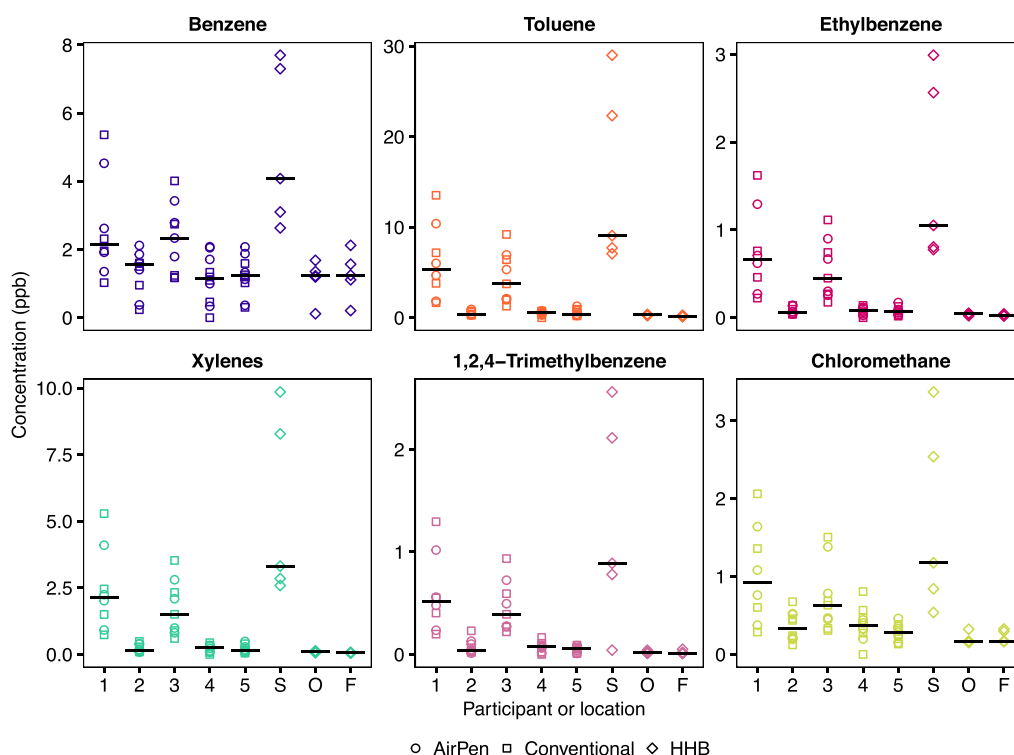


Figure 5. Work-shift averaged VOC concentrations derived from thermal desorption tube samples collected on each participant (1–5) and in each of the three stationary locations (S = in shop, O = in office building, and F = outside in field). Marker shapes indicate the device used to collect the sample (HHB = Home Health Box). Horizontal bars indicate the median concentration of each pollutant measured for each participant or location (using any sampling device).

typically exposed to lower VOC concentrations while away from work than while at work (Figure S17).

Time-activity diaries were an added burden for participants, on top of their regular professional and personal responsibilities, and the level of detail in these diaries varied between participants and dates. Supplementing time-activity diaries with data from the sensors on the AirPen provided more detailed information on the time participants spent in different locations. Data from the light sensor (which was pointed toward the ground when the AirPen was worn as shown in Figure S9) indicated when a participant was inside vs outside and data from the accelerometer indicated when a participant was stationary (e.g., in a meeting, working at a desk) or in motion. AirPen sensor data from Participant 1 are shown in Figure 4 as an example; Participant 1's data were selected for this example because Participant 1 moved between different locations (shop, office building, outside) and activities frequently.

When the fraction of each work shift that each participant spent in the shop was estimated by supplementing time-activity diaries with light and GPS data from AirPens, participant's personal exposures to BTEX were found to be strongly correlated (i.e., correlation coefficient > 0.6)³⁶ with the product of the fraction of the work shift spent in the shop and the concentration of the corresponding VOC measured in the shop (Figure 6b). Based on these results, participants were advised that the amount of time they spent working in the shop was most likely the greatest determinant of their personal exposure to BTEX at work. Participants were also advised that their personal exposures to VOCs might be reduced if ventilation in the shop was improved; fuels, oils, and other chemical products stored in the shop were relocated to an

outdoor cabinet; or if staff completed phone- and computer-based tasks in the office building instead of the shop.

When the fraction of each work shift that each participant spent in the shop was estimated using assumptions based on general knowledge of each participant's job duties combined with light and GPS data from the AirPen, similar results were obtained: participant's personal exposures to BTEX were strongly correlated with the product of the fraction of the work shift spent in the shop and the concentration of the corresponding VOC measured in the shop (Figure 6c). This result suggests that, with the help of the sensors on the AirPen, burden on participants could have been reduced, yet similar insight into sources of pollution exposure could have been obtained, by asking participants to provide a general description of the areas where they worked and the tasks they completed regularly instead of asking participants to keep detailed time-activity diaries.

This result is subject to some caveats: our field study was conducted with participants who spent a lot of time working outside and who moved across relatively large distances compared to workers who typically spend their entire shift in a single building. Regular outdoor excursions likely allowed AirPens to log GPS data with better spatiotemporal resolution than would be logged during an 8–10 h shift inside a typical commercial building. Additionally, even when AirPen data clearly indicated that a participant was indoors, we sometimes had to make assumptions about which building the participant was in by combining knowledge of each participant's office location and job duties with GPS data that had limited spatial resolution. These assumptions might have sometimes resulted in misclassification of the participant's location.

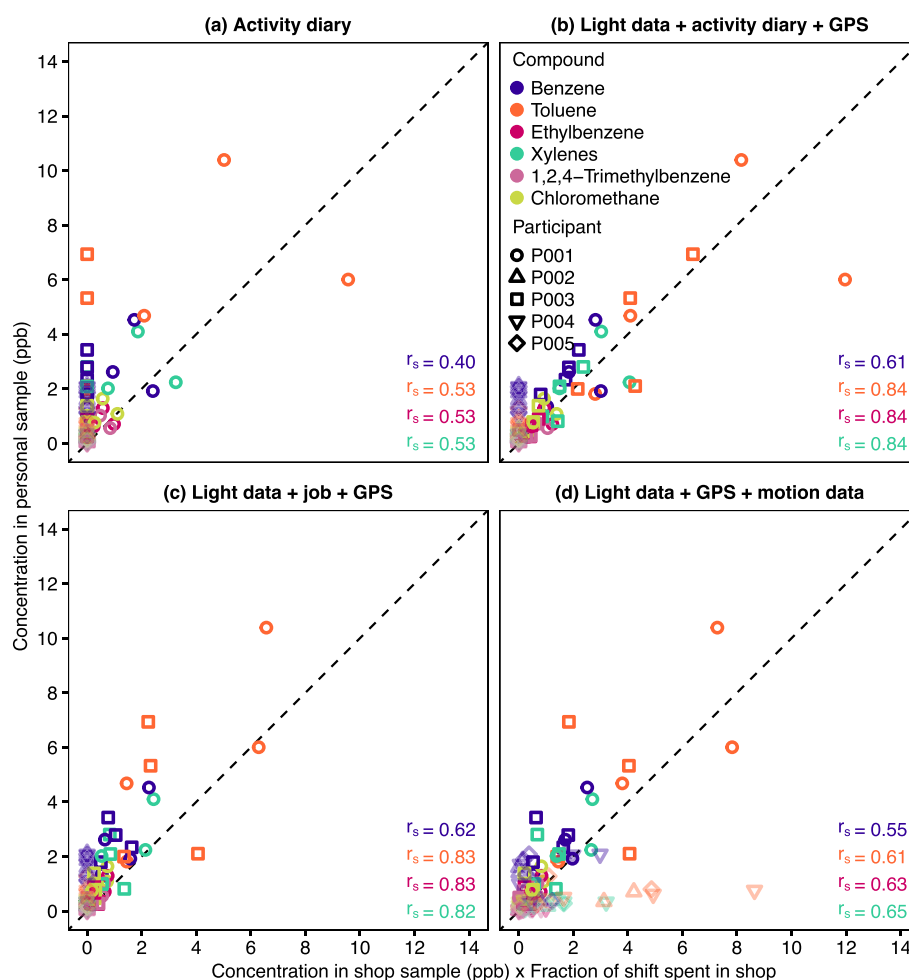


Figure 6. Work-shift averaged personal exposures to VOCs (as derived from AirPen samples) compared to the product of work-shift averaged VOC concentrations measured in the shop and the fraction of the shift spent in the shop. (a–d) Results obtained using four different methods of estimating the fraction of each shift that each participant spent in the shop are shown; results obtained using all six methods are shown in Figure S18. Each point represents a time-averaged concentration measured during a single work shift. The dashed line is $y = x$. Solid markers represent data for Participants 1 and 3, who had offices in the shop; transparent markers represent data from Participants 2, 4, and 5, who were not expected to spend much time in the shop. Spearman's correlation coefficients for BTEX are shown in the lower right corner of each panel.

When data from the sensors on the AirPen were used without any knowledge of participant job duties or activities, it was more difficult to estimate the fraction of the work shift that each participant spent in the shop. Participants 2, 4, and 5 were sometimes estimated to spend large fractions of a work shift in the shop—a result that was not supported by knowledge of participants' office locations or job responsibilities, nor by the information provided by participants in their time-activity diaries (Figures 6d and S18). We attributed this result to the limited resolution of AirPen GPS data, especially when participants were inside buildings constructed of steel and concrete. Combining GPS data with accelerometer and magnetometer data improved our estimates of participant location, but we did not calibrate the accelerometer and magnetometer for use with a dead-reckoning algorithm prior to sampling, and calibration could facilitate more accurate location estimates in future work. Additionally, the wireless radio in the AirPen could be used to gain more precise location estimates based on proximity to other wireless devices (e.g., computers and their peripheral devices, other IoT-enabled devices).^{37,38}

Overall, these results illustrate how data from the sensors on the AirPen can help elucidate the locations and sources

associated with higher personal exposures to air pollutants. In many prior studies that included measurements of personal exposure to air pollutants, information on participant proximity to pollution sources was only available from time-activity diaries^{39,40} or was obtained by asking participants to literally shoulder the burden of wearing many devices at once.^{41,42} In comparison, the AirPen allows species-specific and time-resolved data on personal exposure to PM and VOCs—as well as light, location, motion, temperature, and humidity data that can provide insight into how different places, sources, and activities contribute to an individual's exposome—to be collected using a single, small, lightweight, quiet, and wearable device.

The AirPen does suffer from some limitations. The low rate at which the AirPen samples air through the filter (0.25 L min^{-1}) serves to minimize the size, weight, and noise level of the device, all of which are important for wearability but can make it difficult to collect sufficient PM mass for gravimetric analysis; therefore, the AirPen is best suited for (a) use in occupational environments where time-averaged personal exposures to PM are relatively high and (b) assessing personal exposure to specific PM constituents using non-gravimetric techniques with low limits of detection (e.g., thermal optical

analysis of elemental and organic carbon, XRF analysis of metals). Second, the costs of analyzing physical PM and VOC samples collected with the AirPen—including personnel and instrument time—can be high. These sample analysis costs are not present when personal exposures are measured using low-cost sensors alone, but low-cost sensors provide no information on PM or VOC composition to facilitate source identification and health impact assessment. Sample analysis costs can be minimized by taking advantage of automated systems such as robotic weighing facilities⁴³ and thermal desorption tube autosamplers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.3c02238>.

Additional descriptions of the procedure used to calibrate the AirPens, the procedures used to analyze PM and VOC samples, the methods and results associated with the laboratory PM and VOC sampling experiments, and the methods used to collect and analyze PM and VOC samples collected during the field study (PDF)

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Notes

The authors declare the following competing financial interest(s): The design of the AirPen is based, in part, on the design of the Ultrasonic Personal Air Sampler (UPAS) that is currently manufactured and sold by Access Sensor

Technologies, LLC (AST). John Volckens is a scientific founder of AST and has an equity interest in the company. Additionally, Jessica Tryner and Casey Quinn are part-time employees of AST. The terms of these arrangements have been reviewed and approved by Colorado State University in accordance with its conflict-of-interest policies.

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