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## ORIGINAL ARTICLE

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# Development and evaluation of an ultrasonic personal aerosol sampler

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**Abstract**

Assessing personal exposure to air pollution has long proven challenging due to technological limitations posed by the samplers themselves. Historically, wearable aerosol monitors have proven to be expensive, noisy, and burdensome. The objective of this work was to develop a new type of wearable monitor, an ultrasonic personal aerosol sampler (UPAS), to overcome many of the technological limitations in personal exposure assessment. The UPAS is a time-integrated monitor that features a novel micro-pump that is virtually silent during operation. A suite of onboard environmental sensors integrated with this pump measure and record mass airflow (0.5–3.0 L/min, accurate within 5%), temperature, pressure, relative humidity, light intensity, and acceleration. Rapid development of the UPAS was made possible through recent advances in low-cost electronics, open-source programming platforms, and additive manufacturing for rapid prototyping. Interchangeable cyclone inlets provided a close match to the EPA PM<sub>2.5</sub> mass criterion (within 5%) for device flows at either 1.0 or 2.0 L/min. Battery life varied from 23 to 45 hours depending on sample flow rate and selected filter media. Laboratory tests of the UPAS prototype demonstrate excellent agreement with equivalent federal reference method samplers for gravimetric analysis of PM<sub>2.5</sub> across a broad range of concentrations.

**KEYWORDS**

air pollution, citizen science, exposure, low cost, PM<sub>2.5</sub>, sensor, wearable

## 1 | INTRODUCTION

Indoor and outdoor air pollution are major contributors to human disease, disability, and premature death globally. Household air pollution that, in developing countries, results primarily from the incomplete combustion of primitive fuels for cooking and heating (e.g. wood and charcoal), is considered the 6th leading risk factor for disease and death on the planet.<sup>1</sup> Outdoor air pollution from particulate matter (PM), which has numerous anthropogenic and biogenic sources, is considered the 11th leading risk factor.<sup>1</sup>

Despite these alarming risks, our understanding of human exposure to air pollution (whether indoors or outdoors) is limited. Although

regulatory agencies such as the U.S. EPA maintain national air quality monitoring networks, the monitors that constitute these networks tend to be relatively sparse, costly to maintain, and report only outdoor pollution levels. Furthermore, data from such monitoring networks are only modestly correlated with an individual's daily exposure to air pollution,<sup>2,3</sup> except in cases where the study population is highly sedentary.<sup>4</sup> People spend most of their lives indoors, moving from one microenvironment to the next (e.g. at home, at work, or in transit). For these reasons, assessment of *personal exposure* remains the standard for determining individual risk. Studies that have examined personal exposure to air pollution, however, have consistently demonstrated lognormal variations in exposure that span both space and time.<sup>5–7</sup>

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Characterizing lognormal exposure distributions (for exposure assessment or exposure modeling) requires studies with relatively large sample sizes; however, most studies that employ personal sampling are limited to modest sample sizes because of limitations in the technologies used to assess personal exposure.

A major constraint on our ability to assess personal air pollution exposure is the cost and physical burden of the monitors themselves. For monitoring exposure to PM, personal air samplers typically consist of a battery-powered diaphragm pump connected by tubing to a size-selective inlet (e.g. a cyclone or impactor) to measure inhalable, respirable, or PM<sub>2.5</sub> size fractions of PM within the wearer's breathing zone. Such personal air samplers are expensive (typically costing >\$1500 each), relatively heavy (>0.5 kg in total), and noisy (emitting >60 dB from the pump). The physical burden posed by these monitors (noise, visual esthetic, and weight) makes them difficult to wear for extended periods. Further, the diaphragm pumps must be periodically checked for flow accuracy, and the tubing connections often disconnect or become pinched if the wearer is physically active. For these reasons, studies of personal PM exposure often suffer from small sample size and data loss due to poor user compliance and instrument reliability.

Historically, the development of PM exposure monitors was driven by the need to assess occupational intake for aerosol hazards in the dusty trades such as mining, construction, manufacturing, and agriculture.<sup>8,9</sup> In those workplaces, the weight and noise of the monitors were less of a hindrance. For personal monitoring among the general population (or outside of heavy industry), however, a need exists for technology that overcomes these limitations. The objective of this work was to develop a wearable air pollution monitor to address limitations of the current state of the art (cost, noise, weight) without sacrificing precision, accuracy, and reliability. We leveraged recent advances in consumer electronics, open-source software platforms, and additive manufacturing to iterate upon several versions of a prototype wearable PM sampler. The resultant device, an ultrasonic personal aerosol sampler (UPAS), is compact, lightweight, and virtually silent when running. The UPAS was tested for pump and battery performance, flow accuracy, and size-selective sampling efficiency. Device performance was also evaluated against an EPA-certified reference method for PM<sub>2.5</sub> sampling through laboratory tests (and also compared to an off-the-shelf commercial sampling device).

### Practical Implications

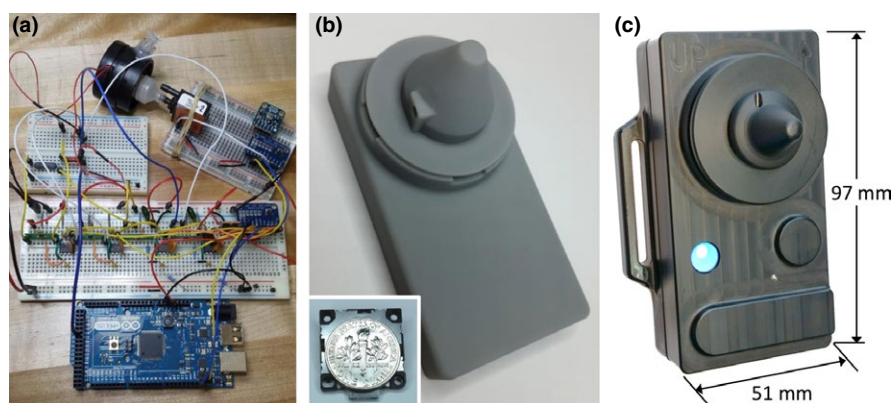
A wearable, low-cost, low-burden sampler for PM<sub>2.5</sub> is described, which should dramatically improve our ability to design and implement air quality exposure assessments, interventions, and health effect research.

## 2 | METHODS

### 2.1 | Sampler design

The UPAS is a time-integrated filter sampler that utilizes an ultrasonic piezoelectric pump to drive flow (as opposed to a traditional diaphragm pump). This pump operates by converting electric charge into reversible mechanical expansion of a ceramic crystal at high frequency (~25 kHz). Air is expelled from a miniature chamber below the crystal and through a diffuser nozzle, which functions as a passively dynamic valve, preventing virtually all backflow.<sup>10-12</sup> Without a traditional check valve, piezo-pumps are not as susceptible to damage from dirty/multiphase flow; further, without any sliding interfaces, piezo-pumps operate at high efficiency and with low noise. An image of the piezo-pump used here is shown at the inset of Fig. 1b. This pump provides key advantages over diaphragm pumps in terms of size, weight, cost, and noise.

Prototyping for the UPAS was carried out using commercially available, "plug and play" electronics that were integrated into a functional circuit based upon an open-sourced, Arduino<sup>®</sup> development board. A proof-of-concept design, in which a pump and flow sensor were connected to a simple filter housing using Arduino and breadboard electronics, is shown in Fig. 1a. Following the proof of concept, functional housing designs were created using computer-aided design software (SolidWorks<sup>®</sup> ANSYS, Inc., Canonsburg, PA, USA) and then rapid-prototyped using stereolithographic printing (Fig. 1b). The use of original equipment manufacturer electronics and rapid-prototype materials enabled a rapid series of iterative design/evaluation steps, which ultimately resulted in the construction of a serial prototype (Fig. 1c). The serial prototype featured a custom-printed circuit board with an integrated microcontroller (mbed<sup>™</sup>; ARM<sup>®</sup> Ltd., Cambridge, UK) and



**FIGURE 1** Iterative design phases of an ultrasonic personal aerosol sampler. (a) Initial pump concept with breadboard and Arduino<sup>™</sup> circuit; (b) functional, rapid-prototype sampler with PM<sub>2.5</sub> cyclone inlet (micropump shown at bottom left); and (c) serial ultrasonic personal aerosol sampler prototype with machined housing and printed circuit board

housing/mechanical components machined from engineered thermo-plastic (ULTEM™ Sabic, Riyadh, Saudia Arabia). The microcontroller contained a Bluetooth Low Energy™ module for app-based wireless communications and programming (iOS and Android). The flow circuit integrates a size-selective inlet (see Cyclone Design), a taper-fit cap designed to hold a standard 37-mm air sampling filter, a pump manifold, and a mass airflow sensor. Additional surface-mount sensors provided measurement of light intensity, acceleration, temperature, pressure, and relative humidity, which are recorded and stored in non-volatile memory. A micro-USB charging (and data communication port) is located on the side of the device to charge an internal, lithium-ion battery.

## 2.2 | Sampler performance testing

For use with the UPAS, two separate, interchangeable cyclones were designed and evaluated; one for operation at 1.0 L/min and another for operation at 2.0 L/min. Design and testing were carried out in the same way for each cyclone. Kenny and Gussman<sup>13</sup> showed that for cyclones of the same shape, the relationship between  $d_{50}$ , the aerodynamic diameter of particles collected with 50% efficiency expressed in  $\mu\text{m}$ ;  $D_c$ , the cyclone diameter in cm; and  $Q$ , the flow through the cyclone in L/min, is as follows:

$$\ln(d_{50}) = a + b \ln(D_c) + (1-b) \ln(Q), \quad (1)$$

where  $a$  and  $b$  are constants that depend on the shape of the cyclone. For cyclones they designate as “sharp cut,” Kenny and Gussman<sup>14,15</sup> report that  $a=1.447\pm 0.018$  and  $b=2.131\pm 0.017$ . These values were used with Equation (1) to determine the diameters of cyclones that would operate at 1.0 and 2.0 L/min and have a  $d_{50}$  of 2.5  $\mu\text{m}$ . Kenny et al.<sup>16</sup> showed that the performance of a sharp cut cyclone conforms well to the  $\text{PM}_{2.5}$  standard specified in the U.S. Code of Federal Regulations.<sup>17,18</sup>

Cyclones designed this way were rapid-prototyped and tested to determine their efficiency as a function of aerodynamic particle size; from these curves, revised values for constants  $a$  and  $b$  were determined. With these new constants, the diameter for each of the two cyclones was revised, and new cyclones were fabricated and tested. This process was repeated until the measured and intended performance of each cyclone adequately matched the  $\text{PM}_{2.5}$  standard, using the method described below to evaluate the quality of the match.

## 2.3 | Cyclone performance

Cyclone performance was evaluated in a 0.76 m<sup>3</sup> aerosol chamber; a schematic for this setup is provided in the Supplementary Material. A one-jet Collision Nebulizer (Mesa Labs, Lakewood, CO, USA) operated at 40 kPa with a timing cycle of 1-second on, 16 seconds off, to generate an aerosol of vacuum pump oil. A fan mixed the chamber aerosol continuously. Filtered dilution air passed through the chamber at a flow of 70 L/min to help control particle concentration. A DustTrak DRX (TSI Inc., Shoreview, MN, USA) was used in the chamber to monitor aerosol concentration, which was stable prior to and during each test.

Chamber aerosol passed through a cyclone or through a bypass (without a cyclone), into an Aerodynamic Particle Sizer (APS; model 3321; TSI Inc.) that measured particle concentration as a function of aerodynamic diameter. Enough clean, filtered air was also metered into the APS inlet to make up the difference between the intended flow through the cyclone and the flow into the APS, which was nominally 5.0 L/min. Four different 1.0 L/min cyclones were evaluated in series (iteratively), each with slightly different dimensions. For each of these, four replicate tests were conducted at flows of: 0.50, 0.75, 1.0, 1.25, and 1.5 L/min. Similarly, four slightly different 2.0 L/min cyclones were evaluated, and for each, four replicate tests were conducted at flows of: 1.5, 1.75, 1.0, 2.25, and 2.5 L/min.

For each test, the cyclone and the bypass were alternately connected to the APS inlet and data recorded for 1 minute until seven such measurements had been made at each flow rate. From the ratio of concentrations measured for each particle size with the cyclone and with the bypass, a series of efficiency measurements was developed for particles of each APS size. When the cyclone was attached to the APS, flow was slightly less due to its pressure drop so that slightly fewer particles were counted for particles of all sizes. This issue was addressed by normalizing cyclone counts for all particle sizes using the ratio of concentration with the bypass to concentration with the cyclone for particles <1  $\mu\text{m}$  in diameter, as these particles were too small for either cyclone to collect.

Fractional efficiency for a cyclone,  $\eta(d)$ , can be expressed using an equation of the form

$$\eta(d) = \frac{1}{1 + [d/d_{50}]^\beta}, \quad (2)$$

where  $d$  is aerodynamic particle diameter and  $\beta$  is a slope parameter. Best-fit values of  $d_{50}$  and  $\beta$  for each test were determined using the “Solver” function in Excel by minimizing the sum of squares for the difference between measured efficiency and the efficiency given by Equation (2). Log-log plots of  $d_{50}$  and  $\beta$  against flow were then prepared for each of the four replicate tests for each cyclone, and second-order curves fit to the data. Curves from these replicate tests were then used to determine average  $d_{50}$  and  $\beta$  values (and their standard deviations) for each cyclone at its design flow of either 1.0 or 2.0 L/min.

## 2.4 | UPAS evaluation

Tests of the serial prototype performance (Fig. 1c) were conducted in the laboratory. Performance of the piezo-pump was established by measuring pump flow as a function of flow resistance posed by a needle valve to induce pressure drop (to simulate that posed by an air sampling filter). These curves were developed using digital pressure/flow sensors that were calibrated against primary standards. Battery life was evaluated using a combination of power measurement and run-time tests at flows of 1.0 and 2.0 L/min. Noise levels emitted by the pump were tested using a Larson Davis (Depew, NY, USA), Spark Series, 703+ noise dosimeter.

The UPAS was also evaluated relative to two commercial technologies: an equivalent federal reference method (FRM) for PM<sub>2.5</sub> monitoring (URG cyclone model URG-2000-30EGN-A; URG Corp., Chapel Hill, NC, USA) and a personal environmental monitor (PEM) for assessing personal exposure to PM<sub>2.5</sub> (PEM 761-203; SKC, Inc., Eighty Four, PA, USA). The FRM sampler was operated at 16.7 L/min, per U.S. EPA guidelines, and served as the reference instrument. The UPAS and PEM both operated at 2.0 L/min.

Three groups of samplers (one FRM, UPAS and PEM per group) were colocated in three locations within the aerosol test chamber (nine samplers per test). Aerosols were generated with National Institute of Standards and Technology Urban PM (Standard Reference Material 1648a) and 6-jet BGI Collison Nebulizer (Mesa Labs). A solution of NIST Urban PM in biological grade reagent water (Lonza Ltd., Basel, Switzerland) was placed in the nebulizer at concentrations ranging from 0.25 to 4.0 mg/mL to achieve desired chamber aerosol concentrations. Concentrations were monitored in real time with a DustTrak DRX (TSI, Inc.), and particle size distribution was monitored with an APS (model 3321; TSI, Inc.).

Six chamber trials were conducted for 8 hours with a seventh trial lasting 16 hours to collect sufficient material for gravimetric analysis at low concentration. Slight adjustments were made during trials to chamber (dilution/exhaust flow) and nebulizer (timed periodic activation with solenoid valve) conditions to achieve a stable aerosol concentration during tests. A fan mixed the chamber aerosol continuously.

The PEM and UPAS samplers used borosilicate glass fiber filters coated with polytetrafluoroethylene (PTFE; Pallflex Fiberfilm T60A20; Pall Inc., Ann Arbor, MI, USA) for the six 8-hour tests and PTFE filters supported with polymethylpentene rings (Teflo; Pall Inc.) for the single 16-hour test. The URG cyclones used PTFE filters with support ring (46.2 mm, PM<sub>2.5</sub> membrane, 2 µm pore size; Tisch Scientific Inc., North Bend, OH, USA), which meet the requirements for EPA PM<sub>2.5</sub> Reference Method under 40 CFR Part 50. The UPAS samplers were fitted with the appropriate PM<sub>2.5</sub> cyclone and set to operate at 2.0 L/min. Flow through the PEMs was maintained using commercially available personal sampling pumps (AirCheck XR5000; SKC, Inc.) that were calibrated to 2.0 L/min flow. The PEM impaction ring was greased according to the manufacturer instructions. Pre- and post-calibrations were performed with the Defender 520 DryCal (Mesa Labs) and Mini-Buck Calibrator (A.P. Buck, Inc., Orlando, FL, USA) utilizing custom-made calibration adapters for the URG and UPAS samplers and an SKC calibration adapter for the PEMs.

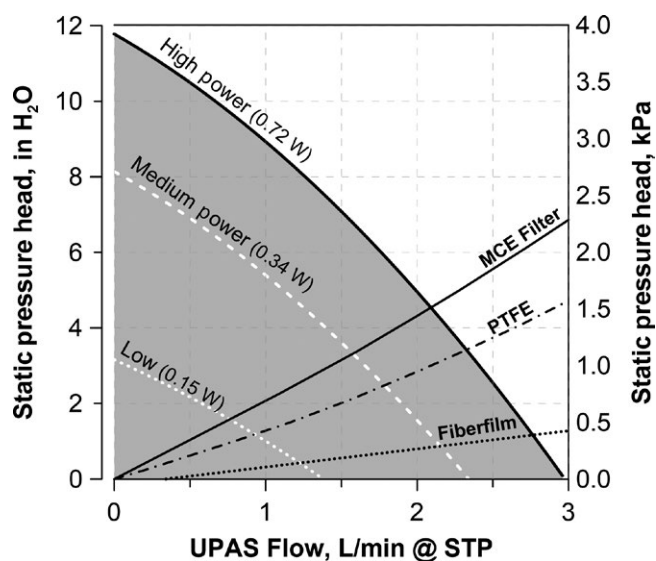
Measured aerosol concentrations were established for each sampling device using gravimetric analysis. A Mettler Toledo XS3DU microbalance accurate to ±1 µg was used to weigh filters. Filters were placed in an equilibration chamber for at least 12 hours before pre- and post-weighing and then discharged on a polonium-210 strip for at least 15 seconds before each weight was taken. Multiple readings were averaged for each filter weight, and blanks were carried for all tests. Data analyses were conducted using Excel (Microsoft Corp., Redmond, WA, USA) and Matlab (The MathWorks, Inc., Natick, MA, USA).

### 3 | RESULTS

Selected sensors and components for the final UPAS design (Fig. 1c) are provided in Table 1; a time-series plot of data collected by these sensors is shown in the Supplementary Information. The retail cost of these sensors, when purchased in single quantity amounts, totals approximately \$150. Shown in Fig. 2 are data depicting the performance of the UPAS pump at three different (arbitrary) power levels for standard temperature and pressure conditions. The shaded area on the figure represents the operating envelope of the pump (flow vs pressure drop across all possible power levels). The operating range

**TABLE 1** Ultrasonic personal aerosol sampler sensor components and electronics

Component	Manufacturer	Part number
Microblower	Murata	MZBD001
Mass Air Flow Sensor	Honeywell	Omron D6F
Light Sensor (vis., UV, IR)	Silicon Labs	SI1145-A10-GMR
Temp., Pressure, RH Sensor	Bosch Sensortec	BME280
Accelerometer/Magnetometer	STMicroelectronics	LSM303DLHCTR
Bluetooth Low-Energy	Switch Science	HRM1017
MicroSD Card	Molex	5031821852
Memory (EEPROM)	Atmel	AT24CM01-XHM-T
Real-time Clock	Maxim Integrated	DS3231MZ+
Battery (2800 mAh)	Samsung	SAEBBG900BBU



**FIGURE 2** Ultrasonic personal aerosol sampler (UPAS) pump performance curve and filter pressure drop vs flow rate. Data shown for three UPAS power levels and three representative 37-mm filters: mixed cellulose ester (MCE; 0.8 µm SKC, Inc.), polytetrafluoroethylene (PTFE; PT37P, MTL Inc.), and PTFE-coated glass fiber (Pallflex Fiberfilm; Pall Inc.)

**TABLE 2** Performance characteristics of the ultrasonic personal aerosol sampler

Characteristic	Performance
Battery life	43 h @ 1.0 L/min <sup>a</sup> 25 h @ 2.0 L/min <sup>a</sup>
Flow accuracy	±4.5%
Weight	190 g
Size	97×51×26 mm
Noise	<40 dB at 20 cm
Flow range	0.3–3.0 L/min

<sup>a</sup>Using a 37 mm Pallflex Fiberfilm T60A20 filter.

of the pump spans 4 kPa of water static pressure head and upward of 3 L/min of flow at the highest power setting. At 1.0 and 2.0 L/min of flow, the pump is capable of drawing air against a back pressure of 2.5 and 1.7 kPa (9.0, 5.0 in H<sub>2</sub>O), respectively. Shown also in Fig. 2 are flow–pressure relationships for the UPAS cyclone inlet operated with three common air sampling filters (nominal 37 mm diameter): mixed cellulose ester (0.8 μm SKC, Inc.), PTFE (PT37P, MTL Inc.), and PTFE-coated glass fiber (Pallflex Fiberfilm; Pall Inc.). The intersection of a given cyclone/filter curve with the UPAS pump curve represents the operating point for the UPAS at any particular power level.

Tests of flow control accuracy using the integrated mass flow sensor were within 5% when evaluated against a primary flow standard (Table 2). The internal UPAS battery (lithium-ion; rechargeable via a micro-USB port on the side of the unit) lasted approximately 25 hours at 2.0 L/min and 45 hours at 1.0 L/min, respectively, when sampling air through a 37 mm Pallflex Fiberfilm filter (with all other sensors running). When tested with a TissueQuartz filter (with approximately twice the pressure drop), the battery life decreased by approximately 2 hours. Additional performance specifications are provided in Table 2. At a distance of 20 cm (the approximate length from the ear to a hypothetical sampler mounted on a lapel within the breathing zone), the UPAS produced 40 dB of A-weighted noise. For comparison purposes, the PEM and XR5000 pump combination emitted 60 dB under similar conditions.

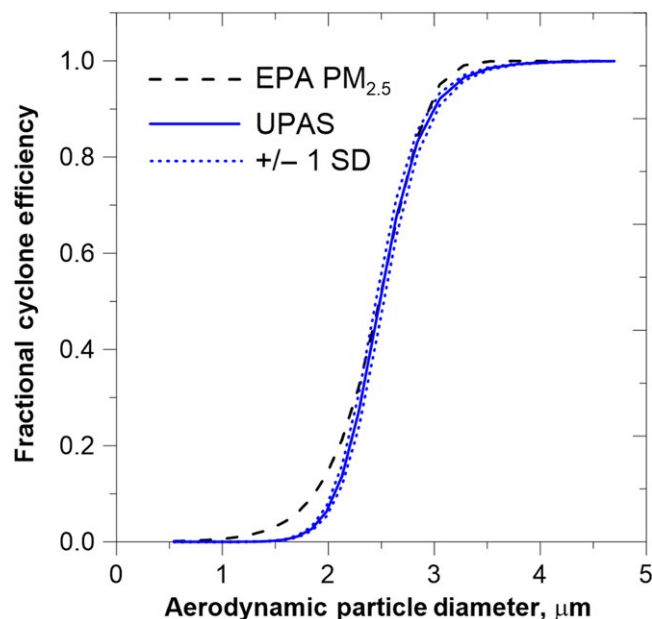
The dimensions of the final 1.0 and 2.0 L/min cyclone designs are provided in Table 3, along with  $d_{50}$  and  $\beta$  values for operation at their design airflows. Equation (3) from Hinds<sup>19</sup> determines within 0.1% the fraction of particles that a cyclone or other device should collect to match the Code of Federal Regulations specification for PM<sub>2.5</sub>,  $\eta(d)_{\text{FRM}}$ ,

$$\eta(d)_{\text{FRM}} = 1 - \left[ 1 + e^{(3.233 \cdot d - 9.495)} \right]^{3.368} \quad (3)$$

**TABLE 3** Dimensions in mm and performance constants for ultrasonic personal aerosol sampler cyclones

Flow, L/min	$D_c$	$D_{in}$	$D_e$	$B$	$H$	$Z$	$S$	$d_{50}$	$\beta$
1.0	7.72	1.85	2.09	1.93	3.32	8.73	2.70	2.49±0.04	13.1±0.8
2.0	12.1	2.91	3.27	3.03	5.21	13.7	4.24	2.48±0.04	12.0±0.8

Definitions for cyclone dimensions  $D_c$  through  $S$  follow Kenny and Gussman<sup>14,15</sup>; see Supplementary Information for details. Confidence intervals for  $d_{50}$  and  $\beta$  are one standard deviation.

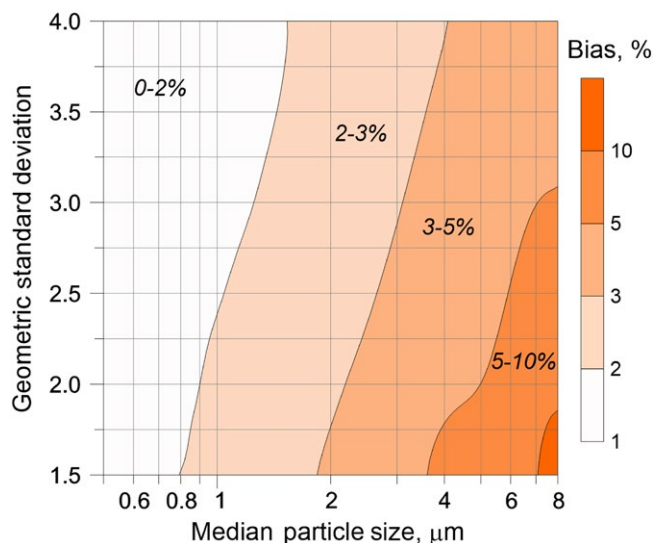
**FIGURE 3** Collection efficiency of 2.0 L/min cyclone relative to the EPA PM<sub>2.5</sub> criterion standard

Particle collection efficiency of the 2.0 L/min UPAS cyclone is shown in Fig. 3, which depicts the corresponding relationship from Equation (2) for the cyclones whose dimensions,  $d_{50}$  and  $\beta$  values, are given in Table 3. Figure 3 also depicts the relationship between aerodynamic particle size and the EPA PM<sub>2.5</sub> criterion [ $\eta(d)_{\text{FRM}}$  from Equation (3)] for comparison. Results for the 1.0 L/min cyclone are nearly identical and shown in the Supplementary Material.

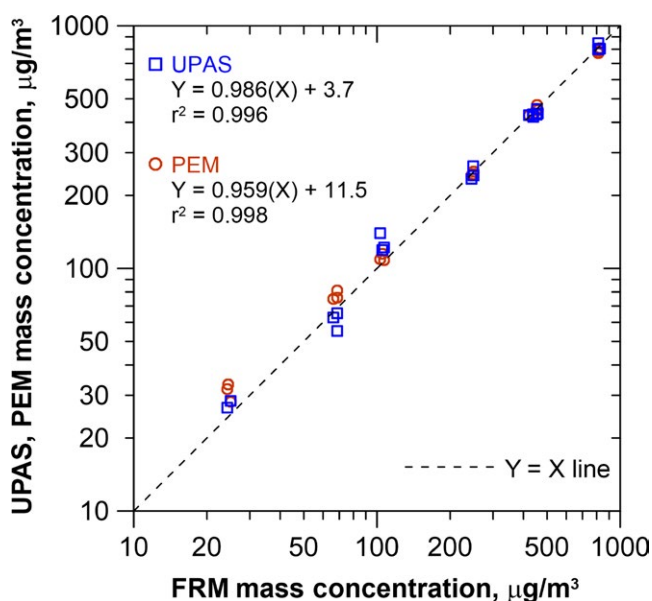
To characterize the adequacy of the two cyclones, the difference between the collection efficiency of an ideal PM<sub>2.5</sub> collector as given by Equation (3) was compared to the efficiency of each cyclone developed here for a series of hypothetical size distributions. This comparison was conducted for 30 lognormally distributed aerosols with median diameters ranging from 0.5 to 8 μm and with geometric standard deviations from 1.5 to 4.0. Results for these simulations are shown in Fig. 4 in the form of a bias plot. For the vast majority of particle size distributions encountered in household or outdoor air, the UPAS cyclone catch should match that of an FRM sampler within approximately 5%. Only one size distribution (8 μm median diameter with a geometric standard deviation of 1.5) produced a bias greater than 10% between the UPAS and EPA PM<sub>2.5</sub> criterion.

The performance of the PEM and UPAS relative to the EPA FRM sampler is shown in Fig. 5 for PM<sub>2.5</sub> test dust. Chamber concentrations spanned a range from approximately 25–800 μg/m<sup>3</sup> over these





**FIGURE 4** Bias Plot for the 2.0 L/min cyclone design. The axes define the median size and geometric standard deviation of a lognormal particle size distribution; colors represent a positive percent bias in collected sample relative to the EPA  $PM_{2.5}$  criterion



**FIGURE 5** Performance of the ultrasonic personal aerosol sampler and a personal environmental monitor (PEM+XR5000 Pump, 2.0 L/min) relative to an EPA federal reference method (FRM) sampler for  $PM_{2.5}$  mass

tests. Both the UPAS and PEMs showed strong correlations with the EPA FRM method across this range (Fig. 5). A simple linear regression between the UPAS and FRM samplers gave a slope of 0.986 with an intercept of  $3.7 \mu\text{g}/\text{m}^3$ . For comparison, the PEM sampler, when regressed against the FRM, gave a slope of 0.959 with an intercept of  $11.5 \mu\text{g}/\text{m}^3$ . Among replicate samples (i.e. instruments colocated within the chamber), the coefficient of variation was 1.4% for the FRM, 5.1% for the UPAS, and 3.4% for the PEM. The average difference (in absolute terms) in measured  $PM_{2.5}$  mass concentration was 7%

between the UPAS and FRM and 6% between the PEM and FRM. A Bland-Altman analysis showed no directional bias between the UPAS and FRM measurements as a function of chamber concentration (data not shown).

## 4 | DISCUSSION

The state of the art for personal exposure assessment has long relied upon expensive and burdensome equipment; this paradigm has limited our ability to determine individual risk at scales relevant to a diverse population (especially for epidemiology). The UPAS represents an attempt to address this limitation with a wearable air sampler that is low cost, lightweight, and low burden (silent, no-tubing, etc.). Advantages of the UPAS include its compact size and weight (about 1/3 that of the SKC PEM and XR5000 pump) and its nearly silent operation. The integration of wireless communications also serves to streamline device programming and data transfer. The inclusion of a cyclone inlet and filter cartridge directly onto the sampler body also removes the need for an external tubing connection; this is an important component of the design as many people complain about the restriction (and visual stigma) of wearing a long piece of tubing across their body.

A point of emphasis for this design was to enable data collection that is comparable to established metrics (i.e.  $PM_{2.5}$  mass concentration) and health-based exposure guidelines.<sup>20,21</sup> For this reason, the UPAS was designed to estimate personal exposure to  $PM_{2.5}$  mass across a 24-hour timescale. To achieve this goal, the development path for the UPAS relied heavily upon the recent emergence of low-cost, do-it-yourself electronics (i.e. Arduino) and additive manufacturing (i.e. rapid-prototyping machines) to move rapidly from a proof-of-concept device through an iterative series of informative design steps. This was especially helpful for the cyclone design, as cyclone design equations such as those used here are semi-empirical; thus, some iteration was required to optimize the size selectivity of the 1.0 and 2.0 L/min UPAS inlets. At 2 L/min of flow, the UPAS will draw approximately  $2.9 \text{ m}^3$  of air through the filter over a 24-hour sampling period. For gravimetric analysis, typical limits of detection are reported in the range of 10–25  $\mu\text{g}$  of mass accumulated onto the filter, which translates to a detectable air concentration of approximately  $8 \mu\text{g}/\text{m}^3$  at the upper end of this range. The unit may also be programmed to operate intermittently, should the user wish for longer run times (for a given flow rate).

Across the range of concentrations tested, the UPAS gave  $PM_{2.5}$  mass concentrations that were in close agreement with the EPA FRM sampler. To note, the agreement at the lowest concentration tested was achieved using pure Teflon filters because at this low concentration ( $\sim 25 \mu\text{g}/\text{m}^3$ ), the adsorption of semivolatile aerosols in the background air can bias a PM sample collected on a fibrous filter (such as the Pallflex T60A20) by as much as 100%.<sup>22,23</sup> When sampling at higher concentrations, such as those encountered indoors for homes burning biomass, this adsorption bias would be negligible with a larger amount of PM mass accumulated onto the filter substrate. The close

agreement between the two instruments is also a function of the cyclone performance, which closely matched the EPA criterion (Figs 3 and 4) for PM<sub>2.5</sub> size selection.

The UPAS contains a suite of environmental sensors to improve the utility of the data collected. The light sensor is used primarily for detecting the presence of a UV signal, which is indicative of the sampler being outdoors.<sup>24</sup> The accelerometer is used to gauge participant activity level, which, in addition to confirming user compliance (i.e. that the sampler is physically worn), can also be used to infer daily behavioral patterns.<sup>25</sup> As a mass-based, time-integrated monitor, the UPAS is geared primarily toward assessing one's cumulative risk from PM exposure. We chose not to include a real-time PM sensor on the UPAS for several reasons. Although several low-cost nephelometers exist on the market,<sup>26,27</sup> these devices suffer from drift and precision issues, in addition to the myriad problems associated with accurate PM measurement by light scattering. These problems include the important loss of signal at submicron particle sizes,<sup>19</sup> humidity effects,<sup>28</sup> the variation of Mie scattering intensity with size and refractive index,<sup>29</sup> and insensitivity to differences in particle density. However, future versions of the UPAS could easily incorporate direct-reading PM (as well as gaseous) sensors, provided those sensors do not add significant cost. Future versions of this device could also leverage geolocating technology, which, when coupled with direct-reading sensors, could provide the advantage of resolving both spatial and temporal exposure patterns of exposure. Other wearable PM monitors have been developed in recent years, such as the MicroPEM and MicroAeth, both of which offer direct-reading capabilities of PM<sub>2.5</sub> mass and black carbon, respectively. Both devices have also been field-validated; however, their costs have similarly limited their deployment to relatively modest sample sizes.<sup>30,31</sup>

At 190 g, the UPAS poses a reduced but still noticeable weight burden to the user (by comparison, the PEM/XR500 sampler weighs approximately 700 g). Approximately half of the instrument weight is taken up by the battery, which was sized to achieve greater than 24 hours of sample time at either 1.0 or 2.0 L/min of flow. These flow rates were selected to meet detection limits of typical gravimetric analysis systems. However, with recent advances in automated filter weighing systems,<sup>32</sup> sensitive, low-cost analytic chemistry,<sup>33–35</sup> and non-destructive sample analysis techniques,<sup>36</sup> it should be possible to develop future versions of the UPAS that operate at lower flow rates. Because the UPAS battery size/weight scales nearly directly with flow (for a predetermined sample duration), these reductions would reduce the weight burden to the wearer. Future reductions in size and weight should also reduce manufacturing costs.

## 5 | CONCLUSIONS

The UPAS shows promise for increasing our ability to assess personal PM exposures by reducing the size, weight, and cost of the sampler. As a result, sampling can be conducted at scales that are more relevant to epidemiologic and community-based research. Development of the UPAS was largely made possible by the recent revolution in

“original equipment manufacturer” electronics and open-source software. Looking forward, these industry trends should continue, and thereby aid the development of low-cost sensors that produce public health gains through applied research, advocacy, and awareness.

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