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Bio³ Air, an Integrative System for Monitoring Individual-Level Air Pollutant Exposure with High Time and Spatial Resolution

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Abstract

Background—Air pollution is a leading cause of global disease burden. Lack of suitable methods for long term measuring exposure level at individual level is crippling environmental epidemiology research of air pollution.

Methods—We report an integrative system, Bio³ Air, for long term measurement of individual level air pollution exposure, currently focusing on ambient particulate matter (PM). The novel system in real-time quantifies individual's outdoor/indoor status, geological location, lung ventilation rate and PM concentration of individual's surrounding environment, and these metrics are subsequently incorporated in calculating PM exposure.

Results—The system is fully developed and tested in China, USA and Canada, and has been successfully applied in epidemiology study. Bio³ Air offers high reliability, sensitivity, reproducibility (>99%) and accuracy. It has high time- and spatial- resolution (2 min and 20 m, respectively). Bio³ Air achieved 91.89% consistency with “gold-standard” method (membrane collection and off-line analysis).

Conclusions—Bio³ Air represents a substantial methodological advance in environmental health research of air pollution. It captures information relevant in measuring individual's PM

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Availability: Bio³ Air is available for research use and request should be sent to ke.hao@mssm.edu

Competing interests

Patent application has been filed for Bio³ Air system (File# CN106546277A) in China.

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exposure (e.g. real-time outdoor/indoor status, location and lung ventilation rate). Such information is typically missed by conventional approaches. Additional features of Bio³ Air include easy-to-use, cost-effectiveness and automated data collection, making it a powerful tool facilitating studies of air pollution exposure and health consequences.

Keywords

environmental health; ambient particulate matter; smartphone application; time and spatial resolution; individual-level exposure measurement

Introduction

Air pollution is growing as global industrialization expands, and exposures can have serious human, medical and monetary consequences (1). Air pollution is identified as a leading cause of global disease burden, especially in low-income and middle-income countries (2). China is one of the regions in the world of severe ambient air pollution (3, 4). Airborne particulate matter (PM) is a major component of air pollutants, and has been linked to pulmonary, cardiovascular diseases, memory impairment and other disorders (5–8). However, most the association between air pollution and health consequences were derived from environmental epidemiology study that relied on pollution exposure computed using subjects' address coupled with fixed-site regional monitors and/or satellite-derived aerosol optical depth (AOD) (9). For example, in a recent study, Lee *et al* used residence location, moderate resolution imaging spectroradiometer satellite-derived aerosol optical depth (AOD), and ground measurements from 78 monitoring stations covering New England to estimate participant's PM_{2.5} exposure (10). Such design (ie., community- or address-based design) provides limited information on causative mechanisms. An individual's activities, location and ventilation volume may change frequently, therefore his/her PM exposure also varies even the individual lives in the same area. Currently, personal PM monitors/collectors carried by individuals are considered the "gold standard" (11, 12). However, these approaches have major shortcoming in epidemiology studies of the individual-level PM exposure. The devices either measure the PM concentration in real-time or collect PM to a membrane for later analysis. However, these methods (1) do not factor in the volume of air subject inhaled; and (2) are relatively heavy and need regular maintenance (e.g. charging) making them difficult to deploy in long term studies (e.g. 1 year), especially impractical for children studies. Without long term individual-level PM exposure, the environmental epidemiology studies are crude, statistically underpowered, and difficult to draw causal inference.

In recent years, advances in two types of technologies made long term individual-level PM exposure monitoring feasible. (1) Smartphone is now an equipment of daily life. About 77% Americans own a smartphone according a Pew Research Center survey conducted in November 2016 (13). The functionality of smartphone is also evolving rapidly, where Global Positioning System (GPS) (14) tracking and motion sensing become standard. (2) Technology in PM sensors made significant advantages. The inexpensive sensors can be placed at individuals living and working locations, and collect PM concentration data with adequate time and spatial resolution. Recently, we thoroughly evaluated common-used

models of sensors with standardized calibration protocols (15). All sensors tested demonstrated high linearity to “gold-standard” measurement based on membrane-collection approach (SidePak, TSI Inc., St. Paul, MN, USA) in a wide concentration range: range of 0-1000 $\mu\text{g}/\text{m}^3$. (15)

The goal of this study is to combine these two types of technologies, and implement a system able to measure individual's PM intake in real time in order to facilitate long-term epidemiology studies. The key functions of the system include real-time measure subjects' location, motion, indoor/outdoor status, and PM concentration in his/her surrounding environment with high precision. Based on these metrics measured, the system will be able to compute the individual's real-time PM intake, e.g. amount of PM (μg) inhaled every minutes. Further, we evaluated its performance in terms of data reproducibility, resolution and accuracy.

Materials and Methods

Systems Architecture and Components

The Bio³ Air system has four major components (Fig 1). **1) Smartphone APP (Bio³ Air)**, which is the core part of the system. It collects three metrics in real-time: user's location (latitude and longitude), indoor/outdoor status and user's motion (steps per minutes). It also communicates with cloud server (Bio³ Cloud) to retrieve the PM concentration of user's surrounding environment. Afterward, the APP computes and displays the exposure levels on the smartphone screen (if the APP is running in the foreground of the phone), and uploads all information collected/computed to Bio³Cloud automatically. APP for both iOS and Android have been developed. **2) Bio³ Cloud**, cloud server and database receive and store data from indoor PM_{2.5} sensor (Bio³ Gear) and from the smartphone APP. It also responses to the APP's request, where APP passes user's location and indoor/outdoor status, and Bio³ Cloud returns the PM concentration of user's surrounding environment. **3) Bio³ Gear**, the indoor PM_{2.5} sensor, is deployed at user's work or residence location (e.g. office and home). It automatically measures PM concentration, the value is displayed on the device and uploaded to Bio³ Cloud. **4) Bio³ Band**, a wearable device real-time monitors user's location and heart rate, and senses ultraviolet (UV) light intensity. Bio³Band communicate with the smartphone APP via Bluetooth protocol, and is an optional component of the Bio³ Air system.

Data Collection

The Bio Air system quantifies four metrics. **1)** User's location (latitude and longitude) is obtained using Apple MapKit (16) or Baidu Map API (17) depends on type of smartphone (e.g. Apple or Android phones). **2)** Indoor/outdoor status is computed based on a function of GPS signal strength, internet connection circumstance, and UV light intensity (Bio³ Band has a built-in UV sensor). **3)** User's motion (number of steps per minutes) is obtained from Apple Health Kit (18) or Google Fit SDK (19). **4)** PM concentration is collected by Bio³ Cloud and Bio³ Gear, and we obtain outdoor and indoor PM concentration through different routes. Hourly outdoor PM concentration is downloaded and stored in Bio³ Cloud from public sources in USA, Canada and China. The data sources include: Urban Air (20),

PM_{2.5} in API (21), AirNow (22) and US EPA (23). Indoor PM concentration is directly measured by Bio³ Gear and uploaded to Bio³Cloud. It should be noted, without direct measurement, the indoor PM₂ concentration is difficult to estimate accurately although mathematical models were proposed (24, 25). It is mainly because indoor PM concentration is affected by multiple factors. However, it is possible that user is located in an indoor environment without Bio³ Gear equipped. In this case, we enabled Bio³ Air to estimate the indoor PM concentration based on outdoor concentration using a simple penetration formula: during cold months (Nov - March), the indoor concentration is 1/3 of outdoor; and during warm months (Apr - Oct), the indoor concentration is 1/2 of outdoor.

Data Processing Flow

The Bio³ Air system executes an iteration every two minutes. In each iteration, the APP firstly determines the indoor/outdoor status (Fig 2). If indoor = FALSE, the APP obtains the PGS location (longitude and latitude), and sends a request to Bio³ Cloud asking for outdoor PM concentration. If indoor = TRUE, but no Bio³ Gear equipped at user's location, the APP obtains the PGS location, sends request to Bio³ Cloud for outdoor PM concentration, and computes indoor concentration using the penetration formula. If indoor = TRUE and Bio³ Gear is deployed at user's location, APP directly obtain indoor PM concentration, where the communication between smartphone and Bio³ Gear is through Bluetooth, WiFi or Cellular networks. In the same iteration, the smartphone APP also obtains user's motion (steps per minute) and computes the user's lung ventilation rate (L/min) based on previously described formula (26), where the correlation between heart rate and ventilation was high with mean r^2 as 0.90 (26). With the information of (1) pollutant concentration of the individual's environment, termed as C_t (ug/m³); and (2) user's ventilation rate (L/min), termed as V_t , the rate of pollutant inhaled (ug/min) can be derived as $I_t = V_t \times C_t$. The cumulative amount of pollutant inhaled in a given period of time ($t_0 \rightarrow t_1$) can be expressed as $I = \int_{t_0}^{t_1} V_t \times C_t dt$. It

should be noted that Bio³ Band is an optional component of the system. It real-time monitors location, heart rate and UV light intensity. The information is transmitted to smartphone via Bluetooth protocol to refine the calculation of lung ventilation rate and indoor/outdoor status.

Time- and Spatial Resolution

The system has a time resolution of two minutes, and spatial resolution 20 meters. The spatial resolution depends on the smartphone, cellular service provider, and accuracy of GPS (14), where the United States government currently claims 4 meter (7.8 meter 95% Confidence Interval) horizontal accuracy for civilian GPS (14). The time resolution is arbitrarily chosen by us as the system's developers. Here, we set the system executes an iteration every two minutes. The choice on time resolution is a balance of precision, data granularity and smartphone battery life.

Assessing Reproducibility of Bio³ Air Measurement

We deployed multiple Bio³ Air systems (each runs on a separate smartphone) to a study subject, who underwent scenarios including (1) good and poor air quality days; (2)

sedentary, walking and running conditions; (3) indoor and outdoor; and (4) with and without Bio³Gear deployment. The experiments were carried out by two volunteers during September to December 2016 within the campus of Tongji University, Shanghai, China. Each experiment lasted 4 hours and contained two replicates. After each experiment, the PM exposure data of the study subject (measured by multiple Bio³ Air systems) were downloaded from the cloud server (Bio³ Cloud) for correlation analysis.

Assessing of Accuracy and Comparing to Conventional Methods

Membrane-collection and off-line analysis approach is considered the “gold-standard” in measuring individual-level PM exposure, and this approach has been adopted in our group’s previous study for calibrating different types of PM_{2.5} sensors (15). We applied the same protocol and used SidePak instrument (TSI Inc., St. Paul, MN, USA) for comparison to PM_{2.5} exposure measured by Bio³ Air. The experiment was conducted during March - April, 2017 at the rooftop terrace of School of Environment Building at Tsinghua University, Beijing, China. In each experiment, SidePak and Bio³ Air were operated at the same location and at the same time to guarantee head-to-head comparison. The Bio³ Air system remained still in the experiments to make the measures comparable, since the SidePak sampled PM_{2.5} at a constant rate and was not able to sense individual’s motion. In total, six experiments were conducted at different dates of various weather and air quality conditions. The procedure of using SidePak for ambient PM_{2.5} collection and analysis was described in our previous report (15). Two Bio³ Air systems were run independently in each experiment. One system linked to Bio³Gear and one did not. The Bio³ Air system that did not linked to Bio³ Gear used PM_{2.5} concentration data from public data source (20). After the experiments, the measurement results of Bio³ Air systems were downloaded from Bio³ Cloud and entered data analysis.

Field Applications of Bio³ Air

The Bio³ Air was deployed to an environmental health panel study of 40 subjects in Shanghai, China, from Oct 2016 to Oct 2017. All subjects provided written informed consent approved by the Institutional Review Boards at Shanghai Tenth People’s Hospital, Tongji University, Shanghai, China. Two approaches were used to quantify PM_{2.5} exposure: (1) Bio³ Air and (2) street address based estimation, where we used the PM_{2.5} concentration reported by the MEP (China Ministry of Ecology and Environment) station nearest to study subject’s residence.

Results

System Reliability and Resolution

The Bio³ Air system is fully developed and tested in multiple cities in China and North America. The system underwent long-term application and field study (>1 year), and demonstrated adequate stability. The system provided very high sensitivity as well as time- and special -resolution in measuring PM exposure and lung ventilation, largely due to the high performance of today’s smartphone in quantifying location and motion.

Measurement Reproducibility

Based on multiple smartphones (each phone runs Bio³ Air APP independently) deployed to the same study subject (Materials and Methods), we found the measures of the lung ventilation and PM_{2.5} intake were highly correlated ($r^2 > 0.99$) (Fig S1). Such results indicate Bio³ Air provides highly reproducible PM exposure measures, mainly because today's smartphones are able to quantify metrics (e.g. location and motion) accurately and reliably.

Assessment of Accuracy and Comparing to Conventional Methods

As described in Materials and Methods, PM_{2.5} intake was measured by TSI SidePak (as “gold-standard”) and Bio³ Air at the same date/time and same experiment site. The Pearson's correlation between SidePak and Bio³ Air not linked to the PM_{2.5} sensor (Bio³ Gear) was 73.68% (Fig 3A). In this scenario, Bio³ Air computed PM_{2.5} intake based on PM_{2.5} concentration published by UrbanAir (20). Next, we found the measures of SidePak and Bio³ Air linked to Bio³ Gear was highly correlated (Pearson's correlation $r^2 = 91.89\%$, Fig 3B), demonstrating the high accuracy of Bio³ Air system. Lastly, we compared the measurement of the two Bio³ Air systems in the study (with and without Bio³ Gear linked), and the correlation was $r^2 = 86.42\%$, Fig 3C), which reflected the discrepancy between PM_{2.5} sensor at the experiment site and UrbanAir (20) published value.

Field Applications of Bio³ Air and Case Study

All the subjects of the panel study live in the Shanghai urban area and we retrieve the PM concentration data from the nearest MEP stations for each subject. In total, data from five stations were used (Fig 4A). In fact, the PM_{2.5} reported by the five stations are highly correlated (Fig 4B). For example the correlation between Yangpu and Hongkou stations were as high as $r^2 = 98\%$. On each subject, two approaches were used to quantify his/her PM_{2.5} exposure: (1) Bio³ Air and (2) street address based estimation, where we used the PM_{2.5} concentration reported by the MEP (China Ministry of Ecology and Environment) station nearest to study subject's residence. We randomly selected two subjects (resided in Yangpu and Hongkou districts, respectively) and compared their PM_{2.5} exposure estimated using street address-based approach (Fig 4C). The hourly exposure of these two subjects were tightly correlated ($r^2 = 98\%$) simply due to the concentrations published by MEP stations were correlated. In other words, the street address-based method estimated these two subjects always had the same exposure level and subsequent association analysis (between PM_{2.5} exposure and health outcomes) becomes infeasible. By factoring in their real-time location (obtained from GPS on the subjects' smartphone) into PM_{2.5} exposure estimation, we captured more variability ($r^2 = 64\%$, Fig 4D), since the subjects traveled within Shanghai and to cities/counties of the Yangze River Delta region. It should be noted that lower r^2 indicated larger difference in the two subjects' exposure level, which meant more information had been captured. The PM_{2.5} exposure measured by Bio³ Air (Fig 4E) captured even more variability between the subjects ($r^2 = 36\%$) because it incorporated real-time location, outdoor/indoor status and motion into exposure calculations.

Discussions

Herein, we report an integrative system, Bio³ Air, for long term measurement of individual level PM exposure. It leverages recent technology advance in smartphone and compact size PM sensors. The primary novelties are the real-time quantification of outdoor/indoor status, geological location, lung ventilation rate and PM concentration of subject's surrounding environment, and incorporation of these metrics into calculating PM exposure. The system offers high reliability, resolution, reproducibility and accuracy. Importantly, it is easy-to-use, cost-effective, and automatically collects data to cloud server in an analysis-ready format. The system is fully developed and functions in China, USA and Canada, and has been successfully tested.

Most of long-term environmental health studies employed the address- or community-based approach to estimate subjects' exposure level. As we showed in Fig 4B, PM concentrations measured by stations within a city were highly correlated. As result, the participants had little variation in PM exposure (Fig 4C) making association test infeasible. A typically compromise to such problem is multi-city studies, where different cities had distinct PM pollution level. However, confounders (e.g. climate, dietary behavior, life style, genetic stratification, *etc*) perfectly correlate with cities' exposure level and cannot be adjusted for, making the findings of such studies bias-prone. The ultimate solution is to measure long-term PM exposure at individual level. To date, there are few suitable systems for long term PM exposure monitoring at individual level. The conventional "gold standard" method, membrane collection and off-line analysis, requires handling membranes/filters regularly, and study subject has to carry the equipment (Table 1). Although manageable in short-term study (e.g. a few days), such methods is prohibitively expensive and labor-intensive for long-term monitoring (e.g. one year). Further, participants' compliance could be very low for long-term deployment. In contrast, Bio³ Air simply requires the participant to maintain the APP running in the background of his/her smartphone (Table 1). It is easy-to-use with minimum maintenance and cost, therefore, able to achieve high compliance and suitable for long-term health study of air pollution.

We systematically benchmarked the time- and spatial- resolution, data reproducibility and accuracy of Bio³Air, and showed it has extremely high reproducibility ($r^2 > 99\%$) and accuracy comparing to "gold-standard" method ($r^2 = 91.89\%$, Fig 3B). Bio³ Air heavily depends on PM concentration data published by government agencies (China MEP, US EPA, *etc*). Therefore, the quality of the public data sources is critical. It is reasonable to expect that advancing technology and denser stations in the future will improve the accuracy/reliability of the government published air quality data, and consequently benefit Bio³Air. Further, Bio³Air is not limited in quantifying PM exposure (Table 1), but versatile in terms of pollutant types (e.g. VOCs, O₃, NO_x, *etc*). It is also expected that the real-time chemical compositions of PM and their concentrations will become available (e.g. by China MEP), which can be straightforwardly incorporated into Bio³ Air, and even retrospectively used to calculate the individual's exposure. Indoor sensors/monitors for pollutants beyond PM are commercially available (e.g. VOCs) but rather expensive for large scale epidemiological studies. As the next step direction, such sensors (e.g. VOCs) will be added into Bio³ Gear.

Importantly, we will conduct extensive testing and evaluation on Bio³Air for monitoring individual exposure to chemical components of the pollutant.

Bio³ Air has two strategies to obtain the PM concentration of individual's indoor environment: (1) direct measurement by Bio³ Gear, and (2) estimating indoor PM concentration based on outdoor concentration. It is difficult to estimate indoor PM_{2.5} concentration based on outdoor concentration even though many mathematical models were proposed (24, 25). It is mainly because that many factors affecting indoor PM concentration cannot be easily measured with high time-resolution in long term epidemiological studies, for example, indoor production of PM (e.g. cooking at home or chalk use at school) and the use of indoor purifier as well as the effectiveness of the purifier. To tackle this challenge, the Bio³ Air system incorporates the indoor PM_{2.5} monitor (Bio³ Gear, Fig 2) which measures the PM concentration in real time. The measured value is transmitted to smartphone APP for computing individual's exposure (Fig 1). The Bio³ Gear can be easily deployed at work place (e.g. office) and home, where an individual spend majority of his/her time, and provides accurate data to Bio³ Air. When the individual is located in an indoor environmental without Bio³ Gear deployed, we applied a simple formula to estimate the PM concentration. The accuracy of Bio³ Gear is critical to the entire system, which was evaluated by comparing to TSI SidePak (Fig 3B). The correlation between Bio³ Gear and the "gold-standard" method was 91.89%. In fact, the low-cost particle sensors were evaluated before all showed good linearity and accuracy (24), where the correction to "gold-standard" method were greater than 89.14% for all sensors we tested (15).

In summary, we developed a novel system, Bio³ Air, for long term measurement of individual level air pollutant exposure. It incorporates information relevant in measuring individual's exposure (e.g. real-time outdoor/indoor status, location and lung ventilation rate), where such information is typically missed by conventional approaches. Bio³ Air demonstrated high reliability, time- and spatial-resolution, reproducibility and accuracy. Bio³ Air has been applied in a one-year panel study in Shanghai, China and collected far richer data than conventional address-based approach. As an important methodology advance, Bio³ Air, could greatly facilitate environmental health study and reveal the impact of air pollutant exposure on health outcomes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet*. 2017;389(10082):1907–18. Epub 2017/04/15.

- doi: 10.1016/S0140-6736(17)30505-6 PubMed PMID: ; PubMed Central PMCID: PMC5439030. [PubMed: 28408086]
2. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet*. 2016;388(10053):1659–724. Epub 2016/10/14. doi: 10.1016/S0140-6736(16)31679-8 PubMed PMID: ; PubMed Central PMCID: PMC5388856. [PubMed: 27733284]
 3. Wang J, Zhao B, Wang S, Yang F, Xing J, Morawska L, et al. Particulate matter pollution over China and the effects of control policies. *The Science of the total environment*. 2017;584–585:426–47. Epub 2017/01/28. doi: 10.1016/j.scitotenv.2017.01.027 PubMed PMID: . [PubMed: 28126285]
 4. Xu J, Chang L, Qu Y, Yan F, Wang F, Fu Q. The meteorological modulation on PM_{2.5} interannual oscillation during 2013 to 2015 in Shanghai, China. *The Science of the total environment*. 2016;572:1138–49. Epub 2016/08/16. doi: 10.1016/j.scitotenv.2016.08.024 PubMed PMID: . [PubMed: 27519324]
 5. Beelen R, Raaschou-Nielsen O, Stafoggia M, Andersen ZJ, Weinmayr G, Hoffmann B, et al. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. *Lancet*. 2014;383(9919):785–95. Epub 2013/12/18. doi: 10.1016/S0140-6736(13)62158-3 PubMed PMID: . [PubMed: 24332274]
 6. Kaufman JD, Adar SD, Barr RG, Budoff M, Burke GL, Curl CL, et al. Association between air pollution and coronary artery calcification within six metropolitan areas in the USA (the Multi-Ethnic Study of Atherosclerosis and Air Pollution): a longitudinal cohort study. *Lancet*. 2016. Epub 2016/05/29. doi: 10.1016/S0140-6736(16)00378-0 PubMed PMID: . [PubMed: 27233746]
 7. Tetreault LF, Doucet M, Gamache P, Fournier M, Brand A, Kosatsky T, et al. Childhood Exposure to Ambient Air Pollutants and the Onset of Asthma: An Administrative Cohort Study in Quebec. *Environmental health perspectives*. 2016. Epub 2016/01/06. doi: 10.1289/ehp.1509838 PubMed PMID: . [PubMed: 26731790]
 8. Cacciottolo M, Wang X, Driscoll I, Woodward N, Saffari A, Reyes J, et al. Particulate air pollutants, APOE alleles and their contributions to cognitive impairment in older women and to amyloidogenesis in experimental models. *Translational psychiatry*. 2017;7(1):e1022. Epub 2017/02/01. doi: 10.1038/tp.2016.280 PubMed PMID: ; PubMed Central PMCID: PMC5299391. [PubMed: 28140404]
 9. Baron PA, and Willeke K. *Aerosol Measurement: Principles, Techniques, and Applications*. Wiley-Interscience, New York 2001.
 10. Lee A, Leon Hsu HH, Mathilda Chiu YH, Bose S, Rosa MJ, Kloog I, et al. Prenatal fine particulate exposure and early childhood asthma: Effect of maternal stress and fetal sex. *J Allergy Clin Immunol*. 2017. Epub 2017/08/13. doi: 10.1016/j.jaci.2017.07.017 PubMed PMID: . [PubMed: 28801196]
 11. Hsu YM, Wang X, Chow JC, Watson JG, Percy KE. Collocated comparisons of continuous and filter-based PM_{2.5} measurements at Fort McMurray, Alberta, Canada. *J Air Waste Manag Assoc*. 2016;66(3):329–39. Epub 2016/01/05. doi: 10.1080/10962247.2015.1136362 PubMed PMID: . [PubMed: 26727574]
 12. Sloan CD, Philipp TJ, Bradshaw RK, Chronister S, Barber WB, Johnston JD. Applications of GPS-tracked personal and fixed-location PM(2.5) continuous exposure monitoring. *J Air Waste Manag Assoc*. 2016;66(1):53–65. Epub 2015/10/30. doi: 10.1080/10962247.2015.1108942 PubMed PMID: . [PubMed: 26512925]
 13. <http://www.pewresearch.org/fact-tank/2017/01/12/evolution-of-technology>.
 14. <https://www.gps.gov/technical/ps/#spssps>.
 15. Wang Y, Li J, Jing H, Zhang Q, Jiang J, Biswas P. Laboratory Evaluation and Calibration of Three Low-Cost Particle Sensors for Particulate Matter Measurement. *Aerosol Science and Technology*. 2015;49(11):1063–77. doi: 10.1080/02786826.2015.1100710.
 16. <https://developer.apple.com/documentation/mapkit>.
 17. <http://api.map.baidu.com/lbsapi/>.
 18. <https://developer.apple.com/healthkit/>.
 19. <https://developers.google.com/fit/>.

20. <https://www.microsoft.com/en-us/research/project/urban-air/>.
21. http://pm25.in/api_doc.
22. http://www.airnow.gov/index.cfm?action=topics.about_airnow.
23. <http://www3.epa.gov/airdata/>.
24. Deng G, Li Z, Wang Z, Gao J, Xu Z, Li J, et al. Indoor/outdoor relationship of PM2.5 concentration in typical buildings with and without air cleaning in Beijing. *Indoor and Built Environment*. 2017;26(1):60–8. doi: 10.1177/1420326×15604349.
25. Deshpande B, Frey HC, Cao Y, and Liu Z, “Modeling of the Penetration of Ambient PM2.5 to Indoor Residential, Microenvironment P-A--A, Proceedings, 102nd Annual Conference and Exhibition, Air & Waste, Management Association D, Michigan, June 16-19, 2009.
26. Zuurbier M, Hoek G, van den Hazel P, Brunekreef B. Minute ventilation of cyclists, car and bus passengers: an experimental study. *Environmental health : a global access science source*. 2009;8:48. Epub 2009/10/29. doi: 10.1186/1476-069X-8-48 PubMed PMID: ; PubMed Central PMCID: PMC2772854.

Highlights:

- We developed a novel system, Bio³Air, for long-term measure of particulate matter (PM) exposure at individual level.
- The system demonstrated high time- and spatial-resolution, data reproducibility and accuracy in quantifying PM exposure.
- Bio³Air is potentially useful tool facilitating studies on air pollutant exposure and health consequences.

Fig 1.
Components of Bio³ Air system.

Fig 2.
Flow chart of data collection and computation.

Fig 3.
Assessment of accuracy of Bio³ Air by comparing to membrane collection off-line analysis method (“gold-standard”).

Information Used in Computing PM2.5 Intake: Residence Address

Information Used in Computing PM_{2.5} Intake: Real-time GPS Location, Indoor/Outdoor Status, and Movement

Fig 4.

Two approaches were used to quantify PM_{2.5} exposure: (1) Bio³ Air, and (2) street address based estimation. We identify the nearest MEP (China Ministry of Ecology and Environment) monitor station of each study subject's residence address, and in total, five stations involved (A), with station name and (latitude, longitude) as: Station A, Putuo (31.26374N, 121.39844E); Station B, Hongkou (31.28250N, 121.49192E); Station C, Xuhui (31.16915N, 121.44624E); Station D, Yangpu (31.30451N, 121.53572E); Station E, Jing'an (31.23538N, 121.45476E). During the study period (Oct 2016 - Oct 2017), we randomly

selected hourly PM_{2.5} concentration of 500 hours, and demonstrated the high correlation of the five stations (**B**). In a case study, the street address based PM_{2.5} exposure of two subjects were highly correlated (**C**). The two subjects showed substantial differences when the estimation factored in their real-time location (**D**) or real-time location, outdoor/indoor status and motion (**E**).

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Table 1.

Comparison of Methods for Individual-Level Pollutant Exposure Measurement

Characteristics	Membrane Collection and Off-Line Analysis *	Bio ³ Air
Participant's Active Involvement	Required (membrane handling, charging, etc)	Minimum (running APP on smartphone)
Lung Ventilation Rate (L/min)	Not considered	Measured and incorporated into computing exposure level
Pollutant Type	Particulate matters (PM)	Any types of pollutant
Automated Data Collections	No	Yes
Participant's Compliance	Low	High
Suitable Study Duration	A few days	A few days ~ 1 year
Study Size	< 100 subjects	Up to thousands of subjects

* Membrane collection and off-line analysis is the conventional approach and often considered as "gold standard" in measuring individual-level PM exposure.