My Air, My Health: An HHS/EPA Challenge

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1. Descriptions of the air pollutant(s) (particulates or individual chemical species) and associated physiological markers that will be used to measure their effect(s) on humans.

Our understanding of the effects of air pollutants on human health has improved dramatically over the last few decades. Epidemiological studies from a number of geographical areas and for populations of widely varying socio-economic status have shown strong and consistent associations between air pollutants and cardiovascular disease (coronary heart disease, congestive heart failure, ischemic heart disease, stroke, arrhythmia, etc.)[1]. The impacts of air pollution relate to both morbidity (disease symptoms and hospitalizations) and premature mortality[2]. Sensitive populations such as the elderly and the chronically ill are considered to be at particular risk when exposed to air pollutants.

In this study we propose to examine the impacts of two pollutants on physiological measures of interest to public health and cardiovascular disease in particular by conducting continuous monitoring of air pollution exposures and physiological symptoms using portable and wearable monitors. The monitoring equipment proposed in this study would be smaller and easier to carry than what is typically used in "backpack" studies[3]. The pollutants are carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) and the physiological mechanisms are heart rate variability and blood oxygen levels. Both of these pollutants are common in urban areas and both are regulated as criteria air pollutants under the Clean Air Act. In New York City, where this study will be conducted, typical ranges for these pollutants are 0-5 ppm for CO and 0-75 ug/m3 for $PM_{2.5}$[4].

In the case of $PM_{2.5}$ time-series studies have estimated that a 10-$\mu g/m^3$ increase in mean 24-hour concentration is associated with an increase in the relative risk (RR) for daily cardiovascular mortality of approximately 0.4-1.0%[5]. Short-term effects of increased concentrations of CO or cardiovascular mortality have also been reported in the literature[6]. Despite the large body of research regarding the link between these pollutants and cardiovascular disease a number of important questions remain regarding plausible biological mechanisms and causal pathways, as well as the physiological mechanisms that link these pollutants to cardiovascular morbidity and mortality.

These two pollutants are different in important ways and including both of them in the study will shed light on the association between air pollution and human health. $PM_{2.5}$ consists of a broad range of liquid and solid particles suspended in the air that are 2.5 microns in diameter or less. Sources of $PM_{2.5}$ are also varied and include both local and regional sources, stationary and mobile sources, and natural sources. In urban areas, CO is primarily emitted from local sources associated with vehicular traffic and can vary significantly across relatively short distances.[7] As such, it is a very good marker for pollution related to traffic.

2. A justification of the linkage of the pollutant(s) and physiological effects, including reference to literature or existing study data.

Both $PM_{2.5}$ and CO have been strongly and consistently associated with various cardiac health end points[8]. However, in the case of CO, it less clear whether it is a primary causal agent or a surrogate marker for another pollutant that may cause the physiological and health responses.[9]

One plausible way in which these pollutants may cause or exacerbate cardiovascular disease is by disturbing the control of heart rate and rhythm. As such one of our main physiological measures of interest is heart rate variability[10]. Several studies conducted under controlled experimental conditions have found that an association between PM concentrations and decreased heart variability occurs in patients with heart disease such as myocardial infarction[11]. Another physiological response of interest is how a pollutant such as CO may interfere with the blood's ability to carry oxygen at the levels of exposure typically found in an urban area.[12]

3. A justification of the proposed sampling modality, sampling window, and sampling frequency as relevant to the linked pollutant(s) and physiological measure(s). This may need to include e.g. temporal offsets between pollutant measurement and physiological effects.

The proposed measurements of heart rate variability include beat to beat changes in heart periodicity and degree of high frequency variability taken over 24 hour periods. The statistical measures for heart rate variability that will be used to assess whether it is associated with CO and $PM_{2.5}$ pollution exposures will include a comparison of measured ambient concentrations of these pollutants and direct measurements of the normal-to-normal (NN) intervals or instantaneous heart rate and differences between NN intervals. Commonly used measures of heart rate variability that would be used in this study include the square root of the mean squared differences of successive NN intervals (RMSSD), the number of interval differences of successive NN intervals greater than 50 ms (NN50), and the proportion derived by dividing NN50 by the total number of NN intervals (pNN50).[13] A number of lagged models will be explored to determine whether the association between pollution exposure and physiological symptoms is time dependent. Methods for analyzing the data have been reported in various studies[14, 15, 16].

To assess how CO affects blood oxygen levels a portable sensor will record SaO_2 levels, which represent the percentage of available hemoglobin that is saturated with oxygen.

The measurement of these variables will take place over periods of several hours. Since the monitoring equipment is portable, the subjects participating in the study would carry them about during their daily activities. Since physical activity can impact these physiological measures, subjects will report the type of physical activity they are engaged in and their level of physical exertion by typing or speaking notes into the AirCasting app (for additional details on the AirCasting app and platform refer to section 4). Participant notes describing physical activity will then be further qualified using information from the smartphone's onboard accelerometer and GPS.

4. Describe technologies/devices that could be integrated to form a personal or portable system for recording and communicating air pollutant and physiological data. Descriptions must include:
   A. Sensor technology to be used (physical characteristics of hardware, sensitivity/accuracy information)
   B. A high-level design of the prototype integrated instrument, including:
      a. Projected weight and dimensions
      b. Air sampling volumes and sampling frequencies
      c. Power sources and requirements

AirCasting is a platform for recording, mapping, and sharing health and environmental data using an Android device. Its component parts include:
1) handheld or wearable sensor packages that monitor health and environmental parameters;
2) an Android app which connects with and displays real-time measurements from sensor packages and transmits these measurements to a web server; and
3) a website (aircasting.org) which maps, graphs, filters, and processes the sensor measurements collected by the app.

The physiological sensor package we will deploy for the "My Air, My Health Challenge" proof-of-concept study will track HRV and SaO_2 using a custom made pulse oximeter fabricated at the CREATE Lab. The device will be designed with a form factor that makes it comfortable to wear and does not interfere with physical activity. We will consider two potential embodiments. The first device would be worn on the ear similar to clip-on headphones. Prior work[17] suggests that this design is feasible, though data quality studies will be performed to ensure validity. Second, for users with good circulation, we plan to incorporate a pulse oximeter into a "smart sock" which will contain the sensing and wireless functionality of the finger clip devices, except the measurement will be taken using a single toe.

The air quality sensor package we will deploy for the "My Air, My Health Challenge" proof-of-concept study will count $PM_{2.5}$ particles using the Shinyei PPD42NS laser particle counter and measure CO gas concentrations using the Figaro TGS2442 metal-oxide sensor. We will also include temperature and humidity sensors in the air quality sensor package and incorporate the data from these sensors into 1) our parameterized sensor model for computing particle concentrations, which is important because condensation around very small particles impacts optical sensor readings, and 2) our calibration curves for computing CO concentrations, which is important because the rate at which the metal-oxide semiconductor adsorbs/desorbs CO varies with temperature and humidity.

While the product specification sheet[18] for the Shinyei PPD42NS has a lower limit of detection in the 1 micron range, we will estimate sub-micron concentrations by using contextual data like temperature, humidity, and GPS location and strength to determine the participant's environment. The participants will also report their location (e.g. indoors, outdoors, in the city, in the park) by typing or speaking notes into the AirCasting app. With this information, we will scale the most likely particle distribution for that environment by our measurement of one-micron particle concentrations to estimate the concentration at smaller sizes.

To improve the accuracy of the Shinyei PPD42NS particle counts we will experiment with averaging the data from these sensors over varying time periods to achieve data quality comparable to commercial particle counters such as the Dylos[19]. We have also been experimenting with other methods of processing the Shinyei sensor data to improve accuracy and response times. By co-locating the Shinyei sensor with a Dylos, we will build optimal parameterized models that use the difference between processed Shinyei sensor data and Dylos data as a cost function. Additionally, we have found that a small fan can greatly improve the Shinyei's ability to detect particles in comparison with its intrinsic convective method.

The product specification sheet[20] for the Figaro TGS2442 metal-oxide sensor reports a lower limit of detection of 30 ppm, however, by reproducing the calibration methodology used by researchers at Northwestern University[21] we believe we can achieve a lower limit of detection approaching 5ppm. Metal-oxide sensors are to known to be variable "out of the box" and this variability is further compounded by factors such as age and exposure. Additionally, they are affected by temperature and humidity and are cross-sensitive to non-target gases. To account for and compensate for this variability, we will calibrate each sensor using at minimum a three-point test method against an accurate sensor. We will also track and model the change in calibration with age and use.

These air quality sensors will be enclosed in a package the size of two decks of cards stacked. An onboard Lithium-Ion battery will provide approximately 10 hours of operation. Bluetooth will enable communication with a smartphone, which will serve as the primary interface between the user and the device.

We have already built a number air quality monitors with similar capabilities. The specifications of the current iterations are summarized below, and are representative of the devices we will develop for this proposal.

Sensors: Particulates, Carbon Monoxide, Temperature, Humidity
Dimensions: 3.5"W x 2"D x 2.5"H
Weight: 8oz
Sampling: Both the CO and particulate sensors sample continuously. Particulates can be sampled as frequently as every second and the air sampling volume is approximately 2 liters per minute with the fan activated. The CO sensor has a sampling time of one second.

C. Description of data management plans and algorithms required to process the data in order to support a plausible and physiologically meaningful relationship between measured pollutants and physiological changes.

Typically, noisy data from low-cost sensors is averaged over a significant period of time to produce stable readings. Unfortunately, though this approach is the simplest to implement, the resulting measurements suffer from two major disadvantages. First, the data is typically either unitless or inaccurate. Second, and more importantly, averaging over time results in significant time delays as a trade-off for the smoothness of the data. We are developing an automated generic calibration procedure for low-cost sensors that will improve the accuracy of measurements while minimizing temporal delays. First, the inexpensive sensor will be co-located with a more reliable and trusted sensor with the capability to output continuous data. We will collect sufficient data, typically over the course of several days in environments where the measured quantity is experienced in both high and low concentrations. Next, we will create a simple two-parameter sensor model based on a center-weighted average of a specified width and scale. We will then vary the width and scale in order to minimize the least-squared error between the sensor model and the trusted data. The resulting parameters will yield a near-optimal sensor model with zero delay, but unfortunately we cannot implement this model in real-time as the center-weighted average utilizes knowledge of future data. Instead, we will use our center-weighted sensor model as our optimal target to which we fit a new three-parameter Markov-based sensor model that uses the previous measurement as a state variable and the immediate raw sensor data as input. We expect that the global minima of the least-squared error between the Markov-based model and the center-weighted average model will result in a very good fit of the data that responds quickly, matches appropriate physical units, and can be implemented in real-time without knowledge of the future.

D. Descriptions of data transmission capabilities, including:
   a. Transmission methods and modalities
   b. Required data networks
   c. Frequency of transmission (data packages per unit time)
   d. Data package size and format
   e. Any possible encryption functionality
   f. Data caching or storage functionality should data networks be unavailable (either local to device or within a separate transmission device e.g. smart phone)

Sensor packages connect to the AirCasting app via Bluetooth. Once a sensor package has been connected and an AirCasting session is initiated by the user, the app begins receiving, mapping, graphing, and enumerating the sensor measurements. Sensor measurements are received, geolocated, and timestamped by the app once a second.

At the conclusion of an AirCasting session, the measurements logged by the AirCasting app are packaged as a JSON file and uploaded to a MySQL database server using either the cellular network or a Wi-Fi connection. Data packages vary in size based on the number of sensor measurements contained in a recording session and their transmission rate depends on the bandwidth of the cellular or Wi-Fi connection to which the Android device is connected. Before transmitting the sensor data to the database server, the user must select whether to make their sensor measurements publicly available via the AirCasting website or keep them private.

Logging sensor measurements with the AirCasting app does not require access to a data network as the data is stored locally on the Android device. A data network is only required for transmitting the data from the device. Also note that sensor data is backed-up locally on the Android device every minute to minimize data loss in the event of the app crashing or the Android device malfunctioning or losing power.

E. Project plan for development of the required system and a proof-of-concept study (including study methods, location, and population)

HabitatMap has already developed and deployed many of the fundamental components of the AirCasting platform including the AirCasting Android app and corresponding website (aircasting.org), prototype mobile air quality monitors, and educational materials about air pollution. Currently, using the AirCasting Android app, AirCasters can record, map, and share: 1) sound levels recorded by their phone microphone 2) temperature, humidity, particulates, carbon monoxide (CO), and nitrogen dioxide (NO2) gas concentrations recorded by the Arduino-powered AirCasting air quality monitors, and 3) heart rate measurements recorded by the Zephyr HxM.

The custom hardware components of the AirCasting platform described in section 4.B. are all in various stages of prototyping. We have already developed air quality monitors that measure temperature using the Analog Devices TMP36, humidity using the Honeywell HIH-4030, CO using the Figaro TGS2442, and particulates using the Shinyei PPD42NS.

The future software improvements to the AirCasting platform described in section 4.c. will be implemented using the same agile development methods that have successfully delivered a fully functioning and feature rich AirCasting website and app. These methods include: 1) utilizing cloud based project management software (kanbanery.com) to describe, refine, and prioritize software related tasks 2) brief daily meetings wherein software features, back-end architecture, front-end design, and bugs are discussed, and 3) thorough testing of software changes using a demonstration server and pre-release app version prior to deploying improvements to the production server and releasing updated app versions to the Google Play Store. Every component of the AirCasting software platform described in section 4.D. has already been implemented with the sole exception of sensor data being backed-up locally to the Android device every minute. AirCasting is open source. All the code for both the website and Android app is available through GitHub and instruction manuals detailing how to build the AirCasting mobile air quality monitors are available through our website.

The Carnegie Mellon CREATE Lab engineers, scientists, and students have been working for the past year on developing a low-cost particulate sensor for citizen science and personal exposure tracking. They are currently pursuing parallel tracks to develop sensing units that contain either custom optics or the inexpensive Shinyei PPD42NS. Additionally, they are currently developing optimization routines and machine learning algorithms to discover faster, more accurate models for inexpensive sensors like the Shinyei PPD42NS. These new models will allow us to extract much more meaningful data than is possible using simple averaging or lookup tables.

The CREATE Lab has also lead research efforts in participatory sensing, most notably the Neighborhood Networks project, as described in “The Neighborhood Networks Project: A Case Study of Critical Engagement and Creative Expression Through Participatory Design” (DiSalvo et al, 2008).

The CREATE lab is currently drawing on both of these areas to develop new platforms for a participatory sensing project which incorporates particulate measurements along with humidity, temperature, and light sensors. We will be able to extend this platform for the "My Air My Health Challenge" to include the pulse oximeter sensor with minimal difficulty.

The proof-of-concept study will be conducted as part of a broader effort of community education and environmental awareness in neighborhoods around Newtown Creek in New York City such as Greenpoint and East Williamsburg in Brooklyn, and Maspeth in Queens. The subjects will be recruited from members of these communities that have historically included a number of facilities associated with water and air pollution and where environmental remediation efforts are currently underway. The presence of major roads, highways, waste transfer stations, a wastewater treatment plant, and industrial facilities in these communities means that they are suitable places to explore linkages between environmental risk factors such as air pollution and potential health impacts, as will be measured by changes in relevant physiological parameters.

Between 5 and 10 adults will participate in order for the team members to test the equipment, calibrate it, and analyze a range of representative data. The participants will be asked to use the monitoring equipment for periods of 4-8 hours and to go about their daily activities. The data will be collected daily and participants will be asked to keep a journal recording their level of activity and any unusual circumstances they think could affect the data being collected for the project. The participants will use the monitors for periods of five days.

Once the equipment is calibrated and the data is collected the team members will analyze the data and apply appropriate time-series statistical models to model the association between the air pollution concentrations measures, heart rate variability and blood oxygen levels, while controlling for physical activity, temperature, humidity, and other potential confounding factors.

While these data will not likely be sufficient to determine the statistical significance of these $PM_{2.5}$ –health associations, our study data will provide preliminary results from which the power of a larger and more definitive health effects study can be designed.

A community meeting will be held before and after the data collection begins in order to explain what the goals of the project are and provide an opportunity to disseminate information about air pollution and its health impacts. The meeting will also provide an opportunity for participating community members to discuss their experiences with the monitoring equipment and the potential for wider use. Once the data is analyzed, another community meeting will be held to discuss the results of the project.

5. Description of data package contents. This should include a data dictionary that describes each data variable included in the package. The data dictionary must include a short textual description of each variable, number of significant figures, units, range (lowest and highest expected values that are considered reliable) and missing value code(s).

The sensor data logged by the AirCasting app is packaged as a JSON file before being transmitted to the AirCasting web server. The JSON file includes the following data variables recorded at approximately one second intervals:

• *Measurement value:* the value the sensor is reporting, e.g. "55"
• *Sensor package name:* the name of the sensor package, e.g. "AirMonitor5"

• *Sensor name:* the name/model number of the sensor, e.g. “HIH4030”
• *Type of measurement:* the parameter being measured, e.g. “relative humidity”
• *Short type of measurement:* an abbreviation of the parameter being measured, e.g. RH
• *Unit name:* the unit name for that parameter’s values, e.g. “percent”
• *Unit symbol/abbreviation:* an abbreviation of the unit name for that parameter’s values, e.g. %
• *T1, T2, T3, T4, T5:* threshold values for fitting “measurement values” to the green, yellow, orange, and red color scale which is used to communicate the intensity of “measurement values” to the user.
• *sigma:* a standard deviation that represents the certainty of the measurement. Using the sensor value as the mean, we can formulate normal distributions over which we can calculate confidence intervals for each reading. We will formulate sigma as a weighted sum of the immediate variance of the sensor, the expected variance of the sensor type (e.g. all metal oxide sensors at that concentration), and an expression representing sensor drift as a function of the time since the last calibration. Analysis of collected data will allow us to tune the weights to match real world expectations.
• *latitude*
• *longitude*
• *date*
• *time*

6. A description of the Solver/Team’s expertise & experience relevant to the Challenge, including a description of facilities to which they have access relevant to producing a prototype system.

Dr. George Thurston is a tenured professor at the NYU School of Medicine who has conducted extensive past epidemiological research into the exposure to and human health effects of air pollution, which has prepared him well for his participation in this proposed project. He has published widely in the scientific literature on the assessment of exposures to ambient air pollution and their human health consequences. He is an expert of particulate matter source apportionment techniques, having decades ago developed a factor analysis based method increasingly used in the field today. He also published the first manuscript relating $PM_{2.5}$ mass and sources to mortality in 1987. Today, he is one of the leading researchers on the epidemiological assessment of the health effects of air pollution, having worked and published upon the analyses of multiple cohorts, including the Six-City and ACS Studies. In February 2011, Dr. Thurston helped organize the recent EPA Multi-pollutant Science and Risk Analysis Workshop, and chaired the first day sessions covering: 1) Human Exposure Assessment, 2) Health Effects and Risk Assessment, and 3) Risk Characterization. His vast experience has included the conduct of cohort studies in children with asthma using personal air pollution sampling. As a result, in his laboratory at the NYU School of Medicine's Nelson Institute of Environmental Medicine, he has available a wide range of particle and gaseous air pollution measurement and calibration equipment available for application to the proposed work including an 85 ft^2 climate controlled Filter Weigh Room that meets the U.S. EPA guidelines for filter conditioning, storage, and gravimetric measurement of $PM_{2.5}$ and PM_{10} filters.

Dr. Carlos Restrepo is a research scientist and adjunct professor at New York University. His areas of expertise include environmental health, environmental policy, environmental impact assessment, infrastructure incident analysis and research methods. Carlos holds a PhD in Public Administration from NYU's Wagner Graduate School of Public Service.

Michael Taylor - PhD Student, Robotics Institute, Carnegie Mellon University - specializes in robotic systems engineering, compact sensing platforms, and machine learning. The Community Robotics Engineering And Technology Empowerment (CREATE) Lab, part of the Robotics Institute at Carnegie Mellon University, specializes in empowering communities and individuals to understand and change their environment through new and existing technologies. The capabilities and collective experience of the CREATE Lab include rapid prototyping, mass manufacture, hardware/software integration, robotics (machine learning, computer vision, human-computer interaction), and data visualization.

Michael Heimbinder - Founder & Executive Director of HabitatMap - is a community organizer, educator, and information designer. HabitatMap is a non-profit environmental health justice organization whose goal is to raise awareness about the impact the environment has on human health. HabitatMap combines social networking and online map making to foster connections between community organizations and their constituents. Since launching HabitatMap in 2006 Michael has worked with dozens of community based organizations and schools to create planning and advocacy maps that publicize the issues they care about most. Bolstering our suite of environmental organizing tools, HabitatMap recently released AirCasting. AirCasting is a platform for recording, mapping, and sharing health and environmental data using smartphones. Each AirCasting session lets the AirCaster capture real-world measurements - e.g. pollutant gas concentrations, sound levels, heart rate - annotate the data to tell their story, and share it with their community via the CrowdMap. Having served as the primary information designer and project manager for the HabitatMap website, AirCasting website, and AirCasting Android app Michael knows how to translate great ideas into successful software. In addition to running HabitatMap, Michael is Chair of the Newtown Creek Alliance, where he has made community knowledge sharing the keystone of the organization's successful efforts to clean up the Creek and improve quality of life in the surrounding neighborhoods. He is also Technical Advisor to the Organization of Waterfront Neighborhoods where he consults on solid waste management issues in New York City.

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