Assessing Particulate Matter Air Pollution Exposures with Low-Cost Sensing Technologies

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Outline

• What’s possible now with low-cost sensing technologies for assessing PM exposures?
• What’s likely to be possible in the near term (3-5 years)?
• What are the benefits and pitfalls of using low cost sensors for PM exposure assessment?
• What lessons can we learn from series of examples that illustrate the use of sensors?
Traditional High Cost PM Sensors: Micro-aethalometer and Aerocet Particle Counter
Traditional Personal Air Pollution Monitoring Backpack used in Epidemiological Studies

- Bulky and heavy
- Limited logging to 48 hours
- Calibration usually needed by trained staff
- Restricts normal movement
- Expensive

Source
Choi et al. (2008)
Or in Scripted Exposure-Health Studies
Air Pollutant Concentrations on Bike Routes in 3-D

Source: Jarjour et al. 2013
Sensing in a Ubicomp World

• The complete embedding of computational technology into our everyday lives (Weiser 1991)

• Pervasive sensing of personal activity, physiological parameters and ambient conditions increasingly possible

• Being driven by health care sector (e.g., field of telemedicine) and other commercial applications related to mobile phones (now 7 billion cell phones globally, 2 billion are smart phones)
Components of Cellular Smart Phone

- Sensing Module
  - Camera
  - Temp/Humidity Sensors
  - Barometer
  - Heart Rate
  - Microphone
  - Inertial Sensor Unit
  - GPS
  - SpO2
  - Compass
  - Ambient Light
  - Proximity

- Central Processing Unit
- Display Unit
- Power Management Unit
- Communication Modules
- Storage
<table>
<thead>
<tr>
<th>Type of Sensor</th>
<th>Type of Sensing</th>
<th>Opportunistic Personal Sensing</th>
<th>Participatory Personal Sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>On Cell Phone</td>
<td></td>
<td>Location with GPS, Physical Activity, Trip Mode (e.g., walk, bike, drive, public transit), proximity to others</td>
<td>Ecological Momentary Assessment of Mood and Affect, Gait and position, Noise, UV Exposure, Blood Oxygen, Heart Rate, Dietary Assessment</td>
</tr>
<tr>
<td>Connected to Cell Phone, but Requiring External Device</td>
<td>None</td>
<td>None</td>
<td>Air Pollution, Water Pollution, Noise, Ultraviolet Exposure, Blood Pressure, Sleep</td>
</tr>
<tr>
<td>Stand Alone Sensors</td>
<td></td>
<td>None</td>
<td>Air Pollution, Physical Activity, Location, Noise, Water Pollution, Chemical Exposures, Numerous Biological Functions</td>
</tr>
</tbody>
</table>
Review of 25 Smart Phone Models

Key Points:

Large variation in types and quality of sensors on smart phones

COMPLICATES the collection of comparable data from large populations

Source: Nameti, Batteate, Jerrett (2017 in review)
Smart phone study: Activity patterns & air pollution

**Aim:** Test novel opportunistic and participatory sensing technology to assess activity patterns and air pollution exposure

**Methods:**
36 volunteers equipped with 3 activity measurement devices including novel smart phone technology CalFit and reporting daily travel activity during 5 days
A. Methods

Hour and day specific ratio using background station

Mode correction factor: Bicycle, car, walking, bus, train...

Indoor/Outdoor Ratio

Personal exposure to air pollution

Energy expenditure from accelerometer data

Slides Courtesy of A. de Nazelle

Air pollution inhalation
GPS tracking and physical activity for 1 workday for each volunteer + air pollution map (NO2)
Travel microenvironments, air pollution, and health

Travel microenvironments
(Barcelona sample, de Nazelle et al. 2013):

- 6% Time
- 11% NO₂ Exposure
- 24% NO₂ Inhalation
GPS Traces from 174 Subjects: Big Data Fast!

Some 10,886,400 observations per week for just 2 sensors on CalFit Phone
If cohort is 1,000,000 people 60,480,000,000!
Lessons

• Location and physical activity can be accurately measured on cell phones

• This information can significantly improve estimates when fused with models of PM$_{2.5}$ exposure

• Data are very big and messy
External Sensors, Technology Moving Fast

The Changing Paradigm of Air Pollution Monitoring

Emily G. Snyder,*† Timothy H. Watkins,† Paul A. Solomon,‡ Eben D. Thoma,‡ Ronald W. Williams,† Gayle S. W. Hagler,† David Shelow,§ David A. Hindin,‖ Vasu J. Kilaru,† and Peter W. Preuss‡
Rapidly Evolving Micro-Sensor Technologies

Snyder (2014)
PM$_{2.5}$ Sensors

Fall into two broad categories:

1. Filter-based instruments that draw particles through size-specific inlets and deposit particles on filter papers for post hoc analyses (mass, chemical-physical properties or both)

2. Light scattering particle counters that use lasers or other light sources to examine light attenuation of light as particles pass by light source
CSU Ultrasonic Personal Aerosol Sampler (UPAS)

- Time-integrated wearable PM Sampler
- \( \text{PM}_{2.5} \) cyclone inlet (1 or 2 L/min flow)
- ‘Microblower’ pump operates at ultrasonic frequencies
- Small, lightweight, quiet, and *low cost (kind of)*
- Collects onto a 37mm filter
- On-board sensors: T, P, RH, GPS, Mass Flow

UPAS Lab and Field Evaluation

Field Data (●) from M. Brauer & A. Birch, UBC

Lab Data (◻) from Volckens et al. Indoor Air 2013

vs. Harvard Impactor (field)
Y = 0.988(X) + 15.3
r² = 0.84

vs. EPA FRM (lab)
Y = 0.986(X) + 3.7
r² = 0.996
Background on the Aliso Canyon Natural Gas Storage Facility Blowout and Impacts on Porter Ranch

Source: CNN

- October 23, 2015, SoCalGas Company announced a leak at its Aliso Canyon natural gas storage facility, north of Porter Ranch, Los Angeles County.
- Resulted in 7000 evacuations and 2000 students displaced.
- Many 1000s reported illness.
The Invisible Catastrophe

Over the course of four months, 97,100 metric tons of methane quietly leaked out of a single well into California's sky. Scientists and residents are still trying to figure out just how much damage was done.

By NATHANIEL RICH
MARCH 31, 2016
Cambridge University Sensing Networks for Air Quality (SNAQ) Monitors

$O_3$, $NO_2$, NO, CO, Total VOCs, H, T Size-speciated particulate matter
Cambridge Monitor in Yard at Porter Ranch
Size-speciated Particles (16 bins from 0.38-15.6 microns in diameter)
Personal, Embedded Monitors for Health Studies (including indoors)  
(UK Medical Research Council funded COPD cohort study)

- $O_3$, $NO_2$, NO, CO
- Size speciated particulate matter
- GPS
- Accelerometer
- Noise
- GPRS
UCLA HEALS
Monitor
Size-speciated Particle Counts Displayed on Phone
Wired vs. Wireless Particle Counts

Indoor Validation Tests

- Wired Alphsense
- Wireless Alphasense

Dust Concentration (mg/m$^3$)

Epoch Time
Data Transferred to Server from Monitor via Phone

Test Plot AlphaSense: User list of users Timestamp list of times
Future Directions:
Small is Beautiful
Lessons

• Decent correlation with reference instruments, but there is bias, unreliability and extensive post processing needed
• Conversion to mass concentrations tricky – dependent on assumptions about particle size and atmospheric conditions
• Human resource cost of post-processing counterbalances low cost of equipment
• Currently infeasible for large studies, but potentially useful for smaller studies with lots of $$
Citizen Science and Ubiquitous (Embedded) Sensors

- Citizens often very interested and attuned to environment exposures, which gives them motivation to help.

- They represent a huge resource for data collection in partnership with government and academics.
Community-based mapping and monitoring of air pollution

Sensors for **non-regulatory** monitoring

“Community Air Monitors”

- Customized low-cost optical particle counter
- Small computer & other env sensors (e.g., temp and RH)
- Wireless Networking
- Robust Enclosure
- Internet Database on the Cloud with data available on the web

System designed by Graeme Carvlin, PhD student UW
Deployed and maintained by Comite Civico del Valle

Slide Courtesy of P. English
Citizen Scientists with Dylos Particle Monitor and Enclosure
Evaluating data quality

• Lab and field validation of monitors

• Colocation with government monitors (CARB and IID)

• Colocation with EBAMs (CARB)

• Technical workgroup of air quality stakeholders
  – Includes local air district, California Air Resources Board, US EPA
Comparison with FEM/FRM

- Relatively linear
- Overprediction at high concentrations
Validation

- Six sites with EBAM monitors

Operated by the California Air Resources Board (CARB)

Table 5. Summary Statistics for EBAM Collocation

<table>
<thead>
<tr>
<th>Site</th>
<th>Dylos ($\mu$g/m$^3$)</th>
<th>EBAM ($\mu$g/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeley</td>
<td>9.21 (-4.23 to 168.78, 8.19)</td>
<td>9.01 (-3 to 261, 11.61)</td>
</tr>
<tr>
<td>Kennedy</td>
<td>4.28 (-2.87 to 44.37, 4.34)</td>
<td>9.23 (-3 to 303, 11.73)</td>
</tr>
<tr>
<td>Westmorland</td>
<td>7.59 (-0.49 to 92.85, 6.27)</td>
<td>11.9 (-3 to 278, 16.92)</td>
</tr>
<tr>
<td>Meadows</td>
<td>6.45 (-3.13 to 266.87, 11.87)</td>
<td>11 (-3 to 514, 16.96)</td>
</tr>
<tr>
<td>Calipatria</td>
<td>6.46 (-5.69 to 154.6, 10.55)</td>
<td>12.45 (-3 to 239, 15.77)</td>
</tr>
<tr>
<td>Calexico Alvarez</td>
<td>11.81 (-1.94 to 82.21, 9.56)</td>
<td>14.34 (-3 to 84, 10.4)</td>
</tr>
</tbody>
</table>

Note: mean (min to max, standard deviation). Measurements are PM$_{2.5}$ in $\mu$g/m$^3$ for both the Dylos and EBAMs. Negative values are used as is.
Current Sensor Distribution
Largest Community Air Network in U.S.
Land Use Regression Model with Smoothed Prediction Surface

Slide Courtesy of G. Carvlin and E. Seto
Lessons

- Higher spatial and temporal coverage could lead to much better predictions of exposure for epidemiological studies
- Accuracy of monitors dependent on location
- Working with communities time-consuming, but rewarding
- Sustainability of network an issue
Conclusion

• Location and physical activity essential for linkage to modeled and measured environmental exposures – high quality info possible from smart phones

• Variable type and quality of sensors on phones presents challenges

• But can be used for PM$_{2.5}$ exposure assessment improvements
Conclusions (Cont’d)

• Direct personal sensors not there yet, but likely in near term, both wearable and awearable
• Embedded sensors now possible for air pollution
• Citizen science and volunteered geographic information show tremendous promise
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THANK YOU!