Exposure to Air Pollution and its Impact on Childhood Mental Health
Outline

• Air Pollution and the Brain

• Cincinnati Childhood Allergy and Air Pollution Study (CCAAPS)
  – Study design
  – Air pollution modeling
  – Childhood exposure to air pollution and mental health at age 12

• Acute Exposure to Air Pollution and Childhood Mental Health

• Personal Exposure to Ultrafine Particles
  – Ecological Momentary Assessment and Personal Particle Exposure (EcoMAPPE) Study
  – Reporting Back Individual Results of Personal Air Monitors
Burden of Air Pollution

- Near ubiquitous environmental exposure

- Ambient PM$_{2.5}$ was the 5th-ranking mortality risk factor in 2015
  - 4.2 million deaths
  - ↓ 103.1 million disability-adjusted life-years

- Estimates of burden based on
  - Ischemic heart disease
  - Cerebrovascular disease
  - Lung cancer
  - Chronic obstructive pulmonary disease
  - Lower respiratory infections

Air Pollution and the Central Nervous System

- Air pollutants of concern
  - PM$_{2.5}$
  - Traffic-related air pollution
    - Elemental carbon
    - Ultrafine particles (UFP, PM$_{0.1}$)

- Mechanisms
  - Direct: Particles and absorbed compounds direct exposure to the brain
  - Indirect mechanisms: Inflammatory response in peripheral organ systems

- Exposure to neurotoxicants during brain development may manifest as functional impairments later in life

Neurodevelopmental Outcomes Associated with Air Pollution

Cincinnati Childhood Allergy and Air Pollution Study (CCAAPS)

- Determine if children exposed to traffic-related air pollution, specifically diesel exhaust particles, are at increased risk for
  - Allergic diseases and asthma
  - Adverse neurodevelopmental outcomes

- Longitudinal cohort of infants born 2001-2003 in greater Cincinnati, OH, USA
  - Birth record address < 400 m major road or > 1500 m from major road

Study Visits (n = 620):
- Questionnaire, allergy testing, biospecimens, spirometry

Study Visits (n = 762):
- Questionnaire, allergy testing, biospecimens, spirometry

Air Sampling + land-use regression models – Estimate elemental carbon attributable to traffic (ECAT) at participants’ addresses

Home walkthrough – Dust collection

Study Visit (n = 620): Previous + BASC-2
<table>
<thead>
<tr>
<th>Child Direct Assessments</th>
<th>Outcome / Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wechsler Intelligence Scale for Children (WISC-IV)</td>
<td>Full scale IQ and subscales</td>
</tr>
<tr>
<td>Conner’s Continuous Performance Test (Conner’s CPT)</td>
<td>Inattentiveness, impulsivity, sustained attention</td>
</tr>
<tr>
<td>Children’s Depression Inventory (CDI-II)</td>
<td>Cognitive, affective, and behavioral signs of depression</td>
</tr>
<tr>
<td>Spence Children’s Anxiety Scale (SCAS)</td>
<td>Generalized anxiety and subscales</td>
</tr>
<tr>
<td>Grooved Pegboard Test</td>
<td>Eye-hand coordination and motor speed</td>
</tr>
<tr>
<td>Wide Range Achievement Test (WRAT-4)</td>
<td>Word reading and sentence comprehension</td>
</tr>
<tr>
<td>Children’s Sleep Habits Questionnaire (CSHQ)</td>
<td>Sleep problems in school-aged children</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Caregiver Survey about Child</th>
<th>Outcome / Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavior Assessment System for Children (BASC-2)</td>
<td>Behavioral and emotional function</td>
</tr>
<tr>
<td>Behavior Rating Inventory of Executive Function (BRIEF)</td>
<td>Executive function in children</td>
</tr>
<tr>
<td>Children’s Sleep Habits Questionnaire (CSHQ)</td>
<td>Sleep problems in school-aged children</td>
</tr>
<tr>
<td>Parenting Relationship Questionnaire (PRQ)</td>
<td>Parent-child relationship and rearing environment</td>
</tr>
<tr>
<td>Social Responsiveness Scale (SRS)</td>
<td>Social impairment and behaviors associated with ASD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Caregiver Direct Assessment</th>
<th>Outcome / Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wechsler Abbreviated Scale of Intelligence (WASI-2)</td>
<td>Full scale IQ</td>
</tr>
<tr>
<td>Beck Depression Inventory – 2nd Ed. (BDI-II)</td>
<td>Measure of depression in adults</td>
</tr>
</tbody>
</table>

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**Study Visits (n = 762):** Questionnaire, allergy testing, biospecimens, spirometry

**Study Visit (n = 620):** Previous + BASC-2

**Study Visit (n = 344):** Neurobehavioral Assessment + Imaging

**Air Sampling + land-use regression models –** Estimate elemental carbon attributable to traffic (ECAT) at participants’ addresses

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**Sequences Acquired**

<table>
<thead>
<tr>
<th>Imaging Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three dimensional T1 weighted imaging</td>
</tr>
<tr>
<td>Standard T2 weighted</td>
</tr>
<tr>
<td>T2 map for quantitative T2 measurements</td>
</tr>
<tr>
<td>Diffusion Tensor Imaging of White Matter</td>
</tr>
<tr>
<td>Magnetic Resonance Spectroscopy</td>
</tr>
<tr>
<td>Functional Magnetic Resonance Imaging</td>
</tr>
</tbody>
</table>

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**Imaging Outcomes**

- Three dimensional T1 weighted imaging
- Whole brain and substructure volumes
- Inflammatory changes noted with hyperintense signals
- T2 rates for brain tissues
- White matter integrity metrics
- Metabolite concentrations
- Neural activation levels
Traffic-Related Air Pollution (TRAP)

• Ambient air sampling campaign (2001-2006) at 27 sampling sites
  – Elemental carbon attributable to traffic (ECAT)
    • 24-hour concentrations (µg/m³) averaged over 5-year sampling campaign
  – Land-use regression (LUR) model
    • Estimate ECAT concentrations at un-sampled locations based on surrounding land and traffic data
Traffic-Related Air Pollution (TRAP)

• Ambient air sampling campaign (2001-2006) at 27 sampling sites
  – Elemental carbon attributable to traffic (ECAT)
    • 24-hour concentrations (µg/m³) averaged over 5-year sampling campaign
  – Land-use regression (LUR) model
    • Estimate ECAT concentrations at un-sampled locations based on surrounding land and traffic data

• Estimate ECAT (µg/m³) exposure for:
  – Early life (birth record address)
  – Average childhood (time-weighted average of all home addresses from birth - age 12)
  – Current (current home address)
Air Pollution and Mental Health

• Evidence of air pollution associated with mental health outcomes in adults
  – ↑ Suicide
  – ↑ ED visits for depression / anxiety

• …but first onset is typically in childhood or adolescence
  – Prevalence of major depressive disorder in childhood is 35%
  – Prevalence of anxiety disorders in childhood has increased to > 40%

• Internalizing behaviors
  – Difficult to detect and undertreated
  – Lifelong implications
    • Substance abuse, suicide risk, recurrent unemployment
Is Childhood Exposure to TRAP Associated with Depression and Anxiety at Age 12 y?

**Parent Report**
- Behavioral Assessment System for Children (BASC-2)
  - Depression
  - Anxiety
    - Mean = 50, SD = 10
    - ↑ score = more problems

<table>
<thead>
<tr>
<th>BASC Subscale</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
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<tbody>
<tr>
<td>Depression</td>
<td>344</td>
<td>49.9</td>
<td>10.2</td>
</tr>
<tr>
<td>Anxiety</td>
<td>344</td>
<td>52.1</td>
<td>12.0</td>
</tr>
</tbody>
</table>

**Child Report**
- Child Depression Inventory II Short Form (CDI-II)
- Spence Children’s Anxiety Scale (SCAS)
  - Mean = 50, SD = 10
  - ↑ score = more problems

<table>
<thead>
<tr>
<th>Outcome</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Child Depression (CDI-II)</td>
<td>339</td>
<td>52.7</td>
<td>10.2</td>
</tr>
<tr>
<td>Child Anxiety (SCAS)</td>
<td>339</td>
<td>44.2</td>
<td>8.2</td>
</tr>
</tbody>
</table>

- Linear regression adjusting for covariates
  - Exposure to TRAP (ECAT) during early life, throughout childhood, and current
  - Parent and child report of depression and anxiety
Childhood Exposure to TRAP and Depression and Anxiety at Age 12 y

- No significant associations observed between TRAP exposure and parent-reported (BASC-2) depression and anxiety
Childhood Exposure to TRAP and Depression and Anxiety at Age 12 y

- Early (6m) exposure to TRAP is significantly associated with child-reported depression and anxiety – β for 0.25 µg/m³ ECAT

- Childhood and current exposure to TRAP is significantly associated with generalized anxiety and social phobia

*Adjusted for maternal age at delivery, average household income from birth through 12y, maternal depression, PRQ relational frustration, race, cotinine

Role of Brain Metabolism in Child Anxiety

• Magnetic Resonance Spectroscopy
  – Insight into brain metabolism occurring with normal childhood maturation and illness
  – Detect perturbations in brain metabolism when anatomical imaging (MRI) reveals no macroscopic abnormalities
Methods: Imaging and Spectroscopy

- MRI sub-study (n = 145) with high / low TRAP at birth
  - MRS Acquisition
    - Point Resolved Spectroscopy (PRESS) to localize signal to 2x2x2 cm³ voxel in anterior cingulate cortex
      - Unique position in the brain with connections to both “emotional” limbic system and the “cognitive” prefrontal cortex

- Mediation analysis
  - Determine indirect and total effects

\[
Y = \alpha_1 + cE + e_1 \\
M = \alpha_2 + aE + e_2 \\
Y = \alpha_3 + bM + e_3
\]
TRAP and Brain Metabolite Levels

- No evidence that early-life exposures are associated with differences in brain metabolite levels

<table>
<thead>
<tr>
<th>Metabolite</th>
<th>β ECAT^B</th>
<th>95% CI</th>
<th>P-value</th>
</tr>
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<tbody>
<tr>
<td>ml</td>
<td>0.26</td>
<td>0.01, 0.51</td>
<td>0.04</td>
</tr>
<tr>
<td>NAA</td>
<td>0.24</td>
<td>-0.13, 0.61</td>
<td>0.22</td>
</tr>
<tr>
<td>Cr</td>
<td>0.09</td>
<td>-0.15, 0.32</td>
<td>0.47</td>
</tr>
<tr>
<td>Cho</td>
<td>0.04</td>
<td>-0.02, 0.11</td>
<td>0.20</td>
</tr>
<tr>
<td>Glu</td>
<td>0.32</td>
<td>0.03, 0.61</td>
<td>0.03</td>
</tr>
<tr>
<td>Glx</td>
<td>0.52</td>
<td>-0.08, 1.11</td>
<td>0.08</td>
</tr>
<tr>
<td>GSH</td>
<td>0.07</td>
<td>-0.08, 0.21</td>
<td>0.38</td>
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</table>
Brain Metabolites and Anxiety

<table>
<thead>
<tr>
<th>Anxiety Symptom</th>
<th>T-Scores</th>
<th>Metabolite Levels</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>SCAS Outcome</th>
<th>β ml</th>
<th>95% CI</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalized Anxiety</td>
<td>2.89</td>
<td>0.94, 4.83</td>
<td>0.004</td>
</tr>
<tr>
<td>Total Anxiety</td>
<td>3.14</td>
<td>0.85, 5.43</td>
<td>0.007</td>
</tr>
<tr>
<td>Social Phobia</td>
<td>2.52</td>
<td>0.34, 4.72</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Evidence of mediation?

- 20% of total effect mediated by myo-inositol

Brunst et al. Myo-inositol mediates the effects of traffic-related air pollution on generalized anxiety symptoms at age 12 years. *Environmental Research.* 2019;175:71-78
Myo-inositol

- 20% of total effect mediated by myo-inositol

- Myo-inositol
  - Important for many brain processes
  - Increased myo-inositol observed in diseases with
    - Marked astrocytic gliosis (response to CNS damage)
    - Microglial activation (mediated inflammatory response)
    - Brain inflammation
  - Transient nature of myo-inositol
    - Concentrations reflect active processes
    - Other metabolites (such as NAA, Cr, and Cho) reflect structural nature of neural systems

TRAP
Constituents deposit within ACC

Behavioral manifestation of anxiety symptoms

ECAT at Age 12 Study Visit

β = 0.26, p=0.04
Total Effect = 3.09 (95% CI 3.01, 3.19)
Indirect Effect = 0.63 (95% CI 0.60, 0.65)

β = 2.89, p<0.004

β = 3.05, p=0.04

Generalized Anxiety

Increased myo-inositol
Air Pollution and Brain Structure

• Limited number of studies have evaluated brain structure in childhood related to TRAP
  – Herting et al. 2019 review → n = 6 studies

• 3T Achieva scanner (Philips Medical Systems, Best, Netherlands) equipped with a 32-channel head coil
  – High-resolution, 3-D, anatomical imaging data collected

• 135 CCAAPS participants
  – 59 low ECAT, 76 high ECAT
Reduced Gray Matter Volume and Cortical Thickness Associated With TRAP

• Bilateral, medial region of reduced cortical thickness within the posterior frontal and anterior parietal lobes associated with ECAT exposure
  – Primary motor cortex and sensory areas
  – Voluntary movements and integrating somatosensory information including touch
• Reduced gray matter volume
  – Primarily in the cerebellum
  – Involved with regulating motor function, cognition, and emotion
• Combination of ↓ cortical thickness within the precentral gyrus and ↓ cerebellar volume suggests TRAP may impact motor function
Acute Exposure to Air Pollution and Mental Health in Children

• Evidence of acute PM$_{2.5}$ exposure and acute mental health outcomes in adults
  – Exacerbations of psychiatric disorders linked to inflammation and microglia activation
  – Limited evidence of acute PM$_{2.5}$ and mental health outcomes in children

• Objective: Investigate the relationship between short-term exposure to PM$_{2.5}$ and the risk for pediatric psychiatric emergency department (ED) visits

• Time-stratified case-crossover study design
  – Cases: Cincinnati Children’s Hospital ED visits (2011-2015) identified by ICD-10 codes
  – Date of ED visit and home addresses extracted from EHR and geocoded
Acute Exposure to Air Pollution and Mental Health in Children

- Time-stratified case-crossover design
  - Appropriate to examine acute effects of transient exposures
  - Removes confounding from time-invariant measured and unmeasured confounders
  - Control: Prior and post exposure history of cases
    - Match control days on day of week, month, and year
    - Model-based adjustment for temporal confounders including temperature, humidity, and holidays
Spatiotemporal PM$_{2.5}$ Model

- Daily concentrations of PM$_{2.5}$ estimated at residential locations on dates specific to cases and controls
- Satellite-based measures of aerosol optical depth
- Meteorological measurements, land use data, roadways, greenspace, grid indicators, day, year
- Calibrated with ground-based PM$_{2.5}$ monitoring data using a random forest model
  - EPA AQS sites (n = 24) + CCAAPS sites (n = 28)
    - 26,369 PM$_{2.5}$ measurements at 52 locations on 4,530 days
    - Cross validated MAE of 0.95 µg/m$^3$ and R$^2$ of 0.91
Visualizing Model Predictions

Daily PM$_{2.5}$ predictions at each grid cell averaged over 2000 - 2015.

Model PM$_{2.5}$ predictions for June 18th, 2010.
# Pediatric Psychiatric Emergency Department Utilization and Fine Particulate Matter: A Case-Crossover Study

*Cole Brokamp,² Jeffery R. Srawn,² Andrew F. Beck,² and Patrick Ryan²*

¹Cincinnati Children’s Hospital Medical Center, Cincinnati, Ohio, USA

²University of Cincinnati; Cincinnati, Ohio, USA

Table 1. Demographic summary information on psychiatric emergency department (ED) visits collected in Cincinnati, Ohio, between 2011 and 2015 and able to be geocoded within Hamilton County.

<table>
<thead>
<tr>
<th>Psychiatric ED visit category</th>
<th>(n)</th>
<th>Median Age (25th, 75th %ile)</th>
<th>Female (n)</th>
<th>African American (n)</th>
<th>Public insurance (n)</th>
<th>High community deprivation (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>13,176</td>
<td>14.4 (11.7, 16.1)</td>
<td>6,643 (50)</td>
<td>5,756 (44)</td>
<td>8,740 (66)</td>
<td>6,556 (51)</td>
</tr>
<tr>
<td>Adjustment disorder</td>
<td>702</td>
<td>13.7 (11.0, 15.8)</td>
<td>366 (52)</td>
<td>322 (46)</td>
<td>442 (63)</td>
<td>346 (49)</td>
</tr>
<tr>
<td>Anxiety</td>
<td>486</td>
<td>14.5 (11.9, 16.2)</td>
<td>288 (59)</td>
<td>123 (25)</td>
<td>204 (42)</td>
<td>167 (34)</td>
</tr>
<tr>
<td>Bipolar disorder</td>
<td>1,001</td>
<td>15.5 (13.8, 16.8)</td>
<td>535 (53)</td>
<td>405 (40)</td>
<td>744 (73)</td>
<td>537 (53)</td>
</tr>
<tr>
<td>Depressive disorder</td>
<td>3,847</td>
<td>15.3 (14.0, 16.2)</td>
<td>2,692 (70)</td>
<td>1,239 (32)</td>
<td>1,989 (51)</td>
<td>1,501 (39)</td>
</tr>
<tr>
<td>Developmental disorder</td>
<td>88</td>
<td>13.7 (9.6, 15.7)</td>
<td>9 (10)</td>
<td>27 (31)</td>
<td>48 (55)</td>
<td>33 (38)</td>
</tr>
<tr>
<td>Externalizing disorder</td>
<td>1,850</td>
<td>11.7 (8.4, 14.5)</td>
<td>572 (31)</td>
<td>1,019 (55)</td>
<td>1,440 (78)</td>
<td>1,143 (62)</td>
</tr>
<tr>
<td>Impulse control disorder</td>
<td>1,755</td>
<td>11.6 (8.8, 14.4)</td>
<td>453 (25)</td>
<td>900 (50)</td>
<td>1,425 (80)</td>
<td>992 (56)</td>
</tr>
<tr>
<td>Other mood disorder</td>
<td>1,903</td>
<td>14.4 (12.2, 16.0)</td>
<td>996 (52)</td>
<td>959 (50)</td>
<td>1,400 (73)</td>
<td>1,155 (60)</td>
</tr>
<tr>
<td>Personality disorder</td>
<td>142</td>
<td>12.0 (8.2, 14.8)</td>
<td>38 (27)</td>
<td>66 (47)</td>
<td>139 (73)</td>
<td>74 (52)</td>
</tr>
<tr>
<td>PTSD</td>
<td>519</td>
<td>14.0 (10.7, 15.8)</td>
<td>354 (67)</td>
<td>269 (51)</td>
<td>412 (78)</td>
<td>317 (60)</td>
</tr>
<tr>
<td>Schizophrenia</td>
<td>500</td>
<td>15.5 (13.0, 16.8)</td>
<td>175 (35)</td>
<td>327 (64)</td>
<td>378 (75)</td>
<td>284 (56)</td>
</tr>
<tr>
<td>Suicidality</td>
<td>275</td>
<td>15.0 (12.8, 16.6)</td>
<td>163 (59)</td>
<td>100 (36)</td>
<td>155 (56)</td>
<td>114 (42)</td>
</tr>
</tbody>
</table>

Note: In total, 13,176 unique ED visits were contributed by 6,812 unique individuals. Each outcome was classified using primary diagnosis ICD-10 codes as indicated in Table S1. Age, sex, self-reported race, and public (i.e., government-provided) insurance information was extracted from the electronic health record. Community deprivation was derived using principal components analysis of six census tract-level American community survey variables. High community deprivation was defined as greater than the median of all census tracts in Hamilton County. \%ile, Percentile; ICD-10, *International Statistical Classification of Diseases and Related Health Problems, Tenth Revision*; PTSD, post-traumatic stress disorder.
Odds Ratio* for 10 µg/m³ increase in PM$_{2.5}$

* Adjusted for temperature, humidity, and holidays
Effect Modification by Community Deprivation

- Associations were modified by community deprivation
  - Higher community deprivation increased risk for suicidality and anxiety
  - Lower community deprivation increased risk for adjustment disorders
Summary and Future Directions

• Summary
  – Exposure to air pollution during childhood may disrupt normal brain development and manifest in multiple neurodevelopmental domains
  – Data from CCAAPS suggests childhood exposure to TRAP is associated with internalizing disorders in adolescence
  – Recent short-term PM$_{2.5}$ exposure is associated with may cause acute mental health outcomes
    • Brain metabolites and inflammation may play a role

• Future Directions
  – Analyses of additional neurodevelopmental domains in CCAAPS
  – Examine potential modifiers of air pollution – neurodevelopmental outcomes including greenspace, noise, heat, community deprivation, and other chemical and non-chemical stressors
  – Identify composition of PM$_{2.5}$ most relevant to neurodevelopmental outcomes
Ultrafine Particles

- Natural sources: biological agents, geological processes, and atmospheric transformations

- Anthropogenic sources: high temperature processes (e.g. welding, smelting), combustion (mobile sources, cooking, heating), and industrial emissions

- Evidence from toxicological studies suggest that UFPs:
  - Play a significant role in PM toxicity due to their size and ability to absorb toxic chemicals (e.g. PAHs, organic compounds, metals) onto large surface areas
    - Generate reactive oxygen species (ROS) and oxidative stress
    - Translocate to the brain and other organs

- Limited epidemiologic studies focused on UFPs
  - Challenges in exposure characterization
Challenges in UFP Exposure Assessment

- UFPs have negligible mass
  - Do not contribute to PM mass concentrations
    - Health effects of PM$_{10}$ and PM$_{2.5}$ based on PM mass
  - UFPs require alternative exposure metrics
    - Particle number, surface area
Challenges in UFP Exposure Assessment

• Personal exposure frequently exceeds monitored data
  – Personal activities
  – Localized (‘hot spots’)
  – Indoor exposures
  – Children → ↑ exposure
Individual-level Exposure Assessment for Epidemiologic Studies

<table>
<thead>
<tr>
<th>Proximity Models</th>
<th>Land-Use Regression</th>
<th>Personal Monitoring</th>
</tr>
</thead>
</table>

Required data
- Complexity
- Effort
- Accuracy

Figure 1. Example of binary classification within a buffering scheme for proximity models.

Figure 3. Elements of a land use regression model showing monitoring location for NOx as the response variable and land use characteristics within buffers as the predictor variables.
Personal UFP Sampling Instruments

Review of measurement techniques and methods for assessing personal exposure to airborne nanomaterials in workplaces

Christof Ashach *1, Carla Alexander *2, Simon Clavaguera *3, Dirk Dahmann *4, Hélène Dozois *5, Bertrand Faure *6, Martin Fierz *7, Luca Fontana *8, Ivo Javicoli *9, Heinz Kaminski *10, Laura MacCalman *11, Asmus Meyer-Plath *12, Barbara Simonovs *3, Martie van Tongeren *3, Ana Maria Toleda *13

<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>MINIDISC DISC MINI</th>
<th>NANO TRACER</th>
<th>PARTECTOR</th>
<th>PUFF C100</th>
<th>PUFF C200</th>
<th>MICROAETH AE51</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIZE (W x D x H) (cm x cm x cm)</td>
<td>18 x 9 x 4.5</td>
<td>16.5 x 9.5 x 3</td>
<td>13.4 x 7.8 x 2.9</td>
<td>19 x 11 x 7</td>
<td>13 x 10 x 7</td>
<td>11.7 x 6.6 x 3.8</td>
</tr>
<tr>
<td>WEIGHT (g)</td>
<td>670</td>
<td>750</td>
<td>400</td>
<td>1,000</td>
<td>750</td>
<td>280</td>
</tr>
<tr>
<td>PARTICLE SIZE RANGE (nm)</td>
<td>10−300</td>
<td>Fast mode 20−120</td>
<td>Advanced mode 10−300</td>
<td>10−1,000</td>
<td>≥ 4.5</td>
<td>–</td>
</tr>
<tr>
<td>CONCENTRATION RANGE</td>
<td>10^3−10^4 #/cm³</td>
<td>0−10^3 #/cm³</td>
<td>0−2*10^4 μm³/cm³</td>
<td>0−2*10^4 #/cm³</td>
<td>0−1 mg BC/cm³</td>
<td></td>
</tr>
<tr>
<td>METRIC</td>
<td>NC d/LDSA</td>
<td>NC</td>
<td>NC d/LDSA</td>
<td>LDSA</td>
<td>NC</td>
<td>Black Carbon concentration</td>
</tr>
<tr>
<td>ACCURACY</td>
<td>± 30%</td>
<td>± 1,500 cm²</td>
<td>± 20%</td>
<td>± 10%</td>
<td>± 10%</td>
<td>±1 μg BC/cm²</td>
</tr>
<tr>
<td>SAMPLE FLOW (lpm)</td>
<td>1</td>
<td>0.3−0.4</td>
<td>0.5</td>
<td>0.3</td>
<td>0.05/0.1/0.15/0.2</td>
<td></td>
</tr>
<tr>
<td>TIME RESOLUTION (s)</td>
<td>1</td>
<td>3</td>
<td>16</td>
<td>1</td>
<td>1</td>
<td>1/10/30/60/300</td>
</tr>
<tr>
<td>BATTERY LIFE TIME (h)</td>
<td>6−8</td>
<td>7</td>
<td>15</td>
<td>3.3−6</td>
<td>6−24</td>
<td></td>
</tr>
</tbody>
</table>
PUFP C200 Technical Specifications

- < 1 s response time
- Concentration range: 0 – 2 x 10⁵ particles/cm³
- Particle size range: ≥ 6 nm (D₅₀)
- Sustainability: ≥ 4 g
- Weight: 0.75 kg (C200), 1 kg (C100)
- Size: 910 cm³ - 13 cm x 10 cm x 7 cm (C200)
- Built-in GPS
- Data interface: USB or Bluetooth
- Data storage: micro-SD card
- Rechargeable Lithium Polymer battery (~3 hrs @ room temp)
- Validated against reference instruments
PUFP Field Testing

Commute Home

Mowing Lawn

Commute Work

Near Roadway Residential
Personal Monitoring Pilot Test

• Objectives
  – Assess the capability of the sensor to provide reliable, accurate, and spatiotemporally resolved measures of exposure to PM1.0 number concentration for asthmatic children
  – Determine the acceptability, usability, and compliance of children and their caregivers

• 20 children ages 9 – 14 with asthma
  – Recruited from 3 Cincinnati Public Schools

• Personal monitoring began in afternoon at school and continued ~3 hours on 2 consecutive days

• 4 ‘microenvironments’ defined based on GPS coordinates
  • School, Transit, Home, and Other
UFPs by Microenvironment

Table 2
Summary of UFP particle number concentration (p/cm³) by location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean (SD)</th>
<th>5th %-tile</th>
<th>25th %-tile</th>
<th>Median</th>
<th>75th %-tile</th>
<th>95th %-tile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal — overall</td>
<td>21,400 (25,100)</td>
<td>900</td>
<td>4900</td>
<td>12,900</td>
<td>26,000</td>
<td>80,200</td>
</tr>
<tr>
<td>School</td>
<td>19,800 (22,800)</td>
<td>1900</td>
<td>4900</td>
<td>11,900</td>
<td>24,300</td>
<td>74,600</td>
</tr>
<tr>
<td>Home</td>
<td>27,000 (28,300)</td>
<td>2800</td>
<td>6800</td>
<td>17,800</td>
<td>34,500</td>
<td>98,600</td>
</tr>
<tr>
<td>Others</td>
<td>4100 (5700)</td>
<td>600</td>
<td>800</td>
<td>1000</td>
<td>4700</td>
<td>17,500</td>
</tr>
<tr>
<td>Transit</td>
<td>21,400 (20,600)</td>
<td>3100</td>
<td>7500</td>
<td>13,600</td>
<td>28,200</td>
<td>71,600</td>
</tr>
<tr>
<td>Walking</td>
<td>38,100 (26,800)</td>
<td>9800</td>
<td>17,300</td>
<td>27,400</td>
<td>61,000</td>
<td>87,900</td>
</tr>
<tr>
<td>School bus</td>
<td>23,400 (20,000)</td>
<td>2300</td>
<td>9400</td>
<td>18,200</td>
<td>30,300</td>
<td>64,500</td>
</tr>
<tr>
<td>Car</td>
<td>11,700 (11,000)</td>
<td>3400</td>
<td>5700</td>
<td>8000</td>
<td>12,800</td>
<td>30,700</td>
</tr>
</tbody>
</table>
Visualization: Personal UFP Exposure

Participant 1
- School and home in an urban area < 400 m from major road
- Elevated exposure throughout sampling including transit (walking)

Participant 2
- School and home in suburban area > 400 m from major road
- Short-term peak exposures during transit
  - Street intersections
Ecological Momentary Assessment and Personal Particle Exposure (EcoMAPPE)

- **Objective**
  - Characterize personal exposure to UFP among adolescents with and without asthma and examine associations with health outcomes
  - 100 participants
  - 7 day sampling periods (x 2)
  - Ecological momentary assessment
  - Additional exposure and health sensors / monitors

![Diagram with various sensors and tools](image-url)
**Ecological Momentary Assessment and Personal Particle Exposure (EcoMAPPE)**

Characteristics of EcoMAPPE Participants (n = 118)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean (range) / n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>15 (13 - 18)</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>52 (44%)</td>
</tr>
<tr>
<td>Female</td>
<td>66 (56%)</td>
</tr>
<tr>
<td>Race</td>
<td></td>
</tr>
<tr>
<td>Black / Bi-racial</td>
<td>30 (26%)</td>
</tr>
<tr>
<td>White</td>
<td>88 (74%)</td>
</tr>
<tr>
<td>Asthmatic</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>50 (42%)</td>
</tr>
<tr>
<td>No</td>
<td>68 (58%)</td>
</tr>
<tr>
<td>Total Duration of UFP sampling (hrs)</td>
<td>2,190</td>
</tr>
<tr>
<td>Maternal Education</td>
<td></td>
</tr>
<tr>
<td>&lt; High School</td>
<td>10 (9%)</td>
</tr>
<tr>
<td>Some College</td>
<td>17 (14%)</td>
</tr>
<tr>
<td>College / Grad School</td>
<td>83 (70%)</td>
</tr>
<tr>
<td>Missing</td>
<td>8 (7%)</td>
</tr>
</tbody>
</table>

**Fitbit Charge 2**
- Activity, sleep, heart rate

**Spirobank Smart**
- FEV1, FVC, Peak Flow, FEF25-75

**Enmont PUF C200**
- GPS
- UFP p/cc

**iButton Logger**
- Temperature
- Humidity

**Blood**
- Inflammatory markers
- Metabolomics

**MadresGPS**
- GPS
- Accelerometer

**Ecological Momentary Assessment (EMA)**
- Questionnaires
- Reminders
- Photographs

**NEATVIBEwear**
- Noise
### UFP Exposure Results

#### UFP particle number concentration (p/cc) by microenvironment

<table>
<thead>
<tr>
<th>Location</th>
<th>Hrs (% total)</th>
<th>Mean</th>
<th>5th %-tile</th>
<th>25th %-tile</th>
<th>Median</th>
<th>75th %-tile</th>
<th>95th %-tile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>2000</td>
<td>21,636</td>
<td>359</td>
<td>1,800</td>
<td>5,010</td>
<td>14,800</td>
<td>94,700</td>
</tr>
<tr>
<td>Home</td>
<td>1239 (62%)</td>
<td>19,529</td>
<td>392</td>
<td>1,730</td>
<td>4,830</td>
<td>14,900</td>
<td>99,920</td>
</tr>
<tr>
<td>School</td>
<td>60 (3%)</td>
<td>7,219</td>
<td>644</td>
<td>2,310</td>
<td>4,180</td>
<td>8,340</td>
<td>24,400</td>
</tr>
<tr>
<td>Transit</td>
<td>158 (8%)</td>
<td>19,360</td>
<td>985</td>
<td>3,639</td>
<td>8,110</td>
<td>18,880</td>
<td>77,900</td>
</tr>
<tr>
<td>Other</td>
<td>384 (19%)</td>
<td>7,219</td>
<td>294</td>
<td>1,920</td>
<td>5,730</td>
<td>17,900</td>
<td>119,900</td>
</tr>
<tr>
<td>Unknown</td>
<td>160 (8%)</td>
<td>11,421</td>
<td>76</td>
<td>1,000</td>
<td>2,600</td>
<td>7,730</td>
<td>59,440</td>
</tr>
</tbody>
</table>
Real-time and geolocated sampling provides in-depth insight regarding specific locations, activities, and times with elevated exposures—fundamentally different than traditional exposure methods using fixed monitoring sites, modeling, or integrated personal monitoring.

Actionable information that is analogous to biological monitoring of chemical exposures—more informative than biomonitoring data!

- Increase awareness of exposure
- Identify specific locations of elevated exposure
- Identify specific times and activities associated with elevated exposure
- Potential to inform behavioral changes to decrease exposure

News | Science Selections

Way to Go
Identifying Routes for Walkers and Cyclists to Avoid Air Pollutants
Exposures to air pollutants may offset a portion of the health benefits of walking and bicycling in cities. However, taking a detour just a block or two away from the busiest streets and roads can make a big difference in your exposure, says Steve Hankey, an assistant professor at Virginia Polytechnic Institute and State University and coauthor of a new study in EHP.
Reporting Back Individual Results of Personal Air Monitors

• Biomonitoring studies
  – Consensus that returning participants biomonitoring results in an understandable and meaningful way is appropriate¹
    • Ethical, right-to-know
    • Increase knowledge of participants and motivate action
    • Unanticipated benefits

• Studies of air pollution do not typically return exposure assessments
  – Modeling uncertainty
  – Influence of time-activity patterns

Reporting Back Individual Results of Personal Air Monitors

- Goal: Collaborate with EcoMAPPE participants and caregivers to develop effective report-back strategies for personal air monitors
  - Increase engagement, improve knowledge of environmental health, and motivate changes to decrease exposure
Summary and Future Directions

• Summary
  – Successfully integrated multiple data streams to capture exposures, locations, health, and activity
    • Challenge: participant burden, sensor technology (e.g. battery life), data management
  – Multiple environmental sensors offer the potential to disentangle correlated exposures (e.g. noise and UFP)
    • Challenge: sufficient sample size, generalizable study populations

• Future Directions
  – EcoMAPPE
    • Health analyses
    • Metabolomic profiles of ultrafine particle exposure
  – Comparison of personal PM$_{2.5}$ and UFP
    • Inhaled dose
    • Health effects
  – Identifying and reducing UFP exposures
    • Develop effective report-back strategies for personal air pollution monitoring
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