Direct Analysis of Chemical Warfare Simulant Aerosol by Paper Spray Mass Spectrometry

Prosolia Breakfast Meeting
June 6, 2017

Elizabeth Dhummakupt, Ph.D.

Distribution Statement A: Approved for Public Release; Distribution is Unlimited
**APG Aberdeen and Edgewood Areas**

- **Geographic Area**
  - Total Acres - 72,000
  - Cantonment Area – 6,900 acres
  - Range Area – 30,600 land acres
  - Water – 34,500 acres or 58 sq miles and 144 miles of shoreline

- **Developed Infrastructure**
  - Test facilities – 57
  - Surety buildings – 13
  - Buildings – 2,410
  - Road network – 210 paved miles
  - Leased Area – 1,015 acres
  - Potential Leased Area – 500+ acres
The Edgewood Chemical Biological Center's (ECBC) science and technology expertise has protected the United States from the threat of chemical weapons since 1917. Since that time, the Center has expanded its mission to include biological materials and emerges today as the nation's premier authority on chemical and biological defense.

1917

President Woodrow Wilson designated Gunpowder, MD as the first chemical shell filling plant in the U.S.

More than 3 million US made gas masks were produced during WWI.

1942

M4 Vapor Detector Kit

1957

M17 Biological Agent Sampling Kit

1968

M8 Portable Chemical Agent Alarm

1990

End of US Chemical Weapons Program

End of U.S. Chemical Weapons Program

UNCLASSIFIED
MISSION: Be the Nation’s premier provider of innovative chemical and biological solutions

VISION: Provider of World Class Solutions
ECBC is the primary DoD technical organization for the Chemistry and Bioscience of CB Warfare.

Mission: Integrate lifecycle science, engineering and operations solutions to counter CB threats to U.S. forces and the nation.

Warfighter Needs

Research & Technology
- Inhalation Toxicology
- Aerosol Physics
- Filtration Sciences
- Agent Spectroscopy/Algorithm Development
- Emerging Threats Science & Technology

Engineering

Operations & Integration

Lifecycle CB Solutions
- CB Concept through Sustainment Solutions
- Lifecycle CB Materiel Acquisition
- Emerging Threats Test & Evaluation
- Full-service CB Testing

- Agent Handling and Surety
- Chemical Munitions Field Operations
- WMD Elimination

Basic research through technology development, engineering design, equipment evaluation, production support, sustainment, field operations and disposal.
Paper spray is an ambient ionization technique invented in Dr. Graham Cooks’ lab at Purdue University in 2010. Over the past seven years numerous publications have demonstrated its ability to quantitatively detect small molecules (illicit drugs, pesticides, explosives, and bacterial fingerprinting) in complex matrices such as blood, urine and tissue.

A schematic of the Paper Spray Ionization approach. The analyte (red) such as blood or urine are directly spotted.

Prosolia’s Velox360

Thermo Fisher Scientific Q Exactive
S/K Challenge: Simulant Aerosol Release
G-Series CWA and Simulants

G-Series Agents

<table>
<thead>
<tr>
<th>Agent</th>
<th>Chemical Structure</th>
<th>M/z Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarin GB</td>
<td><img src="image" alt="Sarin GB Structure" /></td>
<td>m/z 203.08, <strong>m/z 207.10</strong></td>
</tr>
<tr>
<td>Soman GD</td>
<td><img src="image" alt="Soman GD Structure" /></td>
<td>m/z 125.04</td>
</tr>
<tr>
<td>Tabun GA</td>
<td><img src="image" alt="Tabun GA Structure" /></td>
<td><strong>m/z 150.09</strong></td>
</tr>
</tbody>
</table>

Simulants

<table>
<thead>
<tr>
<th>Simulant</th>
<th>Chemical Structure</th>
<th>M/z Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIMP</td>
<td><img src="image" alt="DIMP Structure" /></td>
<td><strong>m/z 203.08</strong></td>
</tr>
<tr>
<td>DMMP</td>
<td><img src="image" alt="DMMP Structure" /></td>
<td>m/z 125.04</td>
</tr>
<tr>
<td>TMP</td>
<td><img src="image" alt="TMP Structure" /></td>
<td><strong>m/z 141.03</strong></td>
</tr>
</tbody>
</table>
Dugway Proving Ground presents S/K Challenge

Deep Purple UAV

RQ-16 T-Hawk UAV

MDARS UGV

Paper spray sampler integrated into ACorns Chem puck

U.S. Army’s S/K Challenge

Technology Driven. Warfighter Focused.
Developed ACORNS Module

ACORNS = Array Configurable on Remote Network Sensors
### Summary of Data Generated at S/K Challenge (August 2016)

<table>
<thead>
<tr>
<th>UAV/UGV Platform</th>
<th>TMP/d$_3$TMP Area Ratio</th>
<th>Amount on Paper [ng/mL]</th>
<th>Mass on Paper (ng)</th>
<th>Flight Time (min)</th>
<th>Air Sampled (L)</th>
<th>Min. Cloud Concentration (ng/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDAR</td>
<td>1.53</td>
<td>3,771.22</td>
<td>45.26</td>
<td>15</td>
<td>23.4</td>
<td>193.0*</td>
</tr>
<tr>
<td>T-Hawk</td>
<td>2.33</td>
<td>5,742.36</td>
<td>68.91</td>
<td>43</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Current Aerosol Approach

PS Cartridge Aerosol Capture Device

Current Aerosol Capture Method

Collection on Glass-Fiber Filters, Extracted in MeOH, and Analysis on QqQ LC-MS
Technique Comparison (non-aerosol)

**Extraction of Standards by QqQ LC-MS**

- **DMMP/d$_9$TMP**
  - LOD: 64.67 ng/mL $R^2$: 0.983
- **TMP/d$_9$TMP**
  - LOD: 78.20 ng/mL $R^2$: 0.981
- **DIMP/$^{13}$Cd$_3$DIMP**
  - LOD: 70.91 ng/mL $R^2$: 0.987

**Standards Analyzed by PS-MS**

- **DMMP/d$_9$TMP**
  - LOD: 13.45 ng/mL $R^2$: 0.999
- **TMP/d$_9$TMP**
  - LOD: 14.05 ng/mL $R^2$: 0.999
- **DIMP/$^{13}$Cd$_3$DIMP**
  - LOD: 16.09 ng/mL $R^2$: 0.999
Aerosol Collection

Limits of Detection is from an ‘Aerosolized Liquid Solution’ of $\mu$g/mL concentration, which is aerosolized at 10 μL/min, 20 L/min airflow rate, and for 10 minutes.

**Traditional Capture & QqQ LC-MS Analysis**

- **DMMP/d₉TMP**
  - LOD: 8.71 μg/mL $R^2$: 0.987

- **TMP/d₉TMP**
  - LOD: 8.11 μg/mL $R^2$: 0.989

- **DIMP/$^{13}$Cd₃DIMP**
  - LOD: 9.26 μg/mL $R^2$: 0.990

**Paper Spray Collection & Analysis**

- **DMMP/d₉TMP**
  - LOD: 6.39 μg/mL $R^2$: 0.986

- **TMP/d₉TMP**
  - LOD: 8.17 μg/mL $R^2$: 0.988

- **DIMP/$^{13}$Cd₃DIMP**
  - LOD: 9.50 μg/mL $R^2$: 0.980
## Generation One Sample Capture Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Traditional Capture LC-QqQ-MS</th>
<th>PS-MS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sampling Efficiency (%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DMMP</td>
<td>TMP</td>
</tr>
<tr>
<td>0 ppm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 ppm</td>
<td>-39.3</td>
<td>252.2</td>
</tr>
<tr>
<td>30 ppm</td>
<td>31.5</td>
<td>59.6</td>
</tr>
<tr>
<td>60 ppm</td>
<td>45.7</td>
<td>51.0</td>
</tr>
<tr>
<td>90 ppm</td>
<td>36.0</td>
<td>35.0</td>
</tr>
<tr>
<td>120 ppm</td>
<td>34.0</td>
<td>31.4</td>
</tr>
<tr>
<td>180 ppm</td>
<td>44.1</td>
<td>40.0</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>39.9</strong></td>
<td><strong>39.4</strong></td>
</tr>
</tbody>
</table>
Generation Two
Aerosol Capture Device Re-Design

**Cartridge Case**

- Air Flow
- Crenellated Orifice
- Whatman Substrate

**Pumping**

- Increased pumping rate from **1.5** L/min to **4.5** L/min.
- The new brushless diaphragm pump is slightly larger but much more robust without a large increase in size, weight and power.
### Generation Two Sample Capture Efficiencies

<table>
<thead>
<tr>
<th>Traditional Capture LC-QqQ-MS</th>
<th>PS-MS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampling Efficiency (%)</strong></td>
<td></td>
</tr>
<tr>
<td>DMMP</td>
<td>TMP</td>
</tr>
<tr>
<td>0 ppm</td>
<td>-</td>
</tr>
<tr>
<td>3 ppm</td>
<td>105.1</td>
</tr>
<tr>
<td>30 ppm</td>
<td>30.2</td>
</tr>
<tr>
<td>60 ppm</td>
<td>26.0</td>
</tr>
<tr>
<td>90 ppm</td>
<td>63.4</td>
</tr>
<tr>
<td>120 ppm</td>
<td>57.5</td>
</tr>
<tr>
<td>180 ppm</td>
<td>56.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>50.7</strong></td>
</tr>
</tbody>
</table>

- Efficiency was only **moderately improved** for DIMP. **No improvement** was observed for TMP or DMMP.
- Although not shown here, due to higher pumping rates, **higher absolute amounts** were captured on paper which allowed for better measurement at 3ppm.
Generation Three
Aerosol Capture Device Re-Design

Cartridge Case

Pumping

4.5 L/min

1.8 L/min

COTS Product

Modified COTS
Although improvements were seen by pulling the aerosol through the Whatman paper, it was not as efficient as the glass fiber filters.
Glass Fiber Viability?

![Bar chart showing average peak area for different samples.](chart_image)

- **Whatman Paper**:
  - DMMP: \(10^5\)
  - TMP: \(10^6\)
  - DIMP: \(10^8\)

- **Untreated Glass**:
  - DMMP: \(10^8\)
  - TMP: \(10^8\)
  - DIMP: \(10^8\)
Does TMP and DMMP bind to the surface of the borosilicate fibers?

DMMP and TMP bind by hydrogen bonding to the surface of borosilicate glass.

CWA simulants and CWAs strongly interact with untreated glass surfaces via hydrogen bonding.

Davis et.al. JPCL, 2014, 5, 1393-1399.
Mechanism to Make Glass Inert Via Treatment with Ammonium Sulfate.
Passivation of Glass Fibers

![Bar chart showing the average peak area for different samples: Whatman Paper, Untreated Glass, and Sulfonated Glass, with treatments DMMP, TMP, and DIMP.](chart_image)
Sulfonated Glass Fiber Substrate Validation

- **DMMP/d₉TMP**
  - LOD: 7.65 ng/mL
  - $R^2$: 0.998

- **TMP/d₉TMP**
  - LOD: 6.05 ng/mL
  - $R^2$: 0.999

- **DIMP/₁³C₃DIMP**
  - LOD: 20.10 ng/mL
  - $R^2$: 0.991
Minimizing Collection Time

The graph shows the change in the ratio of DIMP to $^{13}$Cd$_3$DIMP over time. The x-axis represents the minutes of aerosol collection, with a scale from 0 to 10 minutes, and the y-axis represents the ratio, with a scale from 0 to 70. The data points indicate an increase in the ratio over time for a 120 ppm solution.
Aerosol Collection

Generation Three

Collection Time: 2 minutes
Substrate: Sulfonated glass fiber filters
Air flow: 1.8 L/min
Capture efficiency of the PS-MS approach was equivalent to the traditional technique.

Although not depicted here, the absolute binding at the 3ppm solution was high enough to generate a reliable efficiency calculation.

### Generation Three Sample Capture Efficiencies

<table>
<thead>
<tr>
<th></th>
<th>Traditional Capture LC-QqQ-MS</th>
<th>PS-MS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sampling Efficiency (%)</td>
<td>Sampling Efficiency (%)</td>
</tr>
<tr>
<td></td>
<td>DMMP</td>
<td>TMP</td>
</tr>
<tr>
<td>0 ppm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 ppm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30 ppm</td>
<td>78.9</td>
<td>33.9</td>
</tr>
<tr>
<td>60 ppm</td>
<td>48.9</td>
<td>33.4</td>
</tr>
<tr>
<td>90 ppm</td>
<td>49.24</td>
<td>42.8</td>
</tr>
<tr>
<td>120 ppm</td>
<td>55.2</td>
<td>43.8</td>
</tr>
<tr>
<td>180 ppm</td>
<td>45.5</td>
<td>39.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>50.0</strong></td>
<td><strong>38.6</strong></td>
</tr>
</tbody>
</table>
## Implications for Personnel Exposures

### Generation Three

- **Collection Time:** 2 minutes
- **Substrate:** Sulfonated glass fiber filters
- **Air flow:** 1.8 L/min

### PS Aerosol LOD (mg/m³) vs. Worker Population Limit (mg/m³) for 8 hours / day, 30 years & General Population Limit (mg/m³) for 24/7/365 Indefinitely

<table>
<thead>
<tr>
<th>PS Aerosol LOD (mg/m³)</th>
<th>Worker Population Limit (mg/m³) 8 hours / day, 30 years</th>
<th>General Population Limit (mg/m³) 24/7/365 Indefinitely</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMMP</td>
<td>G-Series</td>
<td>G-Series</td>
</tr>
<tr>
<td>TMP</td>
<td>VX</td>
<td>VX</td>
</tr>
<tr>
<td>DIMP</td>
<td>3.0x10⁻⁵</td>
<td>1.0x10⁻⁶</td>
</tr>
<tr>
<td>DMMP</td>
<td>7.74x10⁻⁶</td>
<td>1.0x10⁻⁶</td>
</tr>
<tr>
<td>TMP</td>
<td>8.51x10⁻⁶</td>
<td>6.0x10⁻⁷</td>
</tr>
<tr>
<td>DIMP</td>
<td>1.91x10⁻⁵</td>
<td></td>
</tr>
</tbody>
</table>

- **Sampling Time:** 2 minutes
- **SOTA:** 4 – 6 hours
Conclusions

• Paper spray cartridges can capture aerosols.

• Integrated 3D printed holder onto autonomous drone.

• Sulfonated glass fiber filters improved aerosol capture over traditional chromatography paper.

• Sub-Worker Population LODs were achieved in **2 minutes** compared to 4-6 hours.
Acknowledgements

Mass Spectrometry Core Facility
- Dr. Trevor Glaros (PI)
- Dr. Bao Q. Tran
- Dr. Phillip Mach
- Dr. Elizabeth Dhummakupt
- Paul Demond
- Daniel Carmany
- Gabrielle Boyd

ECBC
- Jason Gitlin
- Lester Stauch, III
- Dr. Alan Samuels
- Dr. Michael Feasel
- David McCaskey
- Advanced Design and Manufacturing Division
- Dugway Proving Grounds
- Dr. J. Michael Nilles
- Theodore Moran
- Theresa Connell
- Harold Wylie

Los Alamos National Lab
- Dr. Bob Williams
- Mark Alverez

Prosolia
- Dr. Justin Wiseman
- Donna Hollinshead

IUPUI
- Dr. Nicholas Manicke

Funding
- Defense Threat Reduction Agency – Joint Science and Technology Office for Chemical and Biological Defense