AIHA VIDEO SERIES:
MAKING ACCURATE EXPOSURE RISK DECISIONS

Video 2:
Introduction to Bayesian Statistical Approaches and Their Advantages
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AGENDA

• Review: Key points from Video 1A
• Focus on the 95%ile’s Distribution of Uncertainty
• Bayesian Decision Analysis (BDA)
• General Approach
• Parameter Space
• Interpreting BDA Charts
• Examples
• Promise and Perils of Priors
• Censored Data
• Priors/Parameter Space: IHDA Student vs. Expostats
• Summary: Advantages of Bayesian Statistics
• Key Resources
REVIEW: KEY POINTS FROM VIDEO 1A
AIHA Exposure Rating and Control Categories
Increase Efficiency and Effectiveness

• Avoid diminishing returns from “over-refining” exposure estimates
• Streamline Documentation
• Facilitate Qualitative Exposure Judgements
• Drive consistent follow-up management and control activities which lead to consistent risk management.

Figure 1.2 - A Strategy for assessing and managing occupational exposures.
Decision Statistic:
“Strive for at least 95% confidence that the true 95th percentile is less than the OEL”
Inferential Statistics to Manage Variability and Low Sample Numbers . . .

Estimate From What We Looked At (Our Five Samples) . . .

Using Knowledge of Underlying Shape (Lognormal Distribution) . . .

The Actual Population Exposure Profile (SEG of 10 Workers)
Judgement Accuracy is Poor If We Don’t Use Statistical Tools When We Have Monitoring Data

Video Tasks: Quantitative Judgment Accuracy
Pre- and Post- Statistical Training

NIOSH Funded U of MN Study
Actual Workplace Assessments


Use Statistical Tools!!

Traditional Statistics

Bayesian Statistics

Expostats

AIHA IHSTAT©
Use Statistical Tools!!

Traditional Statistics

Bayesian Statistics

Focus on Bayesian Statistics
FOCUS ON THE 95%ILE’S DISTRIBUTION OF UNCERTAINTY
Let’s focus in on the distribution of uncertainty around the 95%ile Point Estimate . . .

n=100

n=5
Let’s focus in on the distribution of uncertainty around the 95%ile Point Estimate . . .

n=100

n=5
Let’s focus in on the distribution of uncertainty around the 95%ile Point Estimate . . .

. . . .To think about what that uncertainty tells us about the likelihood that the true 95%ile is in each of the AIHA Categories. . .
Let’s focus in on the distribution of uncertainty around the 95%ile Point Estimate . . .

. . . .To think about what that uncertainty tells us about the likelihood that the true 95%ile is in each of the AIHA Categories. . .
**Exposure Rating**

<table>
<thead>
<tr>
<th>Category*</th>
<th>0 (&lt;1% of OEL)</th>
<th>1 (&lt;10% of OEL)</th>
<th>2 (10-50% of OEL)</th>
<th>3 (50-100% of OEL)</th>
<th>4 (&gt;100% of OEL)</th>
<th>Multiples of OEL (&gt;500% of OEL or others based on respirator APF)</th>
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<tbody>
<tr>
<td>Recommended Control</td>
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**Sample Results (ppm)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>OEL</th>
<th>GM</th>
<th>GSD</th>
<th>95%ile</th>
<th>95%ile UCL1,95</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>100</td>
<td>10.5</td>
<td>1.67</td>
<td>24.5 ppm</td>
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</tr>
<tr>
<td>15</td>
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<td>12</td>
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</table>

**OEL = 100 ppm**

**Distribution of SEG Exposures (Exposure Profile)**
OEL = 100 ppm

GM = 10.5 ppm
GSD = 1.67
95%ile = 24.5 ppm
95%ile UCL_{1.95} = 91.6 ppm

Sample Results (ppm)

| 18 | 15 | 5  | 8  | 12 |

Distribution of SEG Exposures (Exposure Profile)
OEL = 100 ppm
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95%ile = 24.5 ppm
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Sample Results (ppm)

| 18 |
| 15 |
|  5 |
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| 12 |

Exposure Rating Category*

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Distribution of SEG Exposures (Exposure Profile)

Distribution of Uncertainty in 95%ile Estimate
Focus on the 95%ile uncertainty

95%ile point estimate 95%ile upper confidence limit for the 95%ile estimate

OEL = 100 ppm
GM = 10.5 ppm
GSD = 1.67
95%ile = 24.5 ppm
95%ile UCL_{1.95} = 91.6 ppm

Sample Results (ppm)

\begin{tabular}{|c|}
\hline
18 \\
15 \\
5 \\
8 \\
12 \\
\hline
\end{tabular}

95\% point estimate uncertainty

\begin{tabular}{|c|}
\hline
Exposure Rating Category* \\
\hline
0 \hspace{0.5cm} (<1\% of OEL) \\
1 \hspace{0.5cm} (<10\% of OEL) \\
2 \hspace{0.5cm} (10-50\% of OEL) \\
3 \hspace{0.5cm} (50-100\% of OEL) \\
4 \hspace{0.5cm} (>100\% of OEL) \\
\hline
\end{tabular}

Multiples of OEL (>300\% of OEL or others based on respirator APF)

OEL = 95\%ile GM = 10.5 ppm
GSD = 1.67
95\%ile = 24.5 ppm
95\%ile UCL_{1.95} = 91.6 ppm

\begin{tabular}{|c|c|c|c|c|}
\hline
Sample Results & 18 & 15 & 5 & 8 & 12 \\
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\end{tabular}
OEL = 100 ppm

GM = 10.5 ppm
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Focus on the 95%ile uncertainty

Distribution of Uncertainty in 95%ile Estimate

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95%ile point estimate uncertainty

95%ile point estimate

95% upper confidence limit for the 95%ile estimate

OEL
Most of the 95%ile probability is in Category 2
The next most likely is Category 3
There is a small probability of Category 4
There is almost no probability that the 95%ile is in Categories 0 or 1

Sample Results (ppm)

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Focus on the 95%ile uncertainty

- 95% upper confidence limit for the 95%ile estimate
- Distribution of Uncertainty in 95%ile Estimate

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Focus on the 95%ile uncertainty

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BAYESIAN DECISION ANALYSIS
Statistical Approaches to Understanding the Exposure Profile

Ethanol
OEL = 1000 ppm

Monitoring Results:
215 ppm
52 ppm
395 ppm
700 ppm
75 ppm

Traditional IH Statistics

Best Estimate of the Exposure Distribution and its 95%ile and UTL_{95%,95%} (same as 95%ile UCL_{1,95%})

UTL_{95%,95%} = 18,700 ppm

GM = 188
GSD = 3

95%ile = 1140 ppm

Concentration (ppm)
Statistical Approaches to Understanding the Exposure Profile

Ethanol
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Concentration (ppm)
Statistical Approaches to Understanding the Exposure Profile

Ethanol
OEL = 1000 ppm

Monitoring Results:
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Bayesian Decision Analysis (BDA)

Depiction of 95%ile and its Uncertainty Relative to AIHA Categories

Exposure Rating Category

Likelihood that 95%ile falls into indicated Exposure Rating Category
Bayesian Decision Analysis (BDA)

- An adjunct or alternative to the calculation and interpretation of traditional statistics.
- Characterize 95%ile and its uncertainty
- The goal of BDA is to estimate the probability that the true exposure profile 95%ile falls into a particular category, or AIHA Exposure Rating.
Easier to Interpret!  
Easier to Communicate!

- BDA output gives probabilities - easier for people to understand than traditional confidence intervals
- The uncertainty associated with small data sets shows up clearly so risk can be better communicated
Follow-up is Straightforward

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The tables show the likelihood and decision probability for each exposure rating category.
Quickly Summarize Exposure Scenarios
Bayesian Decision Analysis: Focus on Decision Making and Follow-Up Actions

• BDA helps us determine the probability that the true exposure profile 95%ile falls within each of the five AIHA exposure categories (i.e., OEL-specific control zones)
• ...so that a decision about the appropriate exposure control category can be made with greater accuracy,
• ...and that decision leads to actions.

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BDA Chart NOT the same as the Exposure Distribution

95th Uncertainty Expressed as Likelihood that the 95th is in an AIHA Exposure Rating and Control Category

OEL = 100 ppm
x = 13 ppm, 26 ppm, 18 ppm
GM = 18.2
GSD = 1.41
95th %ile = 32.3 ppm
UTL 95% 95% = 260 ppm
BDA Chart NOT the same as the Exposure Distribution

OEL = 100 ppm

n=3, x = 13, 26, 18
GM = 18.2
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95th %ile = 32.3 ppm
UTL 95%, 99% = 260 ppm

Likelihood that the 95%ile is in an AIHA Exposure Rating and Control Category

SEG Exposure Frequency Distribution (SEG Exposure Profile)
BDA Chart NOT the same as the Exposure Distribution

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SEG Exposure Frequency Distribution
(SEG Exposure Profile)
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n=3, x = 13, 26, 18
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95th %ile = 32.3 ppm
UTL 95%, 95% = 260 ppm

n=6, x = 13, 26, 18, 22, 8, 17
GM = 16.2
GSD = 1.52
95th %ile = 32.3 ppm
UTL 95%, 95% = 76.6 ppm
BDA Chart NOT the same as the Exposure Distribution

OEL = 100 ppm

\textbf{n=3}, \( x \) = 13, 26, 18
GM = 18.2
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95th %ile = 32.3 ppm
UTL 95%, 95% = 260 ppm

\textbf{n=6}, \( x \) = 13, 26, 18, 22, 8, 17
GM = 16.2
GSD = 1.52
95th %ile = 32.3 ppm
UTL 95%, 95% = 76.6 ppm

\textbf{n=10}, \( x \) = 13, 26, 18, 22, 8, 17, 19, 12, 16, 17
GM = 16.0
GSD = 1.39
95th %ile = 27.7 ppm
UTL 95%, 95% = 42.2 ppm
GENERAL APPROACH
Traditional IH Statistics

<table>
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<tr>
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<tr>
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Use sample results, along with understanding of underlying population shape (e.g. lognormal), to calculate best estimate of true population (e.g. SEG) exposure profile and its uncertainty.
**Traditional IH Statistics**

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Use sample results, along with understanding of underlying population shape (e.g., lognormal), to calculate best estimate of true population (e.g., SEG) exposure profile and its uncertainty.

**Bayesian Approach**

Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying 95%ile).

Parameter Space

![Parameter Space Diagram](image)
Traditional IH Statistics

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Use sample results, along with understanding of underlying population shape (e.g. lognormal), to calculate best estimate of true population (e.g. SEG) exposure profile and its uncertainty.

Bayesian Approach

Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying 95%ile).

Calculate likelihood that sample data came from each exposure profile in the universe.

Sample Results (ppm):
- 0.18
- 0.25
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OEL = 1 ppm
Traditional IH Statistics

- **OEL = 1 ppm**

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Bayesian Approach

- Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying 95%ile).
- Calculate likelihood that sample data came from each exposure profile in the universe
- Sum and normalize likelihoods for all universe exposure profiles having 95%iles in each exposure category

Define Sample Results (ppm): 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.12, 0.14, 0.16, 0.18, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0, 24.0, 25.0, 26.0, 27.0, 28.0, 29.0, 30.0, 31.0, 32.0, 33.0, 34.0, 35.0, 36.0, 37.0, 38.0, 39.0, 40.0, 41.0, 42.0, 43.0, 44.0, 45.0, 46.0, 47.0, 48.0, 49.0, 50.0, 51.0, 52.0, 53.0, 54.0, 55.0, 56.0, 57.0, 58.0, 59.0, 60.0, 61.0, 62.0, 63.0, 64.0, 65.0, 66.0, 67.0, 68.0, 69.0, 70.0, 71.0, 72.0, 73.0, 74.0, 75.0, 76.0, 77.0, 78.0, 79.0, 80.0, 81.0, 82.0, 83.0, 84.0, 85.0, 86.0, 87.0, 88.0, 89.0, 90.0, 91.0, 92.0, 93.0, 94.0, 95.0, 96.0, 97.0, 98.0, 99.0, 100.0

**OEL** = 1 ppm

![Image of sample results and likelihood calculations]

Best Estimate

95% Upper Confidence

95% Lower Confidence

![Image of parameter space and exposure profiles]

GM - GSD combinations

Probability of each OEL level

- 0.1% OEL
- 1% OEL
- 10% OEL
- 50% OEL
- 95% OEL

- Probability values: 40.1% for 0.1% OEL, 48.7% for 1% OEL, 48.7% for 10% OEL, 0% for 50% OEL, 0% for 95% OEL.
Bayesian Approach: Extremely Powerful and Flexible

Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying 95%ile).

Calculate likelihood that sample data came from each exposure profile in the universe.

Sum and normalize likelihoods for all universe exposure profiles having 95%iles in each exposure category.

OEL = 1 ppm

Sample Results (sum)

- 0.18
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Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying 95th percentile).

Calculate likelihood that sample data came from each exposure profile in the universe.

Sum and normalize likelihoods for all universe exposure profiles having 95th percentiles in each exposure category.

The Parameter Space “Universe” can be adjusted and weighted according to prior knowledge about possible lognormal exposure profiles and their relative plausibility of occurrence.
Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying 95%ile).

Calculate likelihood that sample data came from each exposure profile in the universe.

Sum and normalize likelihoods for all universe exposure profiles having 95%iles in each exposure category.

The Parameter Space “Universe” can be adjusted and weighted according to prior knowledge about possible lognormal exposure profiles and their relative plausibility of occurrence.

The outcome is weighted according to how plausible each lognormal exposure profile was deemed in advance as defined in the Parameter Space universe.
Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying parameter). Calculate likelihood that sample data came from each exposure profile in the universe. Sum and normalize likelihoods for all universe exposure profiles to characterize the uncertainty distribution of any parameter of interest which can be further explored.
Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying parameter).

Calculate likelihood that sample data came from each exposure profile in the universe.

Sum and normalize likelihoods for all universe exposure profiles to characterize the uncertainty distribution of any parameter of interest which can be further explored.

Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying parameter).

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Sum and normalize likelihoods for all universe exposure profiles to characterize the uncertainty distribution of any parameter of interest which can be further explored.
Define “universe” of possible lognormal exposure profiles (each GM - GSD combination with accompanying parameter). Calculate likelihood that sample data came from each exposure profile in the universe. Sum and normalize likelihoods for all universe exposure profiles to characterize the uncertainty distribution of any parameter of interest which can be further explored.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bayesian Point Estimate</th>
<th>Bayesian 90% Credible Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>0.21 ppm</td>
<td>0.14 - 0.32 ppm</td>
</tr>
<tr>
<td>GSD</td>
<td>1.8</td>
<td>1.4 - 2.8</td>
</tr>
<tr>
<td>95%ile</td>
<td>0.534 ppm</td>
<td>0.335 - 1.35 ppm</td>
</tr>
<tr>
<td>Exceedance Fraction (% &gt; OEL)</td>
<td>0.325 %</td>
<td>0.000496 - 9.11 %</td>
</tr>
<tr>
<td>AM (Arithmetic Mean)</td>
<td>0.247 ppm</td>
<td>0.17 - 0.455 ppm</td>
</tr>
</tbody>
</table>
### e.g. Further Explore 95%ile Likelihood Distribution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bayesian Point Estimate</th>
<th>Bayesian 90% Credible Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%ile</td>
<td>0.534 ppm</td>
<td>0.335 - 1.35 ppm</td>
</tr>
</tbody>
</table>

Sliced to Explore Likelihood that 95%ile Exceeds the OEL

**OEL = 1 ppm**

<p>| Sample Results (ppm) | 0.18 | 0.25 | 0.1 | 0.36 | 0.33 | 0.15 |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bayesian Point Estimate</th>
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</tr>
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</tr>
</tbody>
</table>

Sliced to Explore Likelihood that 95%ile Exceeds the OEL

Sliced to Explore Likelihood that 95%ile is in Each of the AIHA Exposure Control Categories
PARAMETER SPACE
Parameter Space
Defined Properties of the Universe of Lognormal Exposure Profiles to be Considered in the Bayesian Analysis

Exposure Ratings translated into parameter space for OEL=1ppm

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>Cutoff (%OEL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$X_{50} \leq 1%$</td>
</tr>
<tr>
<td>1</td>
<td>$1% &lt; X_{50} \leq 10%$</td>
</tr>
<tr>
<td>2</td>
<td>$10% &lt; X_{50} \leq 50%$</td>
</tr>
<tr>
<td>3</td>
<td>$50% &lt; X_{50} \leq 100%$</td>
</tr>
<tr>
<td>4</td>
<td>$X_{50} &gt; 100%$</td>
</tr>
</tbody>
</table>
Parameter Space
Defined Properties of the Universe of Lognormal Exposure Profiles to be Considered in the Bayesian Analysis

Exposure Ratings translated into parameter space for OEL=1ppm

Each point defines a single unique lognormal distribution. e.g. GSD=2.1, GM=0.11

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>Cutoff (%OEL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>X_{maj} ≤ 1%</td>
</tr>
<tr>
<td>1</td>
<td>1% &lt; X_{maj} ≤ 10%</td>
</tr>
<tr>
<td>2</td>
<td>10% &lt; X_{maj} ≤ 50%</td>
</tr>
<tr>
<td>3</td>
<td>50% &lt; X_{maj} ≤ 100%</td>
</tr>
<tr>
<td>4</td>
<td>X_{maj} &gt; 100%</td>
</tr>
</tbody>
</table>
Parameter Space
Defined Properties of the Universe of Lognormal Exposure Profiles to be Considered in the Bayesian Analysis

For OEL=1 the 95%ile of a lognormal distribution with GSD=2.1 and GM=0.11 is in Category 2
Likelihood That the Sample Data Come From Each Lognormal Exposure Profile in Pre-Defined Parameter Space

Sample Results (ppm)

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.05</td>
</tr>
</tbody>
</table>

OEL = 1 ppm
GM = 0.11 ppm
GSD = 2.1
95%ile = 0.4 ppm
UCL95,95 = 31.0 ppm
Likelihood That the Sample Data Come From Each Lognormal Exposure Profile in Pre-Defined Parameter Space

Sample Results (ppm)

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.05</td>
</tr>
</tbody>
</table>

OEL = 1 ppm
GM = 0.11 ppm
GSD = 2.1
95%ile = 0.4 ppm
UCL95,95 = 31.0 ppm
INTERPRETING BDA CHARTS
Steps in Data Analysis and Interpretation*

1. **Enter Data Into Appropriate Statistical Tool**
2. **Evaluate the Goodness-of-fit**
3. **Review Descriptive and Inferential Statistics**
   Compare...
   - the “decision statistic” (e.g., sample 95th percentile) to the OEL.
   - the 95%UCL to the OEL.
4. **Assign a Final Rating and Certainty Level**
   - **Final Rating:** Compare the sample 95th percentile to the Exposure Control Categories (ECCs) and select a category.
   - **Certainty Level:** Compare the 95%UCL to the ECCs:
     - Low certainty if ≥ 2 categories above the chosen ECC
     - Medium certainty if only 1 category above
     - High certainty if within chosen category
5. **Document the Analysis and Recommendations**
   Recommend controls and/or PPE; work practice evaluation; additional sampling; surveillance sampling, etc.

*After Executing a Carefully Defined Monitoring Plan:
- Defined decision statistic
- Well defined SEG
- Appropriate OEL
- Well described exposure question
- Appropriate sampling strategy
- Valid and appropriate monitoring method
- Validated analytical method
Steps in Data Analysis and Interpretation*

1. **Enter Data Into Appropriate Statistical Tool**
2. **Evaluate the Goodness-of-fit**
3. **Review Descriptive and Inferential Statistics**
   - Compare...
     - the “decision statistic” (e.g., sample 95th percentile) to the OEL.
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     - Low certainty if ≥ 2 categories above the chosen ECC
     - Medium certainty if only 1 category above
     - High certainty if within chosen category

5. **Document the Analysis and Recommendations**
   - Recommend controls and/or PPE; work practice evaluation; additional sampling; surveillance sampling, etc.

*After Executing a Carefully Defined Monitoring Plan:
- Defined decision statistic

Use BDA to Further Inform Final Rating and Certainty Decision

![Diagram showing analysis results with percentages]
BDA Charts to Assign a Final Rating and Certainty Level

- **Final Exposure Rating**
  - Exposure Control Category (ECCs) = category with highest bar

- **Certainty Level Rules of Thumb**
  - Low Certainty – decision probability is < 0.5
  - Medium Certainty – decision probability is between 0.5 and 0.75
  - High Certainty – decision probability is greater than 0.75.

Rules of thumb are guidelines, not bright lines.
Checking Likelihood of Category 4 (95%ile > OEL)

• If ECC ≤ 3, check Category 4:
  • Large Category 4 decision probabilities indicate that the true 95th percentile may exceed the OEL and therefore should be a cause for concern whenever the SEG is unlikely to be reevaluated for an extended period.
  • As a rule-of-thumb, Category 4 decision probabilities up to 0.30 are tolerable, provided the SEG is regularly checked as part of an ongoing monitoring strategy.
    • < 0.05 – acceptable
    • 0.05-0.3 – tolerable, assuming the SEG has a required monitoring plan
    • > 0.3 – problematic, particularly if the SEG has no monitoring plan.

Category 2
(Medium Certainty)

Tolerable assuming SEG has a required monitoring plan
Discussion

It is useful to think of interpreting BDA charts as a two step process:

1) What is the most likely category? (i.e. Which category has the highest likelihood bar?)

2) Is the likelihood in Category 4 less than the decision criteria for the upper percentile (e.g. is there a less-than 5% likelihood that the 95%ile is in Category 4?)
EXAMPLES
**Example 1**

Into which AIHA Exposure Category will the 95th percentile MOST LIKELY fall?

\[ \text{OEL} = 100 \text{ ppm} \]

<table>
<thead>
<tr>
<th>Sample Results (ppm)</th>
<th>15</th>
<th>26</th>
<th>18</th>
</tr>
</thead>
</table>

**OEL = 100 ppm**

<table>
<thead>
<tr>
<th>Exposure Rating Category**</th>
<th>Recommended Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (&lt;1% of OEL)</td>
<td>No action</td>
</tr>
<tr>
<td>1 (&lt;10% of OEL)</td>
<td>Procedures and Training; General Hazard Communication</td>
</tr>
<tr>
<td>2 (10-50% of OEL)</td>
<td>+ Chemical Specific Hazard Communication; Periodic Exposure Monitoring</td>
</tr>
<tr>
<td>3 (50-100% of OEL)</td>
<td>+ Required Exposure Monitoring, Workplace Inspections to Verify Work Practice Controls; Medical Surveillance, Biological Monitoring</td>
</tr>
<tr>
<td>4 (&gt;100% of OEL)</td>
<td>+ Implement Hierarchy of Controls; Monitoring to Validate Respirator Protection Factor Selection.</td>
</tr>
</tbody>
</table>

**Multiples of OEL (>50% of OEL or others based on respirator APR)**

* Decision statistic = 95th percentile
Sample Results (ppm)

<table>
<thead>
<tr>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
</tr>
<tr>
<td>26</td>
</tr>
<tr>
<td>18</td>
</tr>
</tbody>
</table>

OEL = 100 ppm  
GM = 18.3  
GSD = 1.41  
X0.95 = 32.3  
95% UCL = 260

Likely Category 2  
(Medium Certainty)

Cat 4 = 0.1-0.3: Tolerable, assuming the SEG has a monitoring plan

“We have a 14% probability that Process Operator #1 requires additional exposure controls”
### Sample Results (ppm)

<table>
<thead>
<tr>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
</tr>
<tr>
<td>26</td>
</tr>
<tr>
<td>18</td>
</tr>
</tbody>
</table>

- **OEL** = 100 ppm
- **GM** = 18.3
- **GSD** = 1.41
- **X0.95** = 32.3
- **95%UCL** = 260

---

**Likely Category 2**  
(Medium Certainty)

Cat 4 = 0.1-0.3: Tolerable, assuming the SEG has a monitoring plan

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<thead>
<tr>
<th>Exposure Rating Category**</th>
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<tr>
<td>1  (&lt;10%, of OEL)</td>
<td>Procedures and Training; General Hazard Communication</td>
</tr>
<tr>
<td>2  (10-50% of OEL)</td>
<td>+ Chemical Specific Hazard Communication; Periodic Exposure Monitoring,</td>
</tr>
<tr>
<td>3  (50-100% of OEL)</td>
<td>+ Required Exposure Monitoring; Workplace Inspections to Verify Work Practice Controls; Medical Surveillance, Biological Monitoring</td>
</tr>
<tr>
<td>4  (&gt;100% of OEL)</td>
<td>+ Implement Hierarchy of Controls; Monitoring to Validate Respirator Protection Factor Selection.</td>
</tr>
</tbody>
</table>

**Action:** Procedures and Training; Chemical Specific Hazard Communication; Periodic Exposure Monitoring, Immediate Engineering Controls or Process Shut Down, Validate Acceptable Respirators

---

**How do we interpret this?**

**Likelihood**

- Decision Probability: 0.602, 0.258, 0.14

---

**We have a 14% probability that Process Operator #1 requires additional exposure controls.**
Compare traditional statistics vs. BDA ...

“The population 95th percentile point estimate is 32 ppm with a 95% upper confidence limit of 260 ppm”

“We have a 14% probability that Process Operator #1 requires additional exposure controls”
Example 2
Into which AIHA Exposure Category will the 95th percentile MOST LIKELY fall?

OEL = 100 ppm

<table>
<thead>
<tr>
<th>Sample Results (ppm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>?</td>
</tr>
<tr>
<td>26</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>Exposure Rating Category**</th>
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</thead>
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<td>0 (&lt;1% of OEL)</td>
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</tr>
<tr>
<td>1 (&lt;10% of OEL)</td>
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</tr>
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</tr>
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<td>3 (50-100% of OEL)</td>
<td>+ Required Exposure Monitoring, Workplace Inspections to Verify Work Practice Controls, Medical Surveillance, Biological Monitoring</td>
</tr>
<tr>
<td>4 (&gt;100% of OEL)</td>
<td>+ Implement Hierarchy of Controls; Monitoring to Validate Respirator Protection Factor Selection</td>
</tr>
</tbody>
</table>

Multiples of OEL (>50% of OEL or others based on respirator APR)

+Immediate Engineering Controls or Process Shut Down, Validate Acceptable Respirators

* Decision statistic = 95th percentile
Example Likelihood Decision Chart:

Sample Results (ppm)

<table>
<thead>
<tr>
<th>13</th>
<th>26</th>
<th>18</th>
<th>32</th>
<th>18</th>
<th>13</th>
</tr>
</thead>
</table>

OEL = 100
GM = 18.9
GSD = 1.44
X0.95 = 34.4
95%UCL = 73

“(Given the data,) I am moderately confident that the true 95th percentile falls between 10% and 50% of the OEL.”

Likely Category 2 (Medium Certainty)
Cat 4 < 0.05: Acceptable,

Actions:
Procedures and Training; Chemical Specific Hazard Communication; Periodic Exposure Monitoring,
Example 3
Into which AIHA Exposure Category will the 95th percentile MOST LIKELY fall?

OEL = 100 ppm

<table>
<thead>
<tr>
<th>Sample Results (ppm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exposure Rating Category**</th>
<th>Recommended Control</th>
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<tbody>
<tr>
<td>0 (&lt;1% of OEL)</td>
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<tr>
<td>1 (&lt;10% of OEL)</td>
<td>Procedures and Training; General Hazard Communication</td>
</tr>
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<td>2 (10-50% of OEL)</td>
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</tr>
<tr>
<td>3 (50-100% of OEL)</td>
<td>+ Required Exposure Monitoring, Workplace Inspections to Verify Work Practice Controls, Medical Surveillance, Biological Monitoring</td>
</tr>
<tr>
<td>4 (&gt;100% of OEL)</td>
<td>+ Implement Hierarchy of Controls; Monitoring to Validate Respirator Protection Factor Selection, Multiples of OEL (&gt;50% of OEL or others based on respirator APR) + Immediate Engineering Controls or Process Shut Down, Validate Acceptable Respirators</td>
</tr>
</tbody>
</table>

* Decision statistic = 95th percentile
Example Likelihood Decision Chart:

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<tr>
<td>14</td>
</tr>
<tr>
<td>17</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>15</td>
</tr>
</tbody>
</table>

OEL = 100
GM = 14.8
GSD = 1.17
X0.95 = 22
95%UCL = 34

“(Given the data,) I am virtually certain that the true 95th percentile falls between 10% and 50% of the OEL.”

Likely Category 2 (High Certainty)
Cat 4 < 0.05: Acceptable

Actions:
Procedures and Training; Chemical Specific Hazard Communication; Periodic Exposure Monitoring,
Example 4
Into which AIHA Exposure Category will the 95th percentile MOST LIKELY fall?

OEL = 100 ppm

| Sample Results (ppm) | 75 | 50 | 42 |

<table>
<thead>
<tr>
<th>Exposure Rating Category**</th>
<th>0 (&lt;1% of OEL)</th>
<th>No action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (&lt;10% of OEL)</td>
<td>Procedures and Training; General Hazard Communication</td>
<td></td>
</tr>
<tr>
<td>2 (10-50% of OEL)</td>
<td>+ Chemical Specific Hazard Communication; Periodic Exposure Monitoring,</td>
<td></td>
</tr>
<tr>
<td>3 (50-100% of OEL)</td>
<td>+ Required Exposure Monitoring, Workplace Inspections to Verify Work Practice Controls, Medical Surveillance, Biological Monitoring,</td>
<td></td>
</tr>
<tr>
<td>4 (&gt;100% of OEL)</td>
<td>+ Implement Hierarchy of Controls; Monitoring to Validate Respirator Protection Factor Selection,</td>
<td></td>
</tr>
</tbody>
</table>

Multiples of OEL (>50% of OEL or others based on respirator API) | + Immediate Engineering Controls or Process Shut Down, Validate Acceptable Respirators |

* Decision statistic = 95th percentile
Example Likelihood Decision Chart:

<table>
<thead>
<tr>
<th>Sample Results (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>42</td>
</tr>
</tbody>
</table>

Likely Category 4 (Medium Certainty)

Unacceptable

Actions:
Chem. Specific Haz. Com.; Required Exposure Monitoring; Implement Hierarchy of Controls; Monitoring to Validate Respirator Protection Factor Selection.

“(Given the data,) nearly 70% chance that exposures are unacceptable”

OEL = 100  
GM = 54  
GSD = 1.35  
X0.95 = 126  
95%UCL = 549
More examples...

1. “given our sampling data, we have a greater than 95% probability that exposures are acceptable…”

2. “27% probability that exposures are unacceptable…”

3. “less than 10% probability that exposures exceed half the OEL . . .”

4. “greater than 95% probability that exposures require immediate exposure controls…”
### Traditional & Bayesian

<table>
<thead>
<tr>
<th>Sample Results (ppm)</th>
<th>OEL = 100 ppm</th>
<th>GM = 16.8 ppm</th>
<th>GSD = 1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>26</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Category 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium Certainty</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95%ile = 29.5 ppm</td>
<td>95%ile UCL$_{2.5}$ = 71.0 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

> 95% Confident that 95%ile < OEL

<table>
<thead>
<tr>
<th>Sample Results (ppm)</th>
<th>OEL = 100 ppm</th>
<th>GM = 52.5 ppm</th>
<th>GSD = 1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>92</td>
<td>45</td>
<td>62</td>
</tr>
<tr>
<td>Category 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95%ile = 141.7 ppm</td>
<td>95%ile UCL$_{2.5}$ = 662.0 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Highly Confident that 95%ile > OEL

<table>
<thead>
<tr>
<th>Sample Results (ppm)</th>
<th>OEL = 100 ppm</th>
<th>GM = 40.4 ppm</th>
<th>GSD = 1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>33</td>
<td>45</td>
<td>66</td>
</tr>
<tr>
<td>Category 3? 4?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95%ile = 87.5 ppm</td>
<td>95%ile UCL$_{2.5}$ = 291.0 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Not 95% Confident that 95%ile < OEL

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>Decision Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Likelihood

<table>
<thead>
<tr>
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<th>Decision Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Likelihood

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>Decision Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
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</tr>
<tr>
<td>4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Likelihood
Important to Use Statistical Analysis on Noise as Well . . .

<table>
<thead>
<tr>
<th>dBA</th>
<th>Dose (80, 5)</th>
</tr>
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<tbody>
<tr>
<td>80.8</td>
<td>55.9</td>
</tr>
<tr>
<td>76.5</td>
<td>30.8</td>
</tr>
<tr>
<td>82.2</td>
<td>67.8</td>
</tr>
<tr>
<td>83.9</td>
<td>85.9</td>
</tr>
<tr>
<td>78.7</td>
<td>41.8</td>
</tr>
<tr>
<td>77.3</td>
<td>34.4</td>
</tr>
</tbody>
</table>

Normally Distributed
Lognormally Distributed

![Graph showing likelihood and decision probability]
Assist in respirator selection: Expostats or IHDA-Student

Substitute APF x OEL for OEL in data analysis tool – Category 4 now shows the likelihood that APF x OEL will be exceeded given the data.

OEL = 1 ppm  
APF = 10  
Use 10 x OEL

n = 3

x₁ = 0.99 ppm

x₂ = 0.50 ppm

x₃ = 2.0 ppm

APF = 50  
Use 50 x OEL

10.8% Likelihood of exceeding 10 x OEL

0.1% Likelihood of exceeding 50 x OEL
PROMISE AND PERILS OF PRIORS
BDA Promise of Priors:

Transparent integration of qualitative and quantitative judgments to make effective and efficient exposure decisions.

AIHA EA Strategy:
Define Exposure Using All Available Information
BDA Construct

**Previous Knowledge:**
What is known before the data are collected

**New Knowledge Provided by the Data:**
Monitoring Results

**Updated Knowledge:**
Integration of the Previous Knowledge and the New Data-Based Knowledge

Prior + Likelihood → Posterior
BDA Construct

**Prior** + **Likelihood** → **Posterior**

**Previous Knowledge:**
What is known before the data are collected

**New Knowledge Provided by the Data:**
Monitoring Results

**Updated Knowledge:**
Integration of the Previous Knowledge and the New Data-Based Knowledge
BDA Construct

Previous Knowledge:
What is known before the data are collected

New Knowledge
Provided by the Data:
Monitoring Results

Updated Knowledge:
Integration of the Previous Knowledge and the New Data-Based Knowledge

Prior + Likelihood \rightarrow Posterior

Sample Results (mg/M³)

<table>
<thead>
<tr>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>
**BDA Construct**

**Previous Knowledge:**
What is known before the data are collected

**New Knowledge**
Provided by the Data:
Monitoring Results

**Updated Knowledge:**
Integration of the Previous Knowledge and the New Data-Based Knowledge

---

**Prior**

+ **Likelihood**

---

**Posterior**

---

**Sample Results (mg/M³)**

| 28 | 12 | 4 | 8 |

---

**Decision Probability**

| 0.763 | 0.211 | 0.026 |

---

**Exposure Rating**

| 1 | 2 | 3 |

---

[Parameter Space Diagram]

[Sample Results Table]

[Decision Probability Chart]
BDA Construct

**Previous Knowledge:**
What is known before the data are collected

**New Knowledge**
Provided by the Data:
Monitoring Results

**Updated Knowledge:**
Integration of the Previous Knowledge and the New Data-Based Knowledge

---

Sample Results (mg/M³)

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
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</tbody>
</table>

---

Prior Exposure Rating

<table>
<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>0.8</td>
</tr>
<tr>
<td>0.6</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

---

Likelihood

---

Posterior Exposure Rating

<table>
<thead>
<tr>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.763</td>
</tr>
<tr>
<td>0.211</td>
</tr>
<tr>
<td>0.026</td>
</tr>
</tbody>
</table>

---

Decision Probability

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.007</td>
<td>0.23</td>
<td>0.4</td>
<td>0.23</td>
<td>0.07</td>
</tr>
</tbody>
</table>
AIHA EA Strategy:
Define Exposure Using All Available Information

1. Initial Assessment
(OEL = 100 mg/M³)
Typically Professional Judgment or Modeling (no monitoring data)
1. Initial Assessment
(OEL = 100 mg/M³)
Typically Professional Judgment or
Modeling (no monitoring data)

2. Add Monitoring Data
Resolve Uncertainty and
Validate Initial Assessment

Sample Results (mg/M³)

<table>
<thead>
<tr>
<th></th>
<th>28</th>
<th>12</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AIHA EA Strategy:
Define Exposure Using All
Available Information
1. Initial Assessment
(OEL = 100 mg/M³)
Typically Professional Judgment or
Modeling (no monitoring data)

2. Add Monitoring Data
Resolve Uncertainty and
Validate Initial Assessment

3. Integrated Assessment

<table>
<thead>
<tr>
<th>Sample Results (mg/M³)</th>
<th>28</th>
<th>12</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
</table>

Qualitative Modeling
Monitoring

Prior

Likelihood

Posterior

89
Integrated Exposure Assessment Result Leads to Control Recommendations

<table>
<thead>
<tr>
<th>Exposure Rating Category**</th>
<th>Recommended Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (&lt;1% of OEL)</td>
<td>No action</td>
</tr>
<tr>
<td>1 (&lt;10% of OEL)</td>
<td>Procedures and Training; General Hazard Communication</td>
</tr>
<tr>
<td>2 (10-50% of OEL)</td>
<td>+ Chemical Specific Hazard Communication; Periodic Exposure Monitoring</td>
</tr>
<tr>
<td>3 (50-100% of OEL)</td>
<td>+ Required Exposure Monitoring, Workplace Inspections to Verify Work Practice Controls; Medical Surveillance, Biological Monitoring</td>
</tr>
<tr>
<td>4 (&gt;100% of OEL)</td>
<td>+ Implement Hierarchy of Controls; Monitoring to Validate Respirator Protection Factor Selection</td>
</tr>
</tbody>
</table>

Multiples of OEL (>500% of OEL or others based on respirator APF) +Immediate Engineering Controls or Process Shut Down, Validate Acceptable Respirators
Non-informative “Uniform” or “Flat” Prior

Assign an \textit{a priori} probability to each Exposure Rating zone based on qualitative judgment or model

Prior

No previous information included beyond parameter space assumptions

Likelihood

Based on monitoring data:
- \(\text{OEL}=100 \, \text{mg/M}^3\)
- \(n = 4\)
- \(x = \{28, 12, 4, 8\} \, \text{mg/M}^3\)

Posterior

Assign an \textit{a priori} probability to each Exposure Rating zone based on qualitative judgment or model

Informative Prior

Assign an \textit{a priori} probability to each Exposure Rating zone based on qualitative judgment or model

Assign an \textit{a priori} probability to each Exposure Rating zone based on qualitative judgment or model
Prior

No previous information included beyond parameter space assumptions

Likelihood

Based on monitoring data:
OEL = 1 ppm
n = 3
x = {0.20, 0.1, 0.7} ppm

Posterior

Assign an \textit{a priori} probability to each Exposure Rating zone based on qualitative judgment or model

Non-informative “Uniform” or “Flat” Prior

Informative Prior
Critical Point

A non-informative, or “flat” prior should always be used unless the industrial hygienist has a validated qualitative exposure assessment on which to base an informative prior.
**BDA Peril of Priors:**

Qualitative Judgments Often Not Accurate

---

**Video Tasks – Qualitative Judgments**

Accuracy of Qualitative Risk & Post Training Exposure Judgments

---

**Pre- and Post-Checklist Training Accuracy Practicing OSH Professionals**

Accuracy Doubled with Checklist Training and Use

---

NIOSH Funded U of MN Study

Actual Workplace Assessments - Qualitative Judgments
How Can We Improve Our Qualitative Judgments?

• Systematic Exposure Decision Process
• Document Results and Rationale for Judgments  
  e.g. Checklist Tool
• Document Exposure Determinants  
  e.g. Modeling
• Discussion with Colleagues
• Focused Training, Coaching, and Practice
• **Accurate Feedback Mechanisms**  
  e.g. Compare initial qualitative judgment to final result from the statistical analysis of monitoring data

<table>
<thead>
<tr>
<th>SEG</th>
<th>Agent / Chemical</th>
<th>OEL</th>
<th>Initial Exposure Rating</th>
<th>Initial Certainty Rating</th>
<th>Final Exposure Rating</th>
<th>Final Certainty Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IHDA-Student to Provide Feedback for IH Calibration To Improve Professional Judgment

- OEL=1 ppm
- Prior judgment of Category 1
- Monitoring Result:
  - n = 4
  - x₁ = 0.55 ppm
  - x₂ = 0.34 ppm
  - x₃ = 0.12 ppm
  - x₄ = 0.47 ppm

Feedback: Is the Prior consistent with the data-based Likelihood?

Note: Used for feedback ONLY. Final exposure rating determined by Likelihood Chart.
Discussion

Improving our judgments is not particularly complicated – we know from other experiences that it takes practice with accurate feedback, discussion, and structure to overcome our biases. What is difficult is having the discipline to consistently follow through with those activities. We need to work them into our routine professional practice.
CENSORED DATA
BDA Handles Censored Data Very Well (OEL = 100)

None Censored

| X  | 65 | 29 | 48 | 42 | 33 | 16 | 57 |

Partially Censored

| X  | 65 | <29 | 48 | 42 | <33 | <16 | 57 |

Severely Censored

| X  | 65 | <29 | <48 | <42 | <33 | <16 | <57 |
BDA Handles Censored Data Very Well (OEL = 100)

<table>
<thead>
<tr>
<th>Severely Censored</th>
<th>Fully Censored</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X ) &lt; 65 &lt; 29 &lt; 48 &lt; 42 &lt; 33 &lt; 16 &lt; 57</td>
<td>( X ) &lt; 65 &lt; 29 &lt; 48 &lt; 42 &lt; 33 &lt; 16 &lt; 57</td>
</tr>
</tbody>
</table>

- **Severely Censored**
  - \( X \) \< 65
  - \< 29
  - \< 48
  - \< 42
  - \< 33
  - \< 16
  - \< 57

- **Fully Censored**
  - \( X \) \< 65
  - \< 29
  - \< 48
  - \< 42
  - \< 33
  - \< 16
  - \< 57
Reminder: Garbage In = Garbage Out

• Bayesian and traditional statistical tools assume scientifically-sound data.
• Statistical tools know nothing about flow rates, sample times, sampling / analytical detection limits or other factors that can influence the censoring of monitoring results.
• Take the time to plan your sampling strategy to ensure a reasonably low detection limit (e.g. 10% of the OEL or lower)
Caution About Fully Censored Data Near the OEL
(OEL = 1000 ppm)

<table>
<thead>
<tr>
<th>X</th>
<th>64</th>
<th>98</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;65</td>
<td>&lt;99</td>
<td>&lt;43</td>
<td></td>
</tr>
</tbody>
</table>

Decision Probability

- 0: 0.539
- 0.2: 0.402
- 0.4: 0.057
- 0.6: 0.004
- 0.8: 0.001
- 1: 0.000

Likelihood Function

- 0.95
- 0.9
- 0.85
- 0.8
- 0.75
- 0.7
- 0.65
- 0.6
- 0.55
- 0.5
- 0.45
- 0.4
- 0.35
- 0.3
- 0.25
- 0.2
- 0.15
- 0.1
- 0.05

GSD

- 4
- 3.5
- 3
- 2.5
- 2
- 1.5
- 1

PRIORS/PARAMETER SPACE
IHDA STUDENT VS. EXPOSTATS
Priors/Parameter Space
IHDA vs. Expostats

IHDA

Can adjust GMs and GSDs considered in Bayesian analysis “Parameter Space”

• Variable range of GM with default between 0.0005 x OEL and 5 x OEL

• Variable uniform distribution of GSD with default between 1.05 and 4

Can enter an “informative” prior incorporating previous knowledge about the exposure scenario.
Visualization of Parameter Space (OEL = 1)
IHDA Student

- Variable range of GM with default between 0.0005 x OEL and 5 x OEL and uniform on the logarithmic scale.
- Variable GSD with default between 1.05 and 4 and uniform on the logarithmic scale.
Priors/Parameter Space
IHDA vs. Expostats

**IHDA**
Can adjust GMs and GSDs considered in Bayesian analysis “Parameter Space”
- Variable range of GM with default between 0.0005 x OEL and 5 x OEL
- Variable uniform distribution of GSD with default between 1.05 and 4

Can enter an “informative” prior incorporating previous knowledge about the exposure scenario.

**Expostats**
“Parameter Space” has fixed assumptions about GMs and GSDs considered in Bayesian analysis
- GM fixed between 2x10⁻⁹ x OEL and 5x10⁸ x OEL and uniform on the logarithmic scale
- GSD distribution fixed as ln(GSD) is lognormal distribution with GM = 0.84 and GSD = 1.87

At this time one cannot enter a prior incorporating previous knowledge about the exposure scenario beyond the assumptions built into the Expostats Parameter Space.
Visualization of Parameter Space (OEL = 1)

Expostats

- GM fixed between $2 \times 10^{-9}$ x OEL and $5 \times 10^8$ x OEL and uniform on the logarithmic scale

- GSD distribution fixed as $\ln(GSD)$ is lognormal distribution with $GM = 0.84$ and $GSD = 1.87$
Impact of Parameter Space

**Expostats**
Fixed Parameter Space

**IHDA**
Variable Parameter Space

**Sample Results (ppm)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEL</td>
<td>1 ppm</td>
</tr>
<tr>
<td>GM</td>
<td>0.3 ppm</td>
</tr>
<tr>
<td>GSD</td>
<td>1.6</td>
</tr>
<tr>
<td>95th UCL</td>
<td>3.9 ppm</td>
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</tbody>
</table>

**Impact of Parameter Space**

- **Expostats**
  - Fixed Parameter Space

- **IHDA**
  - Variable Parameter Space

**Exposure Probability**

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>Probability</th>
</tr>
</thead>
</table>

**Default**

<table>
<thead>
<tr>
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<th>Probability</th>
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</thead>
</table>

**Likelihood**

<table>
<thead>
<tr>
<th>Exposure Rating</th>
<th>Likelihood</th>
</tr>
</thead>
</table>

**Critical Parameter Estimation**

- **OEL** = 1 ppm
- **GM** = 0.3 ppm
- **GSD** = 1.6
- **95th UCL** = 3.9 ppm

**Expostats**

**Fixed Parameter Space**

**Exposure Probability**

<table>
<thead>
<tr>
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**Default**

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**Likelihood**

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**IHDA**

**Variable Parameter Space**

**Exposure Probability**

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**Default**

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SUMMARY: ADVANTAGES OF BAYESIAN STATISTICS
Advantages of Bayesian Statistics

• More Intuitive Depiction of Exposures and Uncertainty than Traditional Statistics
• Direct Alignment with AIHA Exposure Rating and Control Categories
• Easy to Communicate
• Great for small monitoring data sets . . . Including n=1
• Elegant Handling of Censored Data (Non-Detects) . . . Including Fully Censored Data

Sample Size n=1

OEL = 1 ppm

Sample Results (ppm)

<table>
<thead>
<tr>
<th>Decision Probability</th>
<th>1</th>
<th>0.8</th>
<th>0.6</th>
<th>0.4</th>
<th>0.2</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure Rating</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Sample Results (ppm)

0.65

OEL = 100 ppm

Sample Results (ppm)

<table>
<thead>
<tr>
<th>Decision Probability</th>
<th>1</th>
<th>0.8</th>
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<td>3</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Student Version

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KEY RESOURCES
Free IH Statistical Analysis Tools

• **AIHA IHSTAT®** – Excel application that calculates various exposure statistics, performs goodness of fit tests, and graphs exposure data. [https://www.aiha.org/public-resources/consumer-resources/topics-of-interest/ih-apps-tools](https://www.aiha.org/public-resources/consumer-resources/topics-of-interest/ih-apps-tools)

• Bayesian Decision Analysis – IH Data Analyst Student Edition Computer Tool
  [https://www.easinc.co/](https://www.easinc.co/)

• Expostats Bayesian IH Data Analyst Tool
Free Exposure Assessment Tools

• **IH/OEHS Exposure Scenario Tool (IHEST)**
  Excel tool to aid Basic Characterization

• **IHSkinPerm**
  Excel tool for estimating dermal absorption.

• **Basic Exposure Assessment and Sampling Spreadsheet**
  Excel template for entering EA/BC and sampling data

• **The Qualitative Exposure Assessment Checklist (The Checklist)**

• **IHMOD 2.0**
  Excel-based mathematical modeling spreadsheet

[https://www.aiha.org/public-resources/consumer-resources/topics-of-interest/ih-apps-tools](https://www.aiha.org/public-resources/consumer-resources/topics-of-interest/ih-apps-tools)
## Exposure Decision Analysis: Competency Assessment

**Exposure Decision Criteria**
- Allowable Exceedance
- Needed Confidence
- Use of Exposure Categories

**Traditional Industrial Hygiene Stats**
- Properties of a lognormal distribution
- Upper percentile estimate calculation & interpretation
- Tolerance Limit calculation & interpretation

**Bayesian Decision Analysis (BDA)**
- Properties of a lognormal distribution
- Upper percentile estimate calculation & interpretation
- Tolerance Limit calculation & interpretation

**Data and Similar Exposure Groups (SEGs)**
- Rules for combining data
- Indications that a SEG may need refining

**Decision Heuristics and Human Biases**
- Common sources of bias in data interpretation and exposure assessment
- How to avoid bias in data interpretation

**Exposure Data Interpretation**
- Most likely exposure category given data
- Meet the certainty requirement given data

**Techniques for Improving Professional Judgments**
- Feedback loops (quantitative judgment > monitoring > qualitative judgment)
- Group judgment sessions
- Documentation of rationale
- Break decisions into aggregate parts (Modeling)
Learn More:

- **Papers:**
Learn More:

- **Books:**

- **Opinion:**
  - Mulhausen, J. “How to Improve Exposure Judgments” President’s Message. The Synergist. (December 2021).

- **Videos:**
AIHA VIDEO SERIES:
MAKING ACCURATE EXPOSURE RISK DECISIONS

Join us for the next video in the series . . .

Video 1A: Exposure Variability and the Importance of Using Statistics to Improve Judgements

Video 1B: Rules of Thumb for Interpreting Exposure Monitoring Data

Video 2: Introduction to Bayesian Statistical Approaches and Their Advantages

Video 3A: Free Bayesian Statistical Tools: IHDA Student Edition

Video 3B: Free Bayesian Statistical Tools: Expostats

Video 4: Implementing AIHA Strategy Using Statistical Tools: Examples
AIHA VIDEO SERIES: MAKING ACCURATE EXPOSURE RISK DECISIONS

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