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Bayesian Decision Analysis for Industrial Hygiene

By Perry W. Logan, PhD, CIH and Gurumurthy Ramachandran, PhD, CIH, FAIHA

With new technologies come new challenges and opportunities for advancing the science of exposure risk assessment and management. The rapid growth of technology has created new exposure management challenges, but has also created new valuable tools for industrial hygienists to better manage exposure risks. Many fields including biostatistics, military, econometrics, genetics, engineering, and medicine are now successfully applying Bayesian statistical techniques to solve many problems once thought impossible just a few years ago.^(1,2) Bayesian statistical techniques have recently been adapted for industrial hygiene professionals to determine the most likely task AIHA® exposure control category for a given SEG with sampling data.⁽³⁾ Traditional statistical approaches to selecting exposure control categories typically use point estimates and confidence intervals while Bayesian methods presents data analysis as probabilities for each exposure control category. This technique, called Bayesian Decision Analysis (BDA) and depicted in Figure 22.1, is a mathematical method to create probabilities of the most likely exposure control category using exposure monitoring data, and more formally test or integrate professional judgment into a single decision output.

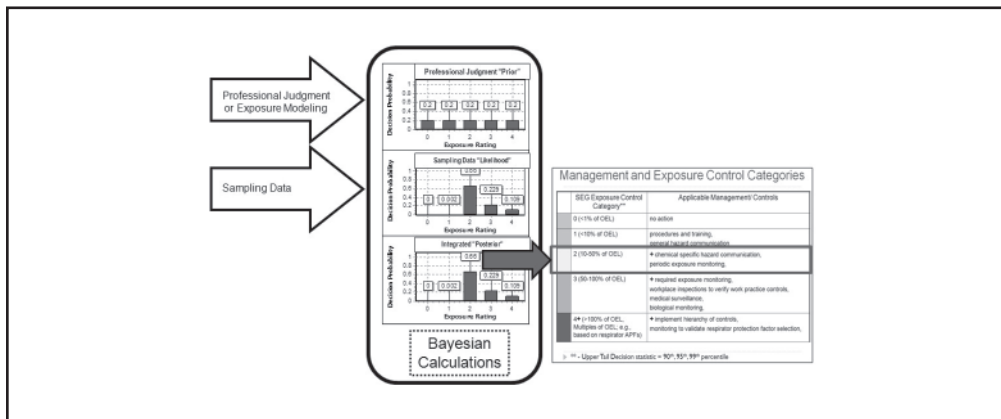


Figure 22.1 – Process for applying Bayesian statistical calculations to identify the most likely AIHA exposure control category.

The output of BDA is a set of three Decision Charts: the Prior Decision Chart, the Likelihood Decision Chart, and the Posterior Decision Chart shown in Figures 22.2 and 22.3. The Prior Decision Chart is used to quantitatively capture the *a priori* belief of the industrial hygienist that the true SEG 95th percentile (or other decision statistic) falls within one of the five AIHA® exposure control categories. These *a priori* probabilities are determined after considering information from multiple sources, including process knowledge; physical chemical exposure models, surrogate data, historical and other applicable data, and information related to past exposures for a given SEG (see Chapter 8). When relevant information needed to construct a professional judgment is lacking or uncertain, an uninformed or “Flat” Prior is constructed indicating that there is an equal probability of the decision statistic falling into any of the exposure control categories. It is critical to note that informed *Prior* exposure judgments should be constructed *prior* to reviewing exposure monitoring data. Once data has been collected, the knowledge of exposure monitoring results should not be incorporated into the prior as this incorrectly increases certainty.⁽⁵⁾

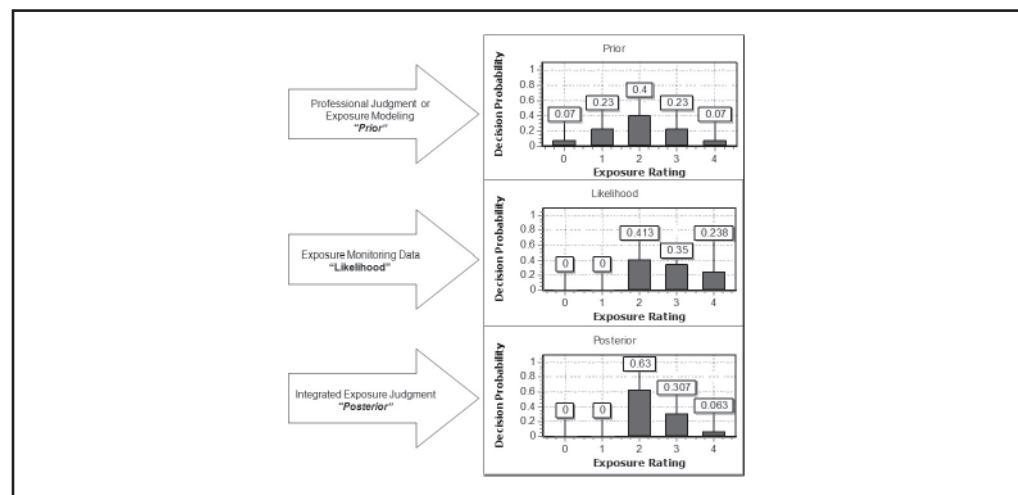


Figure 22.2 – Set of Prior, Likelihood, and Posterior Decision Charts for the industrial hygienist with minimal experience and low certainty with the example SEG.

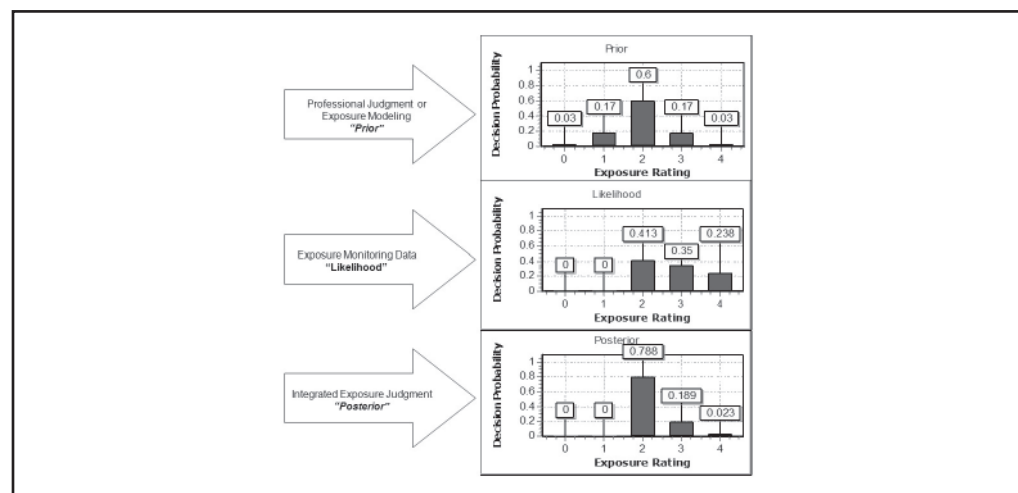


Figure 22.3 – Set of Prior, Likelihood, and Posterior Decision Charts for the industrial hygienist with extensive experience and high certainty with the example SEG.

The category probabilities in the Likelihood Decision Charts are calculated using the likelihood function described in Hewett *et al.*⁽³⁾ These decision probabilities are calculated solely from the exposure data and selected default geometric standard deviation (GSD) universe parameters. The Posterior Decision Chart represents the probabilities of the exposure categories after combining, using the Bayes equation (modified to fit the industrial hygiene decision making process), information contained in the “Prior” decision chart, and the monitoring data constructed “Likelihood” decision chart.

Example

Before collecting exposure data for a substance with an OEL of 1 ppm, an industrial hygienist who has only minimal experience with a particular SEG assigns the SEG an Initial Rating of Category 2, but with low certainty, and then devises a Prior Decision Chart (the top chart in Figure 22.2). The industrial hygienist assigns this prior belief — i.e., the probability of the true 95th percentile being in Category 2 — a 40% probability, and lower but similar probabilities are given to the other four categories. In contrast, another industrial hygienist with extensive experience with the same SEG might give this SEG the same Initial Rating but with high certainty. This hygienist assigns a 60% probability to Category 2 and much lower probabilities to the remaining categories (see the top chart in Figure 22.3). In both cases, the hygienists have decided that exposures are most likely Category 2 and that sampling will be conducted to validate or strengthen their judgments.

The following exposure data were later collected: 0.09, 0.13 and 0.34 ppm. The sample 95th percentile is 0.49 ppm with a 95%UCL of 30.3 ppm. Based upon the statistics, it appears that the SEG could be given a Final Rating of a Category 2 exposure, but since the 95%UCL is considerably greater than the OEL, neither industrial hygienist can determine from the statistics alone if this decision can be made with reasonable certainty.

The Bayesian approach permits the calculation of these decision probabilities. The category probabilities in the Likelihood Decision Chart (the center chart in Figures 22.2 and 22.3) represents the probability of the population’s 95th percentile being in each of the five exposure control categories, given the sampling data and several assumptions regarding the range of possible values for the true GM and GSD. For this example, there is 41% probability that this is a Category 2 SEG, but that there is 23.8% probability that it is a Category 4. (Notice that the Likelihood Decision Charts are identical for both industrial hygienists, as they are calculated using only the actual monitoring data).

The decision probabilities in the Posterior Decision Chart (see Figures 22.2 and 22.3) were calculated using Bayes theorem.⁽³⁾ The Posterior Decision Chart in Figure 22.2 shows that even with a weak set of prior beliefs, the posterior probability that the SEG is a Category 4 has been reduced to nearly 6% which would permit the first industrial hygienist to reject a Category 4 decision with at least 90% confidence. The Posterior Decision Chart in Figure 22.3 shows that for the industrial hygienist with a stronger set of prior beliefs the posterior probability that the SEG is a Category 2 increased from 41% to over 78%, while the posterior probability that the SEG is a Category 4 decreased to less than 3% permitting this industrial hygienist to reject a Category 4 decision with at least 95% confidence.

From this example, it is evident that BDA can be used to encourage the industrial hygienist to quantify and justify their professional judgment regarding a particular SEG before measurements are collected, and then later use that professional

judgment in the analysis and interpretation of the data. The amount of influence the professional judgment has on the Posterior Decision Chart will depend on the amount of data used to generate the Likelihood probabilities. The less data used to generate the Likelihood Decision Chart, the greater the impact the Prior will have on the Posterior Decision Chart. Consequently, if there is no sampling data available, the Prior will become the default Posterior. Conversely, if the only information available is the sampling data, the Likelihood becomes the Posterior. A lack of professional judgment creates an “uninformed” Prior, which means that the *a priori* probability is identical for each of the decision categories.

Advantages to Bayesian Decision Analysis

The Bayesian approach to industrial hygiene decision making requires that the industrial hygienist be aware of the limitations and pitfalls associated with another statistical methodology: restricting the analysis to a reasonable parameter space, communication and interpretation, integration of professional judgment with data analysis, and continuous learning and validation. The advantages appear to outweigh the disadvantages.

Restricting the analysis to a reasonable parameter space: In traditional statistics there is an unrealistic assumption that the true GM and GSD can be nearly any value, no matter how large or physically impossible.* In contrast, the Bayesian analysis calculations require that appropriate minimum and maximum values be set for the population GM and GSD. In the above example, it was assumed that the GSD for the SEG example operation is probably in the range 1.5 to 3.0 and so a conservative minimum GSD of 1.05 and a conservative maximum GSD of 4.0 were set. It was also assumed that the possible GM values range between a minimum and maximum of 0.0005 and 5.0, respectively.

Communication and Interpretation: The Bayesian analysis outputs are in terms of the probability that the decision statistic falls into a given exposure control category. These probabilities are usually much easier to communicate than the standard upper tail estimates and confidence intervals. From the example above, the Posterior Decision Charts in Figure 22.3 can be interpreted as “given both the sampling data and the industrial hygienist’s professional judgment, there is a greater than 95% probability that the exposure profile is a Category 2, therefore exposures for the SEG are acceptable. Implement chemical specific hazard communication and periodic monitoring as needed.” Such probabilities are much easier to communicate than “the point estimate falls in Category 2 and the upper confidence limit of the point estimate falls in Category 4” where it may not be clear whether or not exposures are acceptable.

Continuous Learning and Validation of Qualitative Exposure Judgments: The Bayesian AIHA model allows the industrial hygienist to easily update judgments, and in the process better understand prior professional judgments (Figure 22.4). This provides a framework of a more rigorous method for increasing professional judgment efficiency, accuracy, and validation.⁽⁴⁻⁸⁾ As monitoring data are collected, the accuracy of the initial professional judgment can be systematically evaluated by comparing the professional judgment based Prior Decision Chart to the Likelihood Decision Chart, which is calculated using only the sampling data for a given SEG.

*To demonstrate this, calculate the 99%LCL and 99%UCL for the sample GM and sample GSD for datasets where the sample size is small. The LCL and UCL for the GM will often span one or more orders of magnitude, and the UCL for the GSD will often exceed 10 or 20.

If there is a significant discrepancy the industrial hygienist can conclude that the initial (qualitative) professional judgment “Prior” was incorrect, or collect additional exposure data. If the industrial hygienist is consistently high or low then perhaps a recalibration of professional judgment is needed. Figure 22.4 illustrates an example SEG where the professional judgment “Prior” was significantly different than the “Likelihood” chart defined by monitoring data.

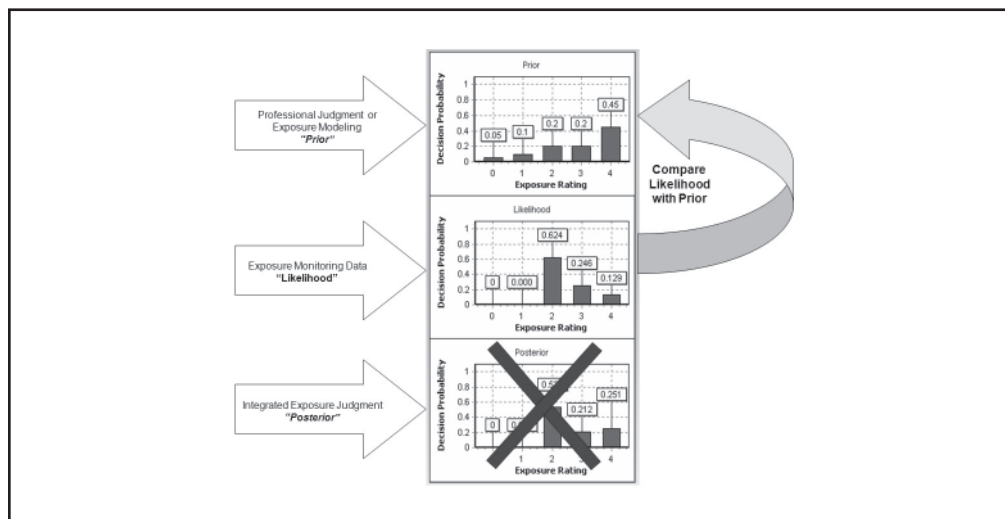


Figure 22.4 – Bayesian integrated AIHA strategy used to test exposure judgment accuracy. The figure illustrates a method for utilizing the Bayesian integrated AIHA Strategy to compare exposure monitoring data analysis (Likelihood) with exposure judgments (Prior) made for a given SEG.

Integration of Professional Judgment with data analysis: The Bayesian method provides a transparent method to utilize the strategy outlined in this manual and incorporate professional judgment or modeling with traditional sampling data to arrive at a final decision. This integration is very helpful for situations where there is minimal or no sampling data, but there is a wealth of experience in the form of a professional judgment. It is also useful in situations where there may be a wealth of monitoring data for a similar SEG for the same chemical. In this case, the likelihood output could be used as the Prior for the related SEG. This ability to integrate professional judgment and data analysis in a transparent way allows for better use of data across SEGs, a site, or an organization.

Future Work

Since Bayesian methods are only beginning to be implemented in industrial hygiene evaluation and control programs, there are many opportunities for learning and improvement. The following list identifies ongoing and future applications.

- Utilize BDA to better understand the factors that influence professional judgment accuracy and efficiency.
- Use BDA to evaluate and validate various exposure models used in control banding methods such as COSHH Essentials or REACH tiered exposure models.
- The current AIHA Exposure Assessment and Management strategy is considered a comprehensive exposure control banding strategy, but could

be further enhanced by experience learned through implementing exposure control categories across many different types of operations.

- Apply BDA to retrospective exposure assessments used for epidemiological studies.^(2,4)
- Use BDA as a framework to more effectively integrate and validate physical chemical models with professional judgment and monitoring data.
- Apply BDA to the selection of appropriate respiratory protection (by expanding the exposure control bands to include respirator Assigned Protection Factors).
- Apply BDA to the analysis of repeated measures datasets (even those containing censored data) to better estimate within and between worker variability.⁽⁹⁾

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Exposure Assessment Strategies Committee

Edited by
Steven D. Jahn, CIH, MBA
William H. Bullock, DHSc, CIH, CSP
Joselito S. Ignacio, CIH, CSP, MPH, REHS/RS

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American Industrial Hygiene Association

3141 Fairview Park Drive, Suite 777

Falls Church, VA 22042

Tel.: (703) 849-8888

Fax: (703) 207-3561

<http://www.aiha.org>

e-mail: infonet@aiha.org