A Method for Evaluating Exposure to Nitrous Oxides by Application of Lognormal Distribution

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Abstract: A Method for Evaluating Exposure to Nitrous Oxides by Application of Lognormal Distribution: S.S. Borjanovic, et al. Department of Work Physiology, Institute of Occupational Health “Dr Dragomir Karajovic” — A lognormal distribution adequately describes exposure to nitrous oxides in a work environment. The aim of this paper was to assign to the measured data a certain degree of variability which defines the interval in which real concentrations can be found with a given probability. Exposures may be evaluated by using estimates of the geometric mean (GM) and the geometric standard deviation (GSD), i.e. central value and dispersion index, to calculate the confidence interval (CI) around the mean exposure and compare this interval to the occupational exposure limit. The concentration of nitrous oxides (114 random temporal measurements covering all three shifts, during 6 consecutive days) on coated electrode welding in a car manufacturing plant, was determined with colourimetric direct reading method. Statistical analysis (chi-square and Kolmogorov-Smirnov goodness of fit tests, lognormal and Gaussian distribution fitting and Q-Q plots) was performed. The distribution of the nitrous oxides concentration in the work environment studied closely resembled that of lognormal distribution. The geometric mean was 4.098 mg/m³, median 4.00 mg/m³, geometric standard deviation 1.829 and 95% confidence interval 3.66–4.58 mg/m³. It is possible to apply the computed GSD for evaluation of exposure limits to nitrous oxides in any other work environment, even with only a few measurements.

Key words: Gaussian distribution, Geometric mean, Confidence interval, Geometric standard deviation, Fit tests

Evaluation of risks associated with hazards in a work environment is one of the fundamental aspects of occupational hygiene. This involves quantification of exposures to hazardous agents or environments. The aim of occupational hygiene is to determine the true exposure based on scientific principles. This is often very difficult due to limitations to measurement technology. In addition, the profile of daily exposure of an individual worker to a single contaminant, e.g. nitrous oxides, varies considerably from day to day. These fluctuations arise from several variables including the following: emission of nitrous oxides from a source, degree of ventilation and mixing with air, as well as different tasks and work practices of the worker1, 2). Since combinations of these variables tend to be multiplicative in effect, it has been postulated as a general rule that a lognormal distribution adequately describes exposure over time for a particular worker. It is therefore useful to assign to the measured data a certain degree of variability which defines the interval in which real concentrations can be found with a given probability. Statistical analysis of the data can satisfactorily meet this requirement3–6).

In real work environments, in the machine industry, the concentration of nitrous oxides varies depending on time and space, but the values can only be ≥0. In addition, errors in determining the concentration of nitrous oxides increase as the concentration level decreases. This is reflected in an asymmetrical distribution of the measured concentrations5). Assessment of compliance is based on the exposure of the individual worker, usually expressed as the 8-hr time-weighted average (TWA) concentration. On a day to day basis, this exposure has to remain under a preset concentration level, irrespective of the different tasks the worker performs with normal work procedures.

Exposures may be evaluated by estimates of the geometric mean (GM) and geometric standard deviation (GSD), i.e. central value and dispersion index, to calculate the confidence interval (CI) around the mean exposure and compare this interval to the occupational exposure
limit. In lognormal distribution, the geometric mean is equal to the median. The median is defined as the concentration corresponding to a cumulative percentage of 50%. The geometric standard deviation is defined as the ratio of the concentration corresponding to a cumulative percentage of 84% and the concentration corresponding to a cumulative percentage of 50%. The distribution is skewed and the geometric mean is always smaller than the arithmetic mean by an amount which depends on the geometric standard deviation. In lognormal distribution 68.26% of all values are between GM/GSD and GM · GSD. The lognormal model is nowadays used routinely for characterising exposure data and it is widely accepted that short term exposure measurements are generally lognormally distributed with geometric standard deviations mostly in the range 1.5 to 2.0. The subsequent sections of this paper will discuss primarily the evaluation of exposure to nitrous oxides, but many of the concepts can also be used in risk assessment for other toxic chemicals in work environment.

Material and Methods

If the distribution of measurement data of airborne contaminations can be approximated by a theoretical distribution function, it should be possible to assess the probability of observing concentrations above or below a certain critical value. It is essential that goodness of fit test is used to estimate the best distribution function. Assuming that the shape of distribution of nitrous oxide measurements x and f(x) is as shown in Fig. 1, which does not follow the Gaussian distribution, the parameters of such distribution, μ and σ, are the mean value and the standard deviation of the lognormally-distributed exposure concentrations.

The parameter S, which is not equivalent to μ, symbolises the geometric mean (GM) and the parameter σ symbolises the geometric standard deviation (GSD). The value S is the median of the lognormal distribution.

The question arises how to find the values for A and B points, so that a particular measured concentration of nitrous oxides falls in the range [A, B] with given probability. It is done by taking the logarithms of the lognormally-distributed air concentrations of nitrous oxides f(logx), so that normal (Gaussian) distribution is created as shown in Fig. 2. If by such transformation a Gaussian distribution is obtained (as proved by goodness of fit tests) and we want to compute the probability (95%), that the measured concentration x is within the range [A, B], then the logA and logB values can be used to find the necessary A and B values.

The following equations then apply:

\[
\log A = \mu - t_{N-1;0.05} \cdot \frac{\sigma}{\sqrt{N}} \quad \text{and} \\
\log B = \mu + t_{N-1;0.05} \cdot \frac{\sigma}{\sqrt{N}}
\]  

(equation 1)

or in another notation:

\[
\log A = \log GM - t_{N-1;0.05} \cdot \frac{\log \text{GSD}}{\sqrt{N}} \quad \text{and} \\
\log B = \log GM + t_{N-1;0.05} \cdot \frac{\log \text{GSD}}{\sqrt{N}}
\]

(equation 2)

Having set confidence limits on the logarithmically transformed scale, it is necessary to reverse the transformation so that the limits can be interpreted on the original scale. To do so requires taking the antilogarithm of the limits resulting from equation 2. By applying antilogs, the values for A and B can be computed as:

\[
A = GM \cdot \text{GSD} \cdot t_{N-1;0.05} \cdot \frac{1}{\sqrt{N}} \quad \text{and} \\
B = GM \cdot \text{GSD} \cdot t_{N-1;0.05} \cdot \frac{1}{\sqrt{N}}
\]
The obtained distribution of 114 original measured concentrations of nitrous oxides is shown in Fig. 3. The distribution is skewed to the right with significant deviations from Gaussian distribution as shown graphically with the Q-Q plot in Fig. 5. Its geometric mean was $GM=4.098$ and geometric standard deviation $GSD=1.829$. The geometric mean was smaller than the arithmetic mean (4.93). The shape of the distribution closely resembled that of the lognormal distribution. This shape, together with the fact that GM is very close to the median (4.0), which is characteristic of the lognormal distribution, gave us the idea to test the goodness of the fit of the observed distribution with the theoretical distribution function such as lognormal. This was done in three ways: by fitting the lognormal function to the data obtained so that the area under the fitted lognormal curve is equal to the area encompassed by the frequency distribution of observed concentrations, and by means of...
chi-square and Kolmogorov-Smirnov goodness of fit tests. The results of the applied tests proved that the distribution of nitrous oxides could be very well approximated by means of lognormal distribution (Fig. 3). It could be assumed that the sample of nitrous oxides measurements which produced the observed probability distribution had been drawn from a lognormal distribution. If that were true, then replacing each measurement by its logarithm should result in a distribution more resembling a Gaussian distribution. Upon such transformation, the distribution that came up was an almost perfect Gaussian distribution (Fig. 4). The observed values of this distribution showed only minor deviations from the expected normal values on a Q-Q plot (Fig. 6). This was also proved by goodness of fit tests and by fitting the Gaussian theoretical distribution function to the log-transformed values of nitrous oxides concentrations. There was almost perfect agreement between the observed and the theoretical distribution as can be seen in Fig. 4. This was the final evidence for the lognormal pattern of the distribution of nitrous oxides concentrations in our survey. If we want to estimate the risk to the employees’ health from nitrous oxides in the work environment, we can assume a confidence level of 95% and a maximum allowable concentration for nitrogen dioxide of 6 mg/m³, assuming that hazard from nitrous oxides is mainly due to nitrogen dioxide (NO₂). We then have to consider the following calculated values. The lower limit of the 95% confidence interval (A) equals 3.66 mg/m³, and the upper limit (B) equals 4.58 mg/m³, according to equation number 4. It can be stated with 95% confidence that the concentration of nitrous oxides (expressed as NO₂) will always be lower than the preestablished standard. Even the 99% confidence interval yields an upper limit value of 4.75 mg/m³ which is still lower than the maximal allowable concentration. In 95 cases out of 100, the geometric mean of the nitrous oxides concentrations will fall within the range 3.66–4.58

Fig. 3. Distribution of nitrous oxides concentrations.

Fig. 4. Distribution of nitrous oxides concentrations - log transformed.

Fig. 5. Normal Q-Q plot of nitrous oxides (mg/m³)

Fig. 6. Normal Q-Q plot of nitrous oxides - log transformed.
mg/m$^3$. In other words, had the entire population been available, the value that would have been obtained as the range around the geometric mean, would include the 95% of geometric means of all possible samples of the same size.

**Discussion**

Air sampling at a workplace is required for compliance with government regulations and should be performed at regular intervals. In many countries, including Yugoslavia, legislation to prevent health risks from exposure to toxic agents is aimed at protection of the individual worker. Monitoring strategies should therefore provide tools for assessing the exposure variability of a single person. Particularly the questions of when to sample and how many samples to take are involved. It is recognised that a small number of samples leads to a biased estimate of GSD. Without prior knowledge of the parameters of the distribution of concentrations in the workplace, the small number of measurements taken in practice will lead to errors in estimates of GSD and in estimates of probability of exceeding a critical value. At least 30 random measurements are required for a reliable estimate of GSD. This was the principal reason for us to include as many as 114 measurements in a sample for evaluation of the exposure limits. Unlike other authors who found values of GSD in excess of 2.5$^{11}$ we found it to be slightly under 2.0 (1.829), at least when exposure to nitrous oxides is concerned. As confidence intervals are very sensitive to the estimate of GSD, the reliable assessment of exposure variability (GSD) is particularly important. A prerequisite for all statistics is that samples are collected in a random fashion to ensure that the individual measurements represent independent (uncorrelated) data$^2$. Unfortunately this seldom is the case in the common practice of workplace evaluation because samples are collected during brief campaigns of a few consecutive days.

A basic strategy to provide accurate assessment of risk must consider the sufficient number of repeated measurements collected during a survey, but often only maximum risk workers are assessed. In this strategy, one deliberately tries to sample during periods of high exposure ("worst case strategy"). But such samples are not random samples any more. If these exposures are below the critical value, it can be assumed that this will also be the case on all other days. Campaign planning is critical for this strategy and the initial phase of monitoring should be focused on predicting patterns of exposure$^{10,11}$.

The sampling schemes adequate for reliable decision-making require highly unrealistic observation periods and number of samples. Instead of that, the results of this work, established on the basis of repeated random measurements, permit one to assess the potential risk from exposure to nitrous oxides during electric-arc welding by means of lognormal distribution. As it is proved that the nitrous oxides concentrations follow the lognormal distribution with GSD=1.829, it now becomes possible to apply this computed GSD for evaluation of exposure limits to nitrous oxides with known probability in any other similar work environment, even with only a few measurements. The computed GSD of 1.829 seems a reasonable estimate of variability of exposure to nitrous oxides as far as electric-arc welding is concerned. It can be safely assumed to be treated as constant under most environmental conditions within occupational exposure to nitrous oxides during electric-arc welding in car manufacturing plants.

Instead of the need to have 40–50 measurements, which is necessary to obtain the Gaussian distribution, even a small number of measurements can be used for evaluation of any risk in any work environment, having proved that the distribution in such a sample follows the lognormal pattern and we have a reliable estimate of exposure variability (GSD). In order to obtain an unbiased estimate of GSD, without prior knowledge of the parameters of the distribution of concentrations in the workplace, it is recommended either to conduct a pilot survey based on an appropriate number of samples, or to use a preliminary GSD established from previous experience and published data$^3$. We prefer to estimate exposure variability by assuming a certain value for the GSD. One study has pointed out the fact that in many workplaces, exposure variability will be characterised by GSDs around 2.7$^{12}$. From that study, based on analysis of 420 workplace data sets covering a representative cross-section of various industries, a GSD of 2.7 could be an appropriate assumption for many distributions of 8-hr TWAs in enclosed workplaces with natural ventilation. It was recommended that this value be used as a preliminary parameter for decision-making, unless it can be proved by repeated random sampling that the GSD is lower, as it was proved with our data. For workplaces with good mechanical ventilation, GSDs will be lower because high exposure will occur less often. For processes leading to high exposure variability, a higher GSD could be more appropriate. Another approach would be to proceed to a "worst case" strategy in which the initial phase of planning aimed at detecting various patterns of exposure is critical. When the evaluation of the degree of employee exposure is concerned it is widely accepted that risk cannot be correlated easily with the results of environmental monitoring. In any case, by whatever route it enters, the consequent body burden of substances is a more direct indication of whether a worker is likely to become adversely affected by it than is the concentration in the air of the workroom. For evaluation of human risk, the best approach would be to conduct biological monitoring, where exposure should be evaluated by biological exposure indices (BEI). BEI is proportional
to the TWA if the biological half-lives are long enough. By arranging that the duration of sample periods equals 3 times the biological half-time there would be a very close identity between variations in the body burden and of the observed concentrations, expressed as TWA, at least for biological half-time values in excess of 0.1 h, and, irrespective of the ventilation provided, it amounts to more than 1 air change per hour. A correct interpretation of air sampling results in term of health protection is more likely if due account is taken of the biological half-times of the contaminants. It means that just as a comprehensive list of hygiene standards is invaluable to the industrial hygienist, so also would be a companion list of biological half-times. Adverse health effects may appear long after the body burden which caused them has disappeared but they cannot occur before it has arrived. In the present discussion, the term body burden is defined as the amount of contaminant in the body at a given time and not the total amount of the contaminant absorbed. If there is a maximum finite steady-state concentration of a substance in air for which no adverse effect is expected in most workers when exposure duration is limited to 8 h per day, the upper limit of such a concentration should be equal to TLV-TWA. If the body burden is kept at two times the standard deviation below that of the steady state TLV-TWA exposure, it will be assured that the body burden is kept on a safe level with a confidence limit of 95%.

References