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A Compliant Mean Is Not a Controlled Workplace: Bioaerosol Exposure, Compliance Testing and Respiratory Protection in Confined Livestock Housing

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ABSTRACT

Background. Workers in confined livestock housing are exposed to organic dust and endotoxin, a cause of chronic airway disease. Exposure is assessed against an occupational exposure limit and controlled by ventilation and respiratory protective equipment. We examined three assumptions: that a workplace meeting the limit on average is controlled, that a small sample establishes compliance, and that a respirator delivers its rated protection.

Methods. Shift exposures were modelled as lognormal with a geometric standard deviation of 2.8, typical of bioaerosols, against a limit of 90 EU/m^3. We computed exceedance fractions analytically, simulated compliance decisions under a sample-mean rule and an upper tolerance limit rule for 3 to 50 samples, derived time-weighted effective protection factors for intermittent respirator use, and compared control options on exceedance and on cumulative exposure over a 40-year career.

Results. A workplace whose arithmetic mean sat exactly at the limit exceeded it on 30.3 per cent of shifts; holding exceedance to 5 per cent required a geometric mean 3.2 times lower. A workplace exceeding the limit on 40.4 per cent of shifts was judged compliant by the sample-mean rule on 48.4 per cent of occasions with three samples and 32.2 per cent with ten, while the tolerance-limit rule rejected it on 96.5 per cent of occasions with three. A respirator of assigned protection factor 10 worn half the exposed time delivered an effective factor of 1.82, 18 per cent of nominal; half the nominal factor required 89 per cent wear at factor 10 and 98 per cent at factor 50. Ventilation alone reduced career cumulative exposure to 60 per cent of uncontrolled without any wear requirement.

Conclusion. Mean-based compliance conceals frequent exceedance, small-sample mean testing cannot detect a clearly uncontrolled workplace, and respirator protection is governed by unprotected time rather than by device rating.

1. Introduction

Confined housing of pigs and poultry generates high concentrations of organic dust carrying bacterial endotoxin, microbial fragments, feed particles and animal dander [1–3]. Workers exposed to these aerosols show accelerated decline in lung function, an excess of chronic bronchitis and asthma-like symptoms, and an acute febrile syndrome after heavy exposure [4–9]. Endotoxin is the component most consistently associated with the airway response, and health-based exposure limits have been proposed on that basis [10,11].

Control follows a familiar structure. Exposure is measured against a limit, and where it is exceeded the response is improved ventilation, changes to husbandry and bedding practice, or the provision of respiratory protective equipment.

Each element of that structure rests on an assumption that is worth testing. Bioaerosol exposures are highly variable, with geometric standard deviations commonly between 2 and 3, so the distinction between a mean and a distribution is not academic [12,13]. Compliance is typically judged on a small number of personal samples, and the statistical properties of that decision depend on the rule applied. And respiratory protection is credited at its assigned protection factor, which assumes the device is worn throughout the exposed period.

Agricultural workplaces make each of these assumptions harder to sustain than the industrial settings for which the framework was developed. Holdings are small, monitoring is infrequent where it happens at all, tasks

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are varied and self-directed, and continuous respirator wear in hot, physically demanding work with intermittent heavy-exposure tasks is difficult to achieve [14,15].

We therefore quantified the consequences of exposure variability for compliance assessment and for control selection, using parameters representative of livestock housing.

1.1 Objectives

We aimed to quantify the exceedance fraction implied by mean-based compliance; to compare the operating characteristics of two compliance decision rules across sample sizes; to derive the effective protection delivered by intermittently worn respirators; and to compare control options on both shift exceedance and cumulative career exposure.

2. Materials and Methods

2.1 Exposure model

Shift-average inhalable endotoxin concentration is modelled as lognormal with geometric standard deviation 2.8, within the range reported for bioaerosols in animal housing [3,16–18], and geometric means varied across the range encountered in practice. The comparison limit is 90 EU/m^3, the health-based recommended value for endotoxin [10].

For a lognormal distribution with geometric mean GM and geometric standard deviation GSD, the proportion of shifts exceeding a limit L is

$$F = 1 - \Phi\left(\frac{\ln L - \ln GM}{\ln GSD}\right) \tag{1}$$

and the arithmetic mean, which is the quantity most limits are formally compared against, is

$$AM = GM \cdot \exp\left(\frac{(\ln GSD)^2}{2}\right) \tag{2}$$

Equation 2 is the source of the first result below: because the arithmetic mean of a lognormal distribution sits well above its median, a workplace whose arithmetic mean equals the limit has a geometric mean substantially below it and a long right tail above it.

2.2 Compliance decision rules

Two rules were compared. The sample-mean rule judges a workplace compliant if the arithmetic mean of n personal samples falls below the limit. The tolerance-limit rule judges it compliant if a 95 per cent upper confidence bound on the 95th percentile of the exposure distribution falls below the limit, computed on log-transformed data [19,20].

Each rule was applied to 4,000 simulated sampling campaigns of n = 3, 6, 10, 20 and 50 samples drawn from a workplace with a geometric mean of 70 EU/m^3, which exceeds the limit on 40.4 per cent of shifts and is therefore clearly uncontrolled.

2.3 Respiratory protection and controls

Where a respirator with assigned protection factor APF [21] is worn for a fraction w of the exposed time, the time-weighted average exposure relative to the unprotected case is $w/APF + (1 - w)$, so the effective protection factor is

$$APF_{effective} = \frac{1}{\frac{w}{APF} + (1 - w)} \tag{3}$$

The structure of Equation 3 is the second result below. As w falls, the unprotected term dominates and the effective factor approaches 1 regardless of APF.

Six control configurations were compared against an uncontrolled workplace with a geometric mean of 120 EU/m^3: improved ventilation reducing the geometric mean by 40 per cent, respirators of assigned factor 10 at two levels of wear, and the combinations. Cumulative career exposure was computed over 40 years at 230 shifts per year. Parameters are in Table 1. Computations and figures were produced in Python with NumPy, SciPy and Matplotlib [22–24].

Table 1. Model parameters.

Parameter	Value	Basis
Exposure distribution	Lognormal	Standard for occupational aerosols
Geometric standard deviation	2.8	Within the range reported for animal-house bioaerosols
Occupational exposure limit	90 EU/m^3	Health-based recommended value for endotoxin
Uncontrolled geometric mean	120 EU/m^3	Representative of poorly ventilated housing
Ventilation effect	40 % reduction in geometric mean	Illustrative engineering control
Respirator assigned factors	10, 20, 50	Spanning filtering facepiece to powered devices
Career length	40 years, 230 shifts per year	Full working life
Sampling campaigns	4,000 per configuration	Sufficient for stable decision proportions

3. Results

3.1 Mean compliance and exceedance are different things

Table 2 and Figures 1 and 2 give the relationship. A geometric mean of 53.0 EU/m^3 produces an arithmetic mean of exactly 90 EU/m^3, so such a workplace formally meets the limit. At that level, 30.3 per cent of shifts exceed the limit and the 95th percentile of shift exposure is 272 EU/m^3 at a comparable geometric mean.

Holding exceedance to 5 per cent of shifts, a conventional criterion, requires a geometric mean of 16.5 EU/m^3. The two criteria therefore differ by a factor of 3.2.

The mechanism is Equation 2 and it is entirely a consequence of variability. A workplace with the same arithmetic mean but a geometric standard deviation near 1 would exceed the limit almost never; at the variability typical of animal housing it exceeds on close to a third of shifts.

The practical implication is that a compliance statement based on mean exposure is not a statement about how often workers are over-exposed, and in this setting the two diverge by an amount that matters. Where the acute febrile response follows heavy single exposures rather than average ones, the distinction is directly clinical.

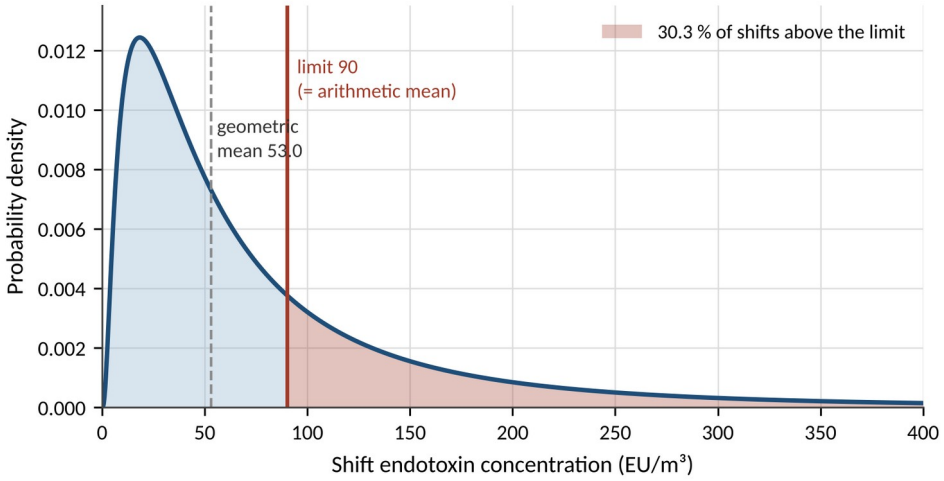


Figure 1. Shift exposure distribution for a workplace whose arithmetic mean sits exactly at the limit.

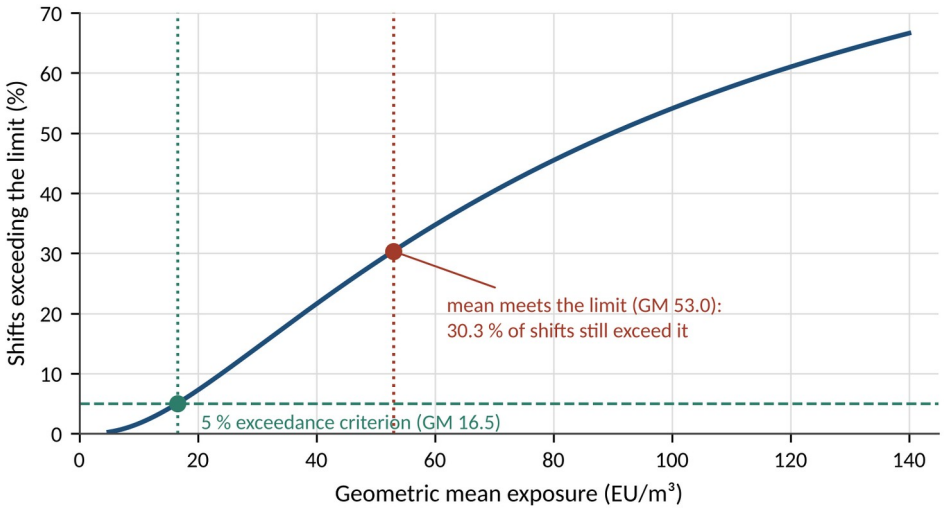


Figure 2. Exceedance fraction against geometric mean, with the two compliance criteria marked.

Table 2. Exposure distribution characteristics against geometric mean.

Geometric mean (EU/m³)	Arithmetic mean (EU/m³)	95th percentile (EU/m³)	Shifts above the limit	Mean meets the limit
20	34.0	109	7.2 %	Yes
35	59.5	190	17.9 %	Yes
50	85.0	272	28.4 %	Yes
70	118.9	381	40.4 %	No
90	152.9	489	50.0 %	No
120	203.9	653	61.0 %	No

Note. *Limit 90 EU/m³, geometric standard deviation 2.8.*

3.2 Small-sample mean testing cannot detect a bad workplace

Table 3 and Figure 3 apply the two decision rules to a workplace with a geometric mean of 70 EU/m³, which exceeds the limit on 40.4 per cent of shifts.

Under the sample-mean rule this workplace was judged compliant on 48.4 per cent of occasions with three samples, 38.9 per cent with six, 32.2 per cent with ten and still 7.8 per cent with fifty.

Under the tolerance-limit rule it was judged compliant on 3.5 per cent of occasions with three samples and essentially never with six or more.

The contrast is not primarily about statistical power. The sample-mean rule is asking a different and easier question — whether average exposure is acceptable — and a workplace with a long right tail can satisfy it while exposing workers above the limit on a large minority of shifts. Increasing the sample size improves the precision of the answer to that question without making it the right question.

For agricultural settings, where three to six samples may be the realistic maximum for a small holding, the choice of rule is therefore the decisive methodological decision. A tolerance-limit rule applied to three samples outperformed a mean rule applied to fifty.

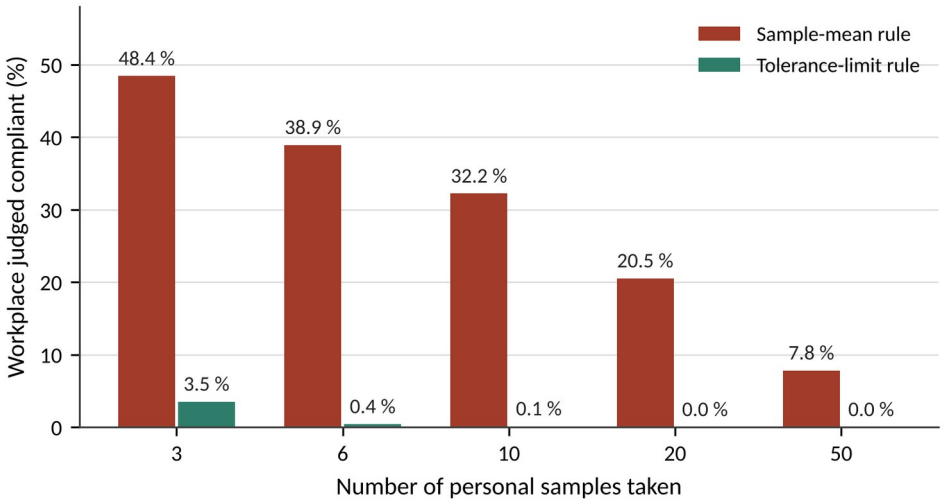


Figure 3. Probability that an uncontrolled workplace is judged compliant, by rule and sample size.

Table 3. Operating characteristics of two compliance rules.

Samples taken	Judged compliant by sample-mean rule	Judged compliant by tolerance-limit rule	Correctly identified as non-compliant by TLR
3	48.4 %	3.5 %	96.5 %
6	38.9 %	0.4 %	99.7 %
10	32.2 %	0.1 %	100.0 %
20	20.5 %	0.0 %	100.0 %
50	7.8 %	0.0 %	100.0 %

Note. *Applied to a workplace with geometric mean 70 EU/m³, exceeding the limit on 40.4 % of shifts. TLR, tolerance-limit rule.*

3.3 Respirator protection is governed by unprotected time

Table 4 and Figure 4 give effective protection factors from Equation 3. A device with assigned protection factor 10 delivered an effective factor of 1.82 when worn half the exposed time, 3.08 at three-quarters and 6.90 at 95 per cent — that is, 18, 31 and 69 per cent of nominal respectively.

Achieving half the nominal protection required 88.9 per cent wear for a device of factor 10, 94.7 per cent for factor 20 and 98.0 per cent for factor 50.

The second of those observations is the one we would put to anyone specifying equipment. The wear compliance needed to realise a given share of the nominal protection rises with the nominal factor, so upgrading from a filtering facepiece to a powered device without changing wear behaviour delivers far less than the ratio of their ratings implies. At 50 per cent wear, factors of 10 and 50 gave effective protection of 1.82 and 1.96 respectively — a difference of less than 10 per cent for a fivefold difference in rating.

This is arithmetic rather than a finding about equipment, but it is arithmetic that specification decisions routinely ignore. In tasks where wear is intermittent by nature — moving between housing units, handling animals, working in heat — the binding constraint is the unprotected fraction, and no device addresses it.

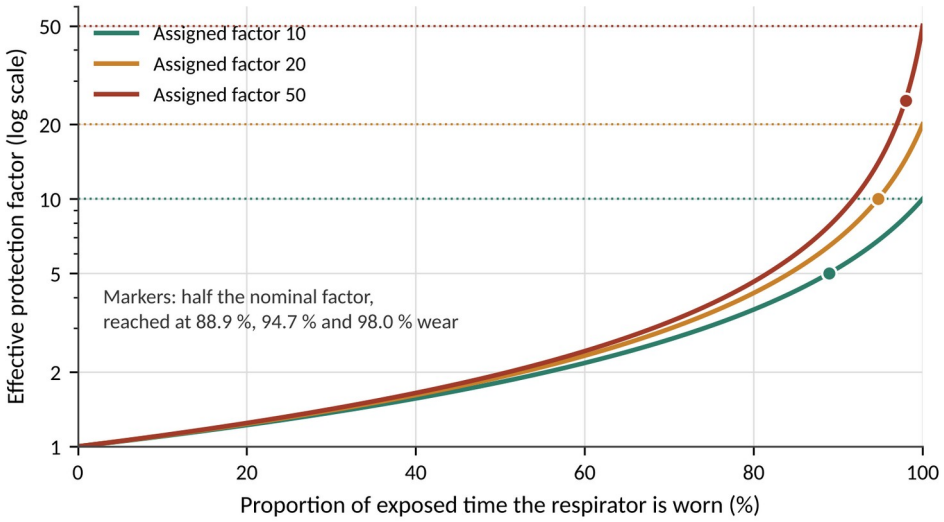


Figure 4. Effective protection factor against the proportion of exposed time the respirator is worn.

Table 4. Effective protection factor by nominal factor and wear compliance.

Wear compliance	Assigned factor 10: effective (% of nominal)	Assigned factor 20: effective (% of nominal)	Assigned factor 50: effective (% of nominal)
0 %	1.00 (10 %)	1.00 (5 %)	1.00 (2 %)
25 %	1.29 (13 %)	1.31 (7 %)	1.32 (3 %)
50 %	1.82 (18 %)	1.90 (10 %)	1.96 (4 %)
75 %	3.08 (31 %)	3.48 (17 %)	3.77 (8 %)
90 %	5.26 (53 %)	6.90 (34 %)	8.47 (17 %)
95 %	6.90 (69 %)	10.26 (51 %)	14.49 (29 %)
100 %	10.00 (100 %)	20.00 (100 %)	50.00 (100 %)

Note. *Wear compliance needed for half the nominal factor: 88.9 % at factor 10, 94.7 % at 20, 98.0 % at 50.*

3.4 Controls compared

Table 5 and Figure 5 apply control options to a workplace with a geometric mean of 120 EU/m^3, which exceeds the limit on 61.0 per cent of shifts.

Improved ventilation reducing the geometric mean by 40 per cent lowered exceedance to 41.4 per cent. A respirator of factor 10 worn 60 per cent of the time lowered it to 31.7 per cent; the same device worn 95 per cent of the time lowered it to 5.5 per cent. The combination of ventilation and high wear compliance reached 1.8 per cent.

Only the configurations involving high wear compliance came close to a 5 per cent exceedance target. The ventilation improvement modelled here was substantial and by itself insufficient, which reflects how high the uncontrolled concentrations are rather than any weakness of engineering control in principle.

The relevant comparison for programme design, though, is between a control that works regardless of behaviour and one that depends on it. Ventilation delivers its effect to every worker on every shift; the respirator delivers its stated effect only under a wear discipline that the literature suggests is rarely sustained in this sector.

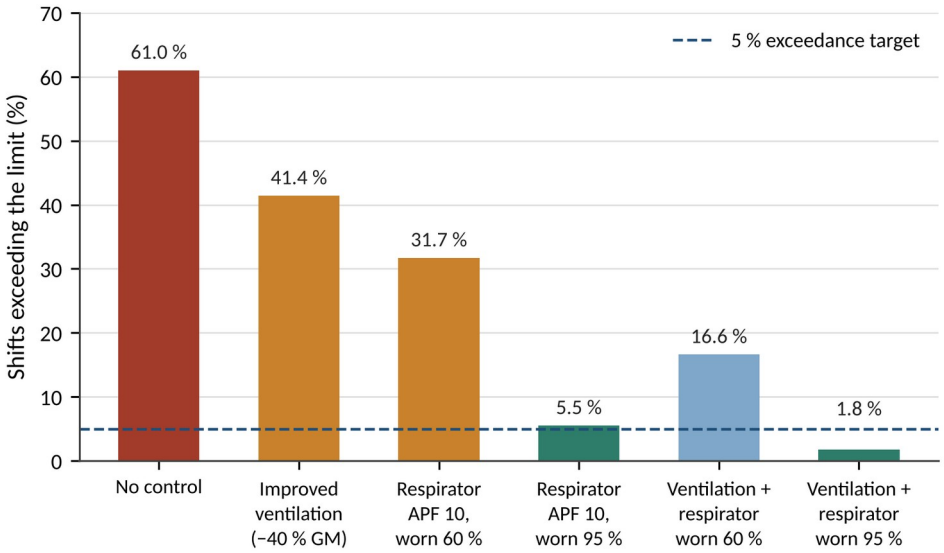


Figure 5. Proportion of shifts above the limit under six control configurations.

Table 5. Control configurations compared.

Configuration	Geometric mean (EU/m³)	Arithmetic mean (EU/m³)	95th percentile (EU/m³)	Shifts above the limit
No control	120.0	203.9	653	61.0 %
Improved ventilation (−40 % GM)	72.0	122.3	392	41.4 %
Respirator APF 10, worn 60 %	55.2	93.8	300	31.7 %
Respirator APF 10, worn 95 %	17.4	29.6	95	5.5 %
Ventilation + respirator worn 60 %	33.1	56.3	180	16.6 %
Ventilation + respirator worn 95 %	10.4	17.7	57	1.8 %

Note. *APF, assigned protection factor; GM, geometric mean.*

3.5 Cumulative career exposure

Table 6 and Figure 6 give cumulative exposure over a 40-year career. Relative to the uncontrolled workplace, ventilation alone reduced it to 59.9 per cent, the respirator at 60 per cent wear to 46.0 per cent, the respirator at 95 per cent wear to 14.5 per cent, and the combination to 8.7 per cent.

Cumulative exposure is the appropriate metric for the chronic outcomes — accelerated lung function decline and chronic bronchitis — that motivate control in this setting, since those relate to dose integrated over a working life rather than to any single shift [25,26]. It gives a different ordering emphasis from shift exceedance: the respirator at 60 per cent wear looks better on cumulative exposure than on exceedance, because it reduces the bulk of routine exposure while leaving the tail.

Neither metric alone is sufficient. Acute responses follow peak exposures and are captured by exceedance; chronic airway disease follows cumulative dose. A control programme monitored only on exceedance would undervalue partial respirator use, and one monitored only on cumulative dose would miss the peaks that produce acute illness.

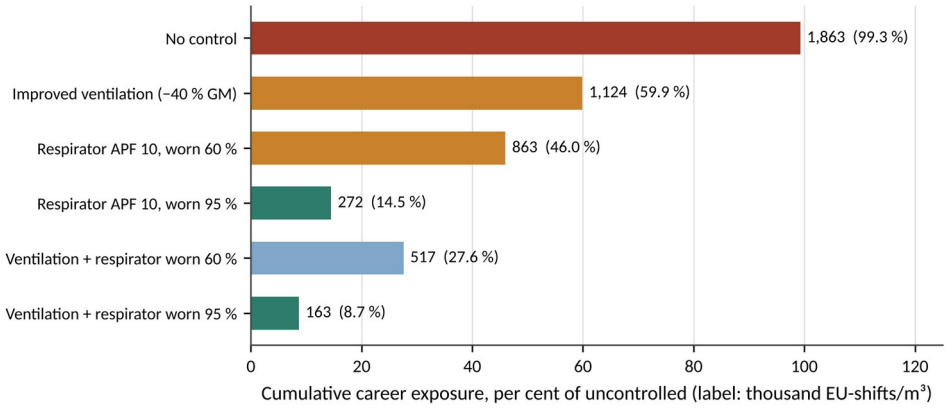


Figure 6. Cumulative career exposure under each control configuration.

Table 6. Cumulative career exposure.

Configuration	Cumulative exposure (thousand EU-shifts/m³)	Per cent of uncontrolled	Shifts above the limit
No control	1,863	99.3 %	61.0 %
Improved ventilation (−40 % GM)	1,124	59.9 %	41.4 %
Respirator APF 10, worn 60 %	863	46.0 %	31.7 %
Respirator APF 10, worn 95 %	272	14.5 %	5.5 %
Ventilation + respirator worn 60 %	517	27.6 %	16.6 %
Ventilation + respirator worn 95 %	163	8.7 %	1.8 %

Table 7. Recommendations.

Recommendation	Addresses	Cost	Evidence here
Assess compliance on an exceedance or percentile criterion	A compliant mean with frequent exceedance	None; a rule change	Section 3.1
Use a tolerance-limit rule even with few samples	Small-sample mean testing that cannot detect a bad workplace	None; a calculation	Section 3.2
Record wear compliance whenever respirators are credited	Protection credited at a factor not delivered	Observation	Section 3.3
Do not upgrade device rating without securing wear time	A higher factor needing higher wear to pay	None; a sequencing decision	Section 3.3
Prioritise engineering control that does not depend on behaviour	Protection contingent on individual compliance	Capital investment	Sections 3.4, 3.5
Report exceedance and cumulative exposure together	Acute and chronic risks captured by different metrics	None	Section 3.5

4. Discussion

4.1 Principal findings

Three findings follow. A workplace whose arithmetic mean sits at the limit exceeds it on 30.3 per cent of shifts, and holding exceedance to 5 per cent requires a mean 3.2 times lower. A workplace exceeding the limit on 40 per cent of shifts passed a sample-mean test on 48 per cent of occasions with three samples and 8 per cent with fifty, while a tolerance-limit rule identified it correctly on 96 per cent of occasions with three. And a respirator of factor 10 worn half the time delivered 18 per cent of its nominal protection, with the wear needed for half the nominal factor rising from 89 to 98 per cent as the rating rises from 10 to 50.

The three share a structure. In each case a summary quantity — the mean, the sample mean, the assigned protection factor — stands in for a distribution, and the substitution fails in the same direction, understating exposure and overstating control.

4.2 Relation to existing work

Exposure to organic dust and endotoxin in animal housing and its respiratory effects are well established, with consistent findings of accelerated lung function decline and increased chronic bronchitis among pig and poultry workers [4–7,27]. Health-based limits for endotoxin have been proposed and debated [10,11]. The lognormal character of occupational exposure and the consequences for compliance assessment are foundational occupational hygiene, and tolerance-limit approaches are long established in that literature [12,13,19,20]. The gap between assigned and workplace protection factors, and the dominance of wear time, are documented in the respiratory protection literature [28–30].

None of the individual results is novel to specialists in exposure assessment. What we offer is their combination and quantification in an agricultural context, where monitoring is sparse, sample sizes are small, holdings are not covered by the industrial hygiene infrastructure that these methods assume, and respirator wear is difficult. The three effects compound in exactly the settings least equipped to detect them.

4.3 Implications for practice

Table 7 sets out six recommendations. Two deserve comment.

Change the decision rule before increasing the sample size. On these figures a tolerance-limit rule applied to three samples identified an uncontrolled workplace more reliably than a mean rule applied to fifty. For small agricultural holdings, where a large sampling campaign is not realistic, this is the single change with the largest effect on whether over-exposure is detected, and it costs nothing beyond the calculation.

Treat wear compliance as part of the control specification. Where a respirator is relied upon, the protection credited should reflect observed wear rather than the assigned factor, and the effort should go into making sustained wear feasible — task design, rest breaks, device comfort in heat — rather than into a higher-rated device. The arithmetic in Equation 3 makes the latter a poor investment while wear remains intermittent.

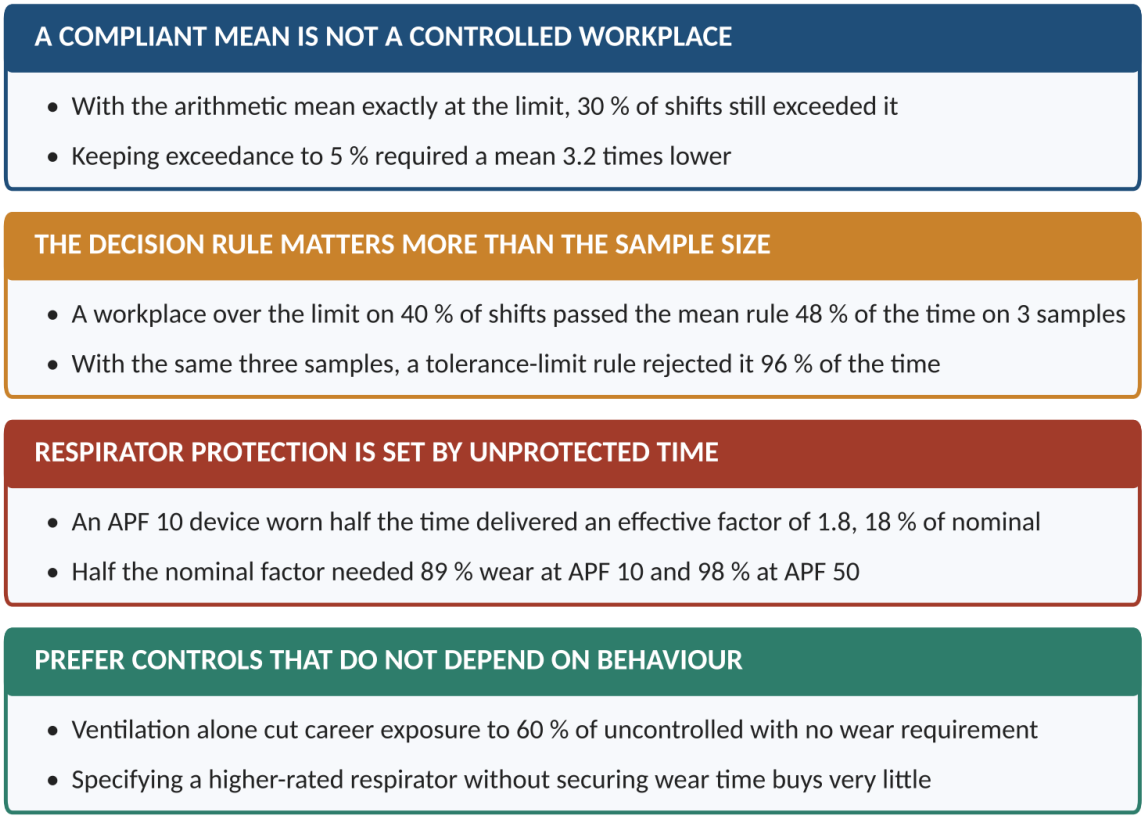


Figure 7. Proposed practice for exposure assessment and control in livestock housing.

5. Limitations

Exposures are modelled as independent lognormal draws with a single geometric standard deviation. Real exposures are autocorrelated within workers and across days, differ systematically between tasks and seasons, and combine a within-worker and a between-worker component [12]. A mixed model would give different and generally wider tail behaviour, so our exceedance figures are conservative in that respect.

We model endotoxin alone as a marker for the wider organic dust mixture. Ammonia, hydrogen sulphide, respirable dust and microbial components each contribute to the airway response, they are imperfectly correlated with endotoxin, and a control that reduces one may not reduce another proportionally.

The effective protection expression assumes that exposure is the same whether or not the device is worn. In practice respirators are more likely to be worn during the highest-exposure tasks, which would make intermittent wear more effective than we report; equally, they are removed in heat and exertion, which may coincide with dusty work. We have not modelled that correlation in either direction.

The ventilation effect is imposed as a fixed proportional reduction in the geometric mean, with no change in variability. A real ventilation improvement may reduce peaks more than the mean, or less, and the exceedance result depends on which.

Finally, we do not model a health outcome. Cumulative exposure is reported as an index rather than converted into lung function decline or disease incidence, because the exposure–response relationships carry substantial uncertainty and combining them with an illustrative exposure model would give a false impression of precision.

6. Conclusion

In confined livestock housing, exposure variability makes a mean-based compliance statement a weak guarantee. A workplace whose arithmetic mean sat exactly at the endotoxin limit exceeded it on 30 per cent of shifts, and restricting exceedance to 5 per cent required a mean 3.2 times lower.

Compliance testing compounded the problem. A workplace exceeding the limit on 40 per cent of shifts passed a sample-mean test half the time on three samples and 8 per cent of the time on fifty, while a tolerance-limit rule on three samples identified it correctly on 96 per cent of occasions.

Respiratory protection failed in the same direction. A device rated at factor 10 worn half the exposed time delivered 1.8, and the wear needed to realise half the nominal factor rose with the rating, so specifying a better device without securing wear time buys very little. Engineering control, which does not depend on individual behaviour, reduced career cumulative exposure to 60 per cent of uncontrolled on its own, and remains the intervention whose effect does not have to be earned on every shift.

Declarations

Ethics approval and consent to participate. Not applicable. This study used entirely synthetic data generated by the author. No workers, animals, human participants, samples or records were involved, and no workplace data were accessed. Institutional review board and ethics committee approval were therefore not required.

Consent for publication. Not applicable.

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Conflicts of interest. The author declares no conflicts of interest, financial or non-financial, in relation to the subject matter of this manuscript. The author has no financial or advisory relationship with any manufacturer of respiratory protective equipment, ventilation systems or air sampling instrumentation.

Data and code availability. No real-world data were used in this study. All results were generated by the model described in Section 2, with every parameter stated in Table 1 and fixed random seeds; every figure and every value in Tables 2 to 6 can be regenerated exactly from it. The simulation script is available from the corresponding author upon reasonable request.

Author contributions. Devendra Kumar Durgam is the sole author of this work and was responsible for the conception and design of the study, development of the exposure and compliance model, implementation of the simulation, analysis and

interpretation of the results, preparation of the figures and tables, formulation of the recommendations, and drafting, revision and final approval of the manuscript. The author is accountable for all aspects of the work.

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