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Results are presented of field determinations of effectiveness (workplace protection factor; WPF) and acceptability (questionnaire responses) by respirator users in indoor swine production, poultry production, and grain handling facilities. Dust mass and endotoxin in air samples collected over 4 hours outside the mask and inside the mask were compared to yield the WPF. Disposable respirators had a mean WPF of 13; quarter-mask respirators, 22; half-mask respirators, 19; and powered air purifying helmets, 30. These values are generally less than laboratory-based measures of effectiveness but similar to other field data. Acceptability among these four classes of respirators varied among the three user groups: poultry operators preferred the powered helmet; grain handlers preferred the half-mask; and swine producers were split between the quarter-mask and half-mask respirators. Fully disposable masks were preferred by only 20 to 22 percent of the workers in each setting. Among all groups of workers, powered helmets were rated best for breathing ease, communication ease, skin comfort, and in-mask temperature and humidity, while disposables were rated best for weight and convenience. However, in all but one of the above acceptability characteristics, the opposite respirator was given the worst rating. Thus, the reusable quarter-mask or half-mask is most often the best compromise. POPENDORF, W.; MERCHANT, J.A.; LEONARD, S.; BURMEISTER, L.F.; OLENCHOCK, S.A.: RESPIRATOR PROTECTION AND ACCEPTABILITY AMONG AGRICULTURAL WORKERS. APPL. OCCUP. ENVIRON. HYG. 10(7):595–605; 1995.

Respiratory health hazards from organic dust in modern livestock production settings were first recognized in the agricultural literature around 1975.[1] Interest increased when endotoxin (similar to that on cotton dust) was detected in aerosols surrounding grain handling and poultry and swine production workers.[2–4] Medical assessments of the effect of these aerosols (and in most cases gases as well) on the respiratory health of farmers began during the mid-1980s.[5–7] Recent industrial hygiene evaluations of these buildings has shown poor air quality to be more frequent than expected.[8,9]

The health implications of repeated and progressively prolonged occupational exposures to poor air quality commensurate with increasing agricultural specialization will eventually require the long-term implementation of better engineering controls and production management practices.

The use of respirators is a logical short-term intervention control option because of the generally diffuse nature of the sources, the mobile activities of the production workers, and the marginal efficiency and effectiveness of current engineering controls for these on-farm hazards. On the other hand, the widespread use of respirators by farmers is hindered by the lack of knowledge within the agricultural community concerning chronic respiratory health risks; the inaccessibility of knowledgeable respirator suppliers in rural areas; and the lack of supervisory, economic, organizational, or regulatory incentives within the industry.[6] As a first step to improve this situation, it seemed fitting to investigate both the effectiveness and acceptability of respirators that might be used in these settings.

Over the years, the effectiveness of respirators has been variously referred to as the ratios of concentrations, percent penetration, efficiency, leakage, performance factor, protection factor, etc. Most current terms are variations of protection factors (PFs), and all are now ratios of the contaminant concentration outside the respirator to that inside. The quantitative fit factor (QFF) is a generic term for this ratio when measured in the laboratory.[10–12] An assigned protection factor is the minimum (lowest 5%) level of protection determined from laboratory tests.[12,13] A separate nomenclature has been developed to describe respirator effectiveness when measured in the field. The workplace protection factor (WPF) has been defined as protection "only while the respirator is properly worn and used during normal work activities," and should be clearly differentiated from an effective protection factor (EPF), which is measured "when [the respirator] is worn for only some fraction of the total exposure period in the workplace."[10,11]

While no published surveys of the qualitative acceptability of respirators were found, interest in the quantitative effectiveness of respirators dates back to at least 1926.[14] However, nearly all of the early published studies of respiratory protection effectiveness were conducted in laboratory settings. Most of these published laboratory test data have been converted into quantitative fit factors and compiled in Table 1. A passing reference to a respirator effectiveness field test as early as 1938[27] was found in the literature.[28] However, the earliest field data found were from 1972.[29] The published field data reported as other ratios were converted into PFs (assuming users were properly trained and fitted); some were adjusted from EPF to WPF; and all were compiled in Table 2. By comparing the summaries of the laboratory data (a simple geometric mean PF of 144) and field data (a simple geometric mean PF of 12) as shown at the bottom of these tables, it was hypothesized at the outset of this study that at least half-mask

TABLE 1. A Compilation of Reported Respiratory PFs Determined from Laboratory Tests

	Challenge			Protection			
Reference	**Physical Form**[A]	**Chemical Form**	**Type Mask**[B]	**Geom. Mean**	**Geom. Dev.**	**No. of People Tested**	**Comments**
Katz *et al.*[15]	A	Pb mist	H	31	3.0	14	
	A	Si mist	H	2.4	1.3	10	
Burgess *et al.*[16]	A	Uranine	H	209	2.05	9	
	A	Uranine	F	1020	5.0	10	
Letts[17]	A	b. spores	H	500			At rest
Adley and Wisehart[18]	G	Freon	H	21	3.2	7	Mean of mid-range
	G	Freon	F	2330	3.0	7	
	G	Freon	F	23	2.8	7	
Guyton and Decker[19]	A	Bacteria	D	3.4	1.15	4	ca. 3M 8500
Hounam *et al.*[20]	A	NaCl	H	31	5	?	Initial position
	A	NaCl	H	3300	1.5	?	After adjustment
White and Beal[21]	A	NaCl	H	>200	4–5	10	MSA self-fit
Hyatt *et al.*[22]	A	DOP	H	333		52	Median
	A	DOP	H	125		36	Median
	A	DOP	H	400		57	Median
	A	DOP	H	500		43	Median
	A	DOP	H	100		32	Median
Hyatt *et al.*[23]	A	NaCl	H	18	5.8	32	With beards
Revoir[24]	A	Coal	D	17	1.35	6	Non-apprv. one-strap
	A	Coal	D	111	4.0	6	Non-apprv. pleated
	A	Coal	D	85	2.8	6	Apprv. two-strap with exhal-valve
Hardis *et al.*[25]	A	DOP	H	280	5.2	195	Neg. press. QFT
	A	DOP	H	415	5.0	179	Irrit. smoke QFT
	A	DOP	F	4350	8.2	265	Both grouped
Thind and Hosein[26]	A	SiO_2	P-Hel	15	2.35	8	Racal AH-5 on a mannequin

Summary of the above prior tests (for approved respirators, worn without beards, with determinant results) and a comparison with the results of the current mass WPF:

	Simple Geom. Mean	**Geom. Dev. of Means**	**Number of Means**	**Range of Means**	**Percent Means Less Than This Study**
Disposable	17	9.7	2	3.4–85	50
Unpowered half-masks	144	6.0	14	2.4–3300	14
Powered helmets	15	—	1	—	100

[A]Physical form of the respirator challenge: A = aerosol; G = gaseous (gas or vapor).
[B]Type of facepiece being worn: D = disposable; F = full mask; H = half-mask; P-F = powered full mask; P-H = powered half-mask; P-Hel = powered helmet.

respirators may not perform as well in actual field use as they did in the lab.

Experimental Methods

Respirator Selection

Respirators from the three classes listed in Table 3 were chosen as representative of the widest range of respirators expected to find common utility in agricultural workplaces. The particular respirators within each class were chosen largely on the basis of their structural integrity to support an in-mask sampling port and filter, their commercial availability to agricultural workers, and, in the case of half-masks, their range of sizes.

Cohort Selection

Respirators were studied in three agricultural work areas known to have relatively high dust exposures (see Table 4). Swine producer participants were recruited selectively by mail and phone and screened by size of operation, work exposure time, and proximity to Iowa City. Fifty participants were enrolled from 17 eastern Iowa swine producers, including cooperatives, corporation-owned farms, and family farms. Participants per farm ranged from one to four. Grain handling sites listed by the Iowa Development Commission were contacted in a similar manner. Forty-six participants were enrolled at eight sites. Work sites tested were feed mills, grain elevators, and seed corn plants.

Poultry confinement operators who regularly spend a minimum of 4 hours working in the confinement buildings were difficult to locate. Working exposures in layer operations of up to 50,000 birds (and even larger turkey operations) typically last 1 hour or less over one or two daily intervals to gather eggs and check birds. This pattern limited possible test sites to only large facilities, and even then test exposures ranged from 1 to

TABLE 2. Compilation of Reported Respiratory PFs Determined from Field Tests

	Challenge			Protection			
Reference	Physical Form[A]	Chemical Form	Type Mask[B]	Geom. Mean	Geom. Dev.	No. of People Tested	Comments
Reist *et al.*[29]	A	Coal	H	3.3	1.65	32	Median EPF for mask 22
Harris *et al.*[30]	A	Coal	H	[3.2]	[1.55]	187	EPF
	A	Coal	H	3.7[C]	[1.55]	187	WPF assuming D=2
	A	Coal	H	7.0[C]	[1.55]	187	WPF assuming D=5
	A	Coal	H	32[C]	[1.55]	187	WPF assuming D=30
Revoir[31]	A	Cotton	D	13	1.4	5	Non-appr. one-strap
	A	Cotton	D	43	1.6	6	Non-appr. pleated
	A	Cotton	D	32	2.0	5	Appr. two-strap with exhaust-valve
Moore and Smith[32]	G	SO_2	H	15	1.4	26	Median WPF
	G	SO_2	H	14	1.4	25	Median WPF
	G	SO_2	H	10	1.4	25	Median WPF
Toney and Barnhart[33]	G	Solvent	H	4.3	2.3	20	AO-5051, Devilbiss, and MSA Comfo-II
	A	Paint	H	5.5	2.5	16	Ditto
	A	Paint	H	>9.8[D]	4.2[D]	20	Ditto
Smith *et al.*[34]	A	Cd fume	H	[5.6]	[1.41]	[9]	EPF
QueHee and Lawrence[35]	A	Pb, Zn, Cu	P-Hel	17	3.0	7	Racal AH-3 WPF
	A	Fume	P-Hel	30	6.6	8	Racal + one WPF=1500
Myers and Peach[36]	A	SiO_2	P-H	49	2.4	7	
	A	SiO_2	P-F	66	3.0	3	
Fergin[37]	A	Mass	D	20	1.6	4	3M 8706/no beard
	A	Mass	D	16	4.5	28	3M 9910/no beard
	A	Mass	D	159	4.2	18	3M 9906/no beard
	A	Mass	D	17	1.7	6	3M 8706 with beard
	A	Mass	D	22	3.8	12	3M 9910 with beard
	A	Mass	D	198	2.1	7	3M 9906 with beard
Lenhart and Campbell[38]	A	Pb dust	H	180	4.1	25	
	A	Pb dust	P-H	380	2.6	25	
Reed *et al.*[39]	A	Mass	D	18	5.8	19	3M 9910

Summary of the above prior tests (for approved respirators, worn without beards, with determinant results) and a comparison with the results of the current mass WPF:

	Simple Geom. Means	Geom. Dev. of Means	Number of Means	Range of Means	Percent Less Than This Study
Disposable	35	2.8	4	16–159	0
Unpowered half-masks	12	3.8	7	3.3–180	86
Powered helmets	30	—	1	—	—

[A]Physical form of the respirator challenge: A = aerosol; G = gaseous (gas or vapor).
[B]Type of facepiece being worn: D = disposable; F = full mask; H = half-mask; P-F = powered full mask; P-H = powered half-mask; P-Hel = powered helmet.
[C]WPF estimated from EPF with reported fraction of time respirator is not worn (f) and various assumed ratios of concentration while worn versus not worn (R) in the following equation from Reference 44.

$$WPF = \left[\frac{EPF\,R\,(1 - f)}{(R - f\,R + f) - EPFf}\right]$$

[D]Including four PFs = 100 percent after 10 minutes' exposure to aerosol reported by Toney and Barnhart[33] as [1 − (Cin/Cout)] × 100; corresponding WPF was assumed to equal 100.

4 hours. Participants were recruited from members of the Iowa Egg Council and the Iowa Turkey Federation. A total of 20 participants in 4 egg laying and 2 turkey finishing operations were enrolled. Participants per farm ranged from two to four.

A modified respirator evaluation was conducted by a total of 12 people on 5 dairy farms during silo uncapping and unloading operations. Evaluations during silo uncapping were desired because it is generally believed to be one of the dustiest operations on farms.[40] However, because the episodic nature of silo uncapping precluded the repeated testing protocol used in other settings, only single-day WPF data were generated. Such data were later included in environmental and WPF tables and summaries but excluded from acceptability tables and comparative analyses.

TABLE 3. The Three Classes of Respirators Tested, Descriptions, and Their Coding for This Study

Class	Code	Description
Disposable	21	3M 9920 particulate half-mask with exhaust valve
Quarter-mask	22	MSA "Dustfoe 77"™, a reusable quarter-mask facepiece with a single internal disposable particulate filter
Half-mask*	31	North 7700, a reusable HEPA cartridge respirator
	32	MSA Comfo II™, a reusable HEPA cartridge respirator
	33	Willson 1200™, a reusable HEPA cartridge respirator
Powered air purifying helmet	41	Racal AH15 Airstream™ battery-powered air purifying helmet
	42	3M W316 Airhat™ battery-powered air purifying helmet

*With ammonia cartridge and dust prefilter for animal confinement operators and only high efficiency filter for grain handlers.

Survey Schedule

In all settings except dairies, each participant was tested for 4 days: during one day (a control day) no mask was provided; on the other three days, one respirator from each of the three classes was worn. The order of respirator class (including no respirator) was randomized over the 4 days of testing. Brands within respirator class were also randomly assigned. The negative pressure respirators were fit tested using a 3M qualitative saccharin fit test kit to assure proper fit; if the assigned brand did not pass the fit test, the alternate brand was fit tested and worn.[41]

Testing was generally conducted over four sequential days, Monday through Thursday or Tuesday through Friday. Six employees completed only 3 days of testing for various reasons, both related and unrelated to work; the missing days were reasonably spread among their days with each respirator class. Of approximately 116 study participants, 14 who usually wore a respirator were unwilling to work without a mask and thus wore their own respirator on the control day.

Respirator Effectiveness

Qualitative (subjective) evaluations were conducted by each participant on each respirator at the end of each respirator test day via scaled (1 to 9) responses to a standardized series of 11

TABLE 4. Lognormal Summary Statistics for Levels of Airborne Contaminants.

	Dust (mg/m^3)			Endotoxin (EU/m^3)			Endotoxin on dust (EU/mg)		
	Geom. Mean	Geom. Dev.	No. of Samples	Geom. Mean	Geom. Dev.	No. of Samples	Geom. Mean	Geom. Dev.	No. of Samples
Intersample summary statistics									
All settings	5.5	4.1	221	218	6.35	456			
Grain	3.75	4.6	67	105	7.6	170	56.2	4.2	64
Poultry	5.5	2.9	56	408	4.8	76	85.2	2.7	56
Swine	4.6	2.2	86	269	4.1	198	57.5	2.3	86
Dairy	136	5.5	12	4280	8.2	12	31.5	3.8	12

	Dust Geom. Dev.	Dust No. of People	Endotoxin Geom. Dev.	Endotoxin No. of People	Endotoxin on dust Geom. Dev.	Endotoxin on dust No. of People
Intrapersonal, interday variability						
Grain	2.36*	25	3.31*	47	2.27*	25
Poultry	3.00	20	3.82*	20	2.02*	20
Swine	1.99	30	3.26*	51	2.19	30
Dairy	—	—	—	—	—	—

	Dust Geom. Dev.	Dust No. of Days	Endotoxin Geom. Dev.	Endotoxin No. of Days	Endotoxin on dust Geom. Dev.	Endotoxin on dust No. of Days
Intraday, interpersonal variability						
Grain	2.95*	21	3.62*	47	2.12*	21
Poultry	2.49	24	2.86*	25	1.75*	24
Swine	2.29	39	3.36*	64	1.82*	39
Dairy	6.03	3	6.00	3	1.38*	3

*Statistical probability is <0.01 that the intrapersonal or intraday variance is equal to that for all settings.

TABLE 5. Subjective Questions to Which Study Participants Responded on a Scale of 1 (Unfavorable) to 9 (Favorable)

1. Breathing ease	How easy was it for you to breathe while you wore this respirator?
2. Communication ease	How easy was it for you to communicate with others while you wore this respirator?
3. Range of vision	How much was your range of vision obstructed by the respirator facepiece? (Do not consider obstruction caused by the filter cassette.)
4. Eye comfort	Did you experience eye irritation, itching, or other eye discomfort while you wore this respirator?
5. Skin comfort	Did you experience itching or other skin irritation while you wore this respirator?
6. Odor control	Did you notice that odors were eliminated or weaker while you wore this respirator?
7. In-mask temperature and humidity	Did you feel that the respirator became uncomfortable because of moist or hot air inside the facepiece?
8. Face and head fit	How well do you feel this respirator fit your head and face shape? (Consider if any slipping, pinching, or air leaks occurred around your face.)
9. Weight	Do you think this respirator is too heavy to be worn comfortably for a full work day?
10. Convenience	How easy was it for you to put on and remove the respirator?
11. Overall comfort	How would you rate this respirator overall for comfort and acceptability?

questions (see Table 5). At the end of the 4 days, the participants were also asked which respirator they most preferred (they were not provided retail cost figures).

Quantitative WPFs were determined by air sampling for dust mass and endotoxin concentration. Personal total dust samples were collected from the breathing zone of each person on each of the 4 days of testing on 37-mm polyvinylchloride filters (DM800 and VM-1) housed in closed-face two-piece cassettes attached to personal air sampling pumps. Flow rates in the study were set near 1.5 L/min. When dust levels were high, these filters were changed as frequently as hourly to prevent the dust sample from accumulating and being dislodged from the filter.

On days when respirators were worn, in-mask samples were also collected by fitting a custom-made aluminum probe (patterned after Liu's Inlet II) to the front of the respirator.[42] Aluminum was found to be adequately sturdy and one-third the weight of stainless steel. A second 37-mm filter cassette was attached to the probe outside the respirator and to a second personal air sampling pump whose flow rate and running time were set to match the breathing zone sample.

A preliminary study of two farms showed that excess moisture from respiration accumulated in the in-mask sampling line behind disposable and half-mask respirators, creating problems with wet filters, excessive pressure drops through the sampling line, inconsistent air flow rates, and damage to air sampling pumps. Changing in-mask cassettes frequently, usually at 1 to 2-hour intervals, was found to alleviate moisture accumulation on the filter, but adding a silica gel-filled moisture trap between the cassette and air sampling pump was also used to minimize moisture accumulation in the sampling tube and pump.

Filters were preweighed and postweighed to the nearest 0.001 mg initially on a Cahn model 20 balance and later on a Cahn 31 balance. Before each weighing, all test filters and six control filters were equilibrated to laboratory air (but protected from dust) for a minimum of 12 hours. The six control filters were weighed with the test filters throughout the study to allow a correction in weight changes due to ambient humidity levels. Used filters were refrigerated before and after postweighing prior to endotoxin analysis using the microtiter method of the *Limulus* amebocyte lysate assay.[43]

Results and Discussion

Lognormal summary statistics for airborne dust and endotoxin concentrations are presented in Table 4. Similar statistics for the quantitative performance of respirators expressed as WPFs [calculated as the ratio of simultaneously measured outside (ambient) versus inside mask concentrations] are presented in Table 6. Median subjective response statistics are summarized in Table 7. Overall preferences to respirators are summarized in Table 8.

The mean environmental conditions in Table 4 were first compared vertically among grain, poultry, and swine operations. The median total dust levels of $\approx$4 to 5 mg/m^3 in these settings would generally be considered quite high for organic dust, but the dust levels during dairy silo operations (at over 100 mg/m^3) are clearly over an order of magnitude higher. The first three working conditions were found to be statistically similar to each other but quite different from the few dairy operations observed, as expected, further justifying their separate treatment herein.

The geometric deviations in Table 4 indicate the magnitude of intersample variability caused by different farms or plant settings, different subtasks from day to day, different people doing ostensibly the same job, and sample imprecision. The intersample geometric deviations among dust concentrations were somewhat less in poultry and swine settings (at 2 to 3×) than among grain and dairy settings (4.5 to 5.5×), reflecting the relative uniformity among generally mechanically ventilated, farm-based processes compared to differences among naturally ventilated silos and grain handling operations at different companies. The most variability was found while uncapping or unloading naturally ventilated (at best) silos suffering from different degrees of feed mold and decay.

Analyses of variance were performed to determine the geometric deviations both within individuals among the 4 days they were monitored and within the same day among individuals at the same farm or work site. (Again, no repeated individual measures of exposure were collected for dairy workers.) As shown in the bottom portion of Table 4, dust variability was significantly less between days or work sites only among grain handlers, reflecting the fact that in other settings variations within jobs and conditions cause frequent variations

TABLE 6. Lognormal Summary Statistics for WPFs

	Dust WPF			Endotoxin WPF		
	Geom. Mean	Geom. Dev.	n	Geom. Mean	Geom. Dev.	n
Disposable						
All settings and times[A]				6.0	14	113
All settings before Oct 3[B]	16	5.1	73			
Excluding dairy all times				3.3	12	104
Excluding dairy before Oct 3	13	4.1	69	5.0	14	67
Grain	12	5.1	22	5.1	9.0	21
Poultry	18	4.2	18	38	22	18
Swine	11	3.3	29	1.3	5.0	28
Dairy	507	4.6	4	778	5.8	4
Half-masks						
All settings and times				9	12	112
All settings before Oct 3	20	4.3	74			
Excluding dairy all times				6.1	10	100
Excluding dairy before Oct 3	19	4.3	70	8.9	10	67
Grain	14	4.8	23	7.9	8.0	20
Poultry	33	3.4	18	73	12.1	18
Swine	18	4.4	29	2.6	3.8	29
Dairy	58	1.9	4	328	5.4	4
Powered helmet						
All settings and times				31	8.4	117
All settings before Oct 3	30	4.9	73			
Excluding dairy all times				20	8.0	96
Excluding dairy before Oct 3	27	4.8	69	33	7.4	69
Grain	33	6.7	22	42	6.4	22
Poultry	28	2.7	19	137	5.6	19
Swine	23	5.0	28	10.2	5.0	28
Dairy	193	3.3	4	521	3.7	4

	Dust WPF			Endotoxin WPF		
	Geom. Mean	Geom. Dev.	n	Geom. Mean	Geom. Dev.	n
[A]All settings and times						
Respirator 21				4.3	15	58
Respirator 22				8.5	12	55
[B]All settings before oct 3						
Respirator 21	11	4.7	39			
Respirator 22	22	5.4	34			

in exposures both day-to-day and among co-workers at the same farm.

Median airborne endotoxin concentrations in Table 4 show a trend by work setting generally similar to dust, varying from ≈100, 270, and 400 endotoxin units/m^3 (EU/m^3) for grain, swine, and poultry, respectively, while dairy silos were near 4300 EU/m^3. The geometric mean endotoxin-on-dust concentration was not significantly different among the various settings studied and ranged from 31 to 85 EU/mg.

Analyses of variance indicated that the endotoxin concentrations were generally significantly less variable from day to day for a given person (intrapersonal, except for EU/mg in swine) and within settings on a given day (intraday, except for EU/m^3 in dairy silos). The geometric deviation of airborne endotoxin concentration (EU/m^3) within each setting was about 65 percent greater than the variability within airborne dust levels, almost exactly what would be expected by propagation of error theory from the random variabilities of dust concentration and measured endotoxin on the dust endotoxin units per milligram (reported in the right-most set of columns in Table 4).[44] The slight differences between statistical theory and observation suggest that slight (but statistically insignificant) positive correlations between dust concentration and endotoxin-on-dust existed in grain and

TABLE 7. Median Response to Each Subjective Question in Table 5, Listed by Respirator Class and Agricultural Operation

	Disposable			Half-Mask			Powered Helmet		
	All	1	2	All	1	2	All	1	2
1. Breathing ease									
All settings	6.1[A]	6.0	6.2	7.1[A]	7.1	7.2	8.2[A]	8.2	8.2
Grain	6.0			7.2			8.3		
Poultry	6.0			6.4			8.2		
Swine	6.2			7.2			8.1		
2. Communication ease									
All settings	3.4[A]	5.1[A]	2.1[A]	2.1[A]	2.5	2.0	4.5[A]	5.6[A]	3.6[A]
Grain	4.0			2.0			3.8[B]		
Poultry	5.0			3.0			6.3[B]		
Swine	2.9			1.9			4.0[B]		
3. Range of vision									
All settings	6.7[B]	7.4[A]	5.5[A]	6.7[B]	6.7	7.1	5.7[B]	5.4	6.1
Grain	6.2			7.3			6.1		
Poultry	7.3			7.2			7.0		
Swine	6.8			6.3			5.1		
4. Eye comfort									
All settings	8.1	8.1	8.2	8.1	8.1	8.2	8.1	8.2	8.2
Grain	8.0			8.3			8.2		
Poultry	8.1			8.1			8.2		
Swine	8.2			7.7			8.0		
5. Skin comfort									
All settings	6.1[A]	5.5	7.2	6.7[A]	7.4	6.4	7.8[A]	8.0	7.8
Grain	5.7			7.0			8.0		
Poultry	7.0			6.5			8.2		
Swine	6.3			6.7			7.4		
6. Odor control									
All settings	5.7	5.4	6.1	6.7	6.4	6.8	6.2	6.4	6.2
Grain	5.4			5.8			6.1		
Poultry	6.0			7.0			6.5		
Swine	6.1			7.2			6.1		
7. In-mask temperature and humidity									
All settings	4.1[A]	3.1[A]	5.3[A]	4.4[A]	5.0	3.7	7.1[A]	7.4	7.0
Grain	4.6			4.3			6.5		
Poultry	2.8			3.0			7.5		
Swine	3.8			5.0			7.3		
8. Face and head fit									
All settings	6.6	6.7	6.7	6.9	7.4[A]	6.2[A]	6.8	7.0	6.8
Grain	6.4			7.1			6.5		
Poultry	7.0			5.0			7.6		
Swine	6.7			7.1			6.4		
9. Weight									
All settings	7.1[A]	7.4	6.6	5.6[A]	5.9	5.5	2.5[A]	4.4[A]	1.6[A]
Grain	6.8			6.8[B]			1.9		
Poultry	7.3			3.7[B]			5.0		
Swine	7.2			4.6[B]			2.6		
10. Convenience									
All settings	7.1[A]	7.4	6.7	6.9[A]	6.8	7.1	5.7[A]	6.5[B]	5.0[B]
Grain	7.4			7.4			5.5		
Poultry	7.7			6.3			7.2		
Swine	6.5			6.4			4.8		
11. Overall comfort									
All settings	5.5	5.6	5.6	5.4	6.2[B]	5.0[B]	5.1	6.0	4.6
Grain	5.4			6.0			5.0		
Poultry	5.5			3.7			7.0		
Swine	5.6			5.2			4.6		

[A]Kruskal-Wallis chi-squared $p < 0.001$ among or between corresponding groups.
[B]Kruskal-Wallis chi-squared $p < 0.01$ among or between corresponding groups.

TABLE 8. Preference Votes (n) Reported from N Participants After Wearing One Respirator Within Each Class, Expressed as a Percent of All Classes and Brands, and as a Percent of Those Wearing Each Brand Within a Class

	Disposable			**Half-Mask**			**Powered Helmet**		
Class Brand	**All**	**21**	**22**	**All**	**31**	**32**	**All**	**41**	**42**
All settings									
N	117	64	54	116*	62	52	117	59	58
n preferred	40.5	25	15.5	43.5*	26	16.5	35	25	10
% of all	35	21	13	37*	22	14	30	21	9
% of class		39	29		42	32		42	17
Grain									
N	46	26	20	45	22	23	45	22	23
n preferred	13	10	3	23	14	9	10	6	4
% of all	29	22	7	51	31	20	22	13	9
% of class		38	15		64	39		27	17
Poultry									
N	18	11	7	18	10	8	20	10	10
n preferred	5	4	1	3	1	2	12	7	5
% of all	28	22	6	17	6	11	60	35	25
% of class		36	14		10	25		70	50
Swine									
N	53	26	27	53*	30	21	52	27	25
n preferred	22.5	11	11.5	16.5	11	5.5	13	12	1
% of all	42	21	21	31	21	10	25	23	2
% of class		42	43		37	26		44	4

*Two swine participants could only be fitted with brand 33. One of them subsequently chose it as their preferred class.

dairy settings and slight negative correlations existed in poultry and swine settings.

The quantitative measurements of WPFs in Table 6 are presented in several ways, reflecting both real and methodological artifacts. First, because WPFs in dairy silos were found to be significantly higher than in any other setting, WPFs in settings excluding dairy are shown separately. Second, mass data prior to October 3 are not believed to be reliable. The daily mean control filter weight changes throughout the study are plotted in Figure 1. As can be seen in this figure, the application of high control filter mass adjustments with the balance used prior to October 3 caused a high relative deviation when measuring low aerosol concentrations, particularly affecting within-mask samples and their associated PFs. As a result, only determinations of PFs based on dust mass (referred to herein as WPF_d) determined after October 3 were used in later analyses by setting.

The geometric mean PFs are used to indicate the median characteristic protection available in each combination of setting and respirator class. The median WPF for all settings other than dairy increased progressively in the order expected from disposable to half-mask to powered respirators (i.e., 13, 19, and 27 based on dust mass and 5, 9, and 33 based on endotoxin). Silo unloaders clearly had the highest median WPFs of ≈500, 60, and 190 for disposable, half-mask, and powered helmets, respectively. Among the remaining groups, poultry operators had the highest median WPFs for all nonpowered respirators, especially for WPF_e (that based on endotoxin) where they also had the highest variation.

Probably because of the wide range of WPFs found within each setting, class, and mask, there were no statistically significant differences between or among respirators. The WPF values in Table 6 are generally comparable to previous laboratory and field studies, except that the mean WPF for half-masks was 19 in our study versus 144 for laboratory quantitative fit tests listed at the bottom of Table 1, and the mean WPF for disposable respirators was 13 in our study versus a simple geometric mean (unweighted for n) of 35 in other field studies listed at the bottom of Table 2.

In addition to poor fit (involuntary leakage), there are many

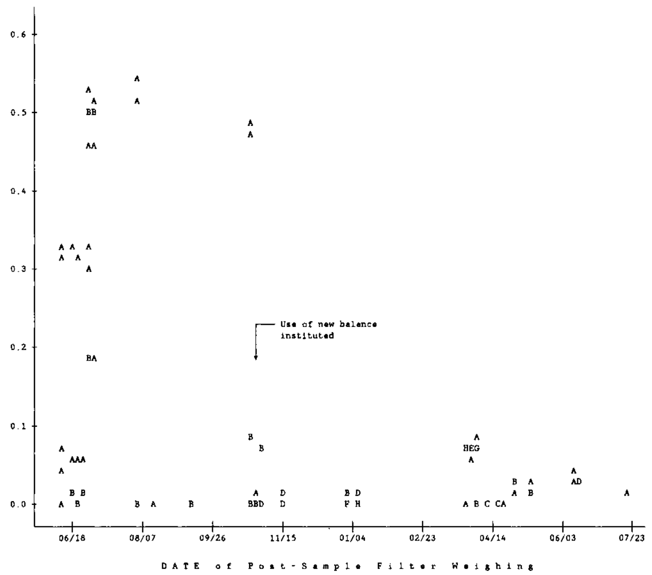

FIGURE 1. Mean control filter weight change (mg) versus time. A indicates 1 data point; B indicates 2 data points; etc.

possible reasons for WPF values to be lower than QFF. Moore and Smith[32] identified respirator strap tension, facial hair, and normal work activities as three subjective factors contributing to low WPF; they also noted an association of WPF with airborne concentration. The agricultural participants herein were instructed on how to adjust their mask at the outset of each day and were asked during the shift if it was still snug or too tight. They were all clean shaven. Work activities varied among the settings but were reasonably consistent within settings, and are therefore not expected to play an associative role in this study. Other possible reasons for low WPF include the effects of in-mask sample probe location and design, in-mask sources of emission, the imprecision of the analytic method, the lack of user compliance with experimental protocols, and the lack of user knowledge or experience with respirators.

The effects of in-mask sample probe location and design have previously been recognized[12,41,45–47], are currently not resolved, are not thought to be of this large a magnitude, and most importantly, should not be significantly different between laboratory and field studies involving aerosols. Internal sources of emission are unlikely to have contributed to sample mass; all in-mask samples collected on nonfarming volunteers in non-farm settings found endotoxin too low to detect, but the remote possibility that habitually exposed workers harbor and release endotoxin should not be overlooked. Based on an analysis of analytic conditions believed to represent most closely those characterizing this study,[44] imprecision was likely to have been a significant factor only in samples from the early stages of the study (before October 3), which were already omitted from Table 6.

User compliance was generally quite good in those circumstances where they could be observed. It did vary slightly among settings and was probably worst among swine producers, who often need to communicate briefly with co-workers. It is known that the net effect of not wearing the mask for short intervals (expressed as a ratio of WPF to measured EPF or WPF/EPF) is a function of the fraction of time the mask is not worn, but it is also shown by Popendorf[44] that this effect is practically detectable only at high WPFs. In this study the fraction of time where the participants might have been noncompliant was very low (1 to 2%). Such noncompliance could conceivably have decreased only the otherwise high WPFs (those >50), but it is incapable of explaining the relatively high frequency of low WPFs (e.g., those <5).

Experience per se is also unlikely to have been a factor based on an inverse relationship between the median WPF of those participants with and without prior regular use of respirators. None of the poultry producers and only 8 percent of the dairy workers (the two groups with the highest WPFs) reported prior use of "a mask over 75 percent of the time in dusty areas," while such use was reported by 28 percent of the swine producers and 26 percent of the grain handlers (those with the lowest group WPF). Furthermore, comparisons of WPFs within settings between participants experienced in wearing a mask versus those inexperienced showed that most inexperienced users had higher WPFs.

It can only be conjectured that other physiological and/or psychological factors (not assessed herein) may have contributed to a difference in a group's behavior. For example, if the wearers knew the air contaminant created an acute respiratory irritation, or could cause a delayed systemic reaction (such as organic dust toxic syndrome), or if they had been subjected to an effective formal or informal hazard communication program, they may have worn the masks more tightly, contributing to a higher median WPF. In retrospect, several additional factors not assessed by the subjective questionnaire might have been useful group correlates of respiratory protection: for example, the wearing of glasses, the frequency and extent of oral communication required by the job, the presence of irritating gases such as ammonia, and the ambient noise level (perhaps converted into speech interference levels).

Table 7 lists the median response to the questions in Table 5 grouped horizontally for each respirator class (All) and within class by brand (two-digit codes), and vertically for All settings and within individual settings excluding dairy. Wilcoxon rank sum scores were examined via the Kruskal-Wallis chi-squared approximation to test for the significance of differences among groups in the distribution of responses to the subjective questions in Table 5. The results of this test are believed to be more representative of overall differences than other tests, for example, the median score one-way analysis (number of points above the median stat). These statistical tests were conducted among respirator classes in all settings (other than dairy), between brands within each class for all settings, and among settings within each class. For purposes of comparison, significance criteria of both $p < 0.01$ and $p < 0.001$ are noted in Table 7.

When all settings were grouped together, there were no significant differences among the classes of respirators for eye comfort, odor control, face and head fit, or overall comfort (questions 4, 6, 8, or 11). Range of vision (question 3) was rated equal for disposables and half-masks, but slightly poorer ($p < 0.01$) for powered helmets. The classes differed most significantly ($p < 0.001$) for the following characteristics (question numbers in parentheses):

	Rated Best	*Rated Worst*
(1) Breathing ease	Powered helmets	Disposables
(2) Communication ease	Powered helmets	Half-masks
(5) Skin comfort	Powered helmets	Disposables
(7) In-mask temperature and humidity	Powered helmets	Disposables
(9) Weight	Disposables	Powered helmets
(10) Convenience	Disposables	Powered helmets

The ability to compare acceptability between respirators within each class is limited because by study design each participant normally wore only one mask within each class; thus, these within-class comparisons are only suggestive and should not be taken as direct comparisons. Given this caveat, the acceptability of disposable respirators differed ($p < 0.001$) for communication ease (mask 21 preferred over 22), range of vision (mask 21 preferred), and in-mask temperature and humidity (mask 22 preferred). Acceptability of the two half-masks differed for face and head fit (with mask 32 preferred, $p < 0.001$) and overall comfort (mask 31 slightly preferred, $p < 0.01$). Powered helmets differed for communication ease, weight, and convenience (mask 41 was preferred, $p < 0.001$ in each case).

Noting the frequency of statistical differences in the subjective responses between the two disposable respirators and recalling that the quarter-mask respirator (mask 22) WPF results were more similar to the half-mask WPF than to the totally disposable respirator WPF (mask 21), secondary analyses were made to compare the subjective responses of the quarter-mask with the two half-masks. There were no questions for which the quarter-mask was rated significantly different at $p < 0.01$ from both half-masks taken as a group. Individually, the quarter-mask was rated poorer than mask 31 for breathing ease and poorer than mask 32 for range of motion (both at $p = 0.008$). Thus, it seems that the quarter-mask was more similar to the half-mask cartridges than the fully disposable mask in terms of both WPF and acceptability.

When comparing acceptability among the various settings, there were no characteristics within which disposable respirator acceptability varied among settings. The acceptability of half-masks varied only for weight (question 9), which was significantly ($p < 0.01$) more acceptable among grain handlers than among swine and poultry workers. Setting seemed to affect the acceptability of powered helmets only in terms of communication ease (question 2), and then in just the opposite way (i.e., more acceptable for poultry than for swine and grain workers).

Finally, the overall preference for respirators among all settings was quite equally distributed among all classes as shown in Table 8. If mask 22 were included with the half-masks as above, then that group would have been preferred by 45 percent of the participants. Preferences appear to differ among the various settings for reasons compatible with the communication and weight characteristics noted above. Grain handlers preferred half-masks, poultry workers showed a strong preference for powered helmets, and swine producers were more mixed between half- and quarter-masks. Fully disposable masks were preferred by only 20 to 22 percent of the workers in each setting.

Conclusions

In conclusion, looking at Table 6, a median measured WPF of 13 for disposable respirators used in dusty agricultural settings by workers largely inexperienced in wearing respirators approximates the mean of the median laboratory PF of 17 in Table 1, but is less than the WPF of 35 in most other field tests (Table 2). On the other hand, a median measured WPF of 19 for half-mask respirators in these agricultural settings was about equal to other field studies where the WPF was 12 (Table 2), but was more than seven times less than the mean reported median laboratory PF of 144 (Table 1). The performance of powered air purifying helmets has not been well reported, but they seem to perform about as well in agricultural settings (a WPF of 30) as the PFs of 15 and 30 in another laboratory (Table 1) and field (Table 2) study, respectively. The consistently large variability in performance within each mask and in every setting indicates that some wearers can experience very little protection. For these workers respirators are a little like the emperor's new clothes: almost like wearing nothing. Further research to test the effectiveness of various approaches to improve the protection afforded to wearers initially showing poor WPFs would be very valuable.

The overall acceptability of the three classes of respirators varied significantly among the settings tested. Poultry operators preferred the powered helmet. Grain handlers preferred the half-mask, as did swine producers if the quarter-mask was included as a half-mask; otherwise they preferred the disposable respirator. The expressed reason for this pattern appears to be that poultry workers like the communication ease and don't mind the weight of the powered helmets as much as grain and swine workers; for some reason poultry workers rated the weight of the half-mask significantly less acceptable than did the grain and swine workers. Among all groups of workers, powered helmets were rated best for breathing ease, communication ease, skin comfort, and in-mask temperature and humidity, while disposables were rated best for weight and convenience. However, in all but one of the above acceptance characteristics, the opposite respirator was given the worst rating. Thus, the reusable half-mask is most often the best compromise.

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