Respirator Physiology Research: Answers in Search of the Question

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Adverse effects of respirators have been the focus of considerable research over the past decade. Individual research projects have generally focused on one specific category of effects: ventilatory, respiratory control, work limitation, subjective discomfort, psychologic effects, thermal loading, and cardiovascular changes. Most were studied in experimental laboratory situations rather than in actual worksites. Very little attention has been given to compliance with use and actual effectiveness in preserving health. Inasmuch as many types of effects have been demonstrated, there is a need to carefully define which type(s) of effects is/are most important for respirator design selection and worker medical certification in particular situations. In general, respirators should be assessed for their effect on all relevant variables.

Over the past decade, a great deal of information has been acquired from research studies on the effects of respirator use. Despite the plethora of information, it is not clear how to apply the information to protect worker health, nor is there a clear definition of what additional specific data must be acquired.

Unfortunately, although respirator studies have provided many answers to quite specific research questions, the ultimate question for which the data have been collected is still unclear. Which of the many demonstrated effects is "significantly adverse" and should be minimized by respirator design or worker testing? Thus, respirator research currently appears to have many answers but *the* question still needs to be defined. The search for answers through additional research will be of much greater significance once the most important question has been well defined.

This paper attempts to define the underlying questions in respirator research by reviewing "answers" from research in three areas: 1) effects of respirators; 2) types of stresses used; and 3) worker personal characteristics modifying response. (The review is not exhaustive, and it intentionally deemphasizes "traditional" physiologic questions which have been previously well framed.)

EFFECTS OF RESPIRATORS (OUTCOME MEASURES)

Respirators may have both beneficial and adverse effects. Table 1 summarizes the general categories of effects. Inasmuch as most studies have focused on one particular category of effect, it is not clear which category is the most important.

Ventilatory Effects

Many studies have described the ventilatory effects of respirators or respirator surrogates; these have been reviewed elsewhere.[1–4] A generally consistent pattern emerges: maximum work performance is decreased and respiratory pattern changes (usually with increased tidal volume and decreased rate). Some studies have shown decreased total minute ventilation and have assumed that this represented hypoventilation.[5,6] Others, however, have shown increased efficiency of breathing.[7]

The specific respiratory variables studied are summarized in Table 1; they fall into the following general categories: total ventilation, flow rates, ventilatory work rates and pressures generated, and metabolic parameters (CO_2 output, O_2 consumption).

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TABLE 1
Measurements Used

Physiologic measures			
	Respiratory volumes		
		Minute ventilation	
			Inspiratory
			Expiratory
		Tidal volume	
	Respiratory control and pattern		
		Respiratory timing	
			Inspiratory time
			Expiratory time
			Inspiratory: expiratory time ratio (duty cycle)
			Frequency
		Respiratory pattern	
			Rib cage: abdominal motion ratio
		Cardiac	
			Heart rate
			Cardiac output
			Right atrial pressure
	Work performance		
		Field course performance	
		Time to exhaustion	
		Maximal attainable work rate (non-steady state)	
		Physiologic adaptation	
Subjective measures			
	Respiratory sensation		
		Rating scales	
		Borg scales	
		Visual analog scales	
	Impact on work		
		Relative perceived exertion	
		Visual analog scales	
		Nonrespiratory discomfort	
Protective value for inhalation diseases			
	Occupational asthma		
	Rhinitis		
Compliance with proper use			

Wilson and Raven[8] have tried to devise a single test of ventilation to assess workers for fitness to use respirators, suggesting that the maximal voluntary ventilation (MVV) is the most useful measure. The MVV measures the maximum ventilation achievable over a 15-second period. The logic employed is as follows[8-10]: the MVV is decreased if performed while the subject is wearing a respirator; there is a correlation between a person's MVV without a respirator and with a respirator[8]; MVV is a measure of one type of maximum ventilation (15 seconds); another measure of ventilation (the sustainable fraction) is important for working; hence, MVV without a respirator should be useful to predict who can work with a respirator. Future studies are of course needed to validate this chain of assumptions.

Respiratory Control and Pattern

The variables described above tend to reflect the "output" of the ventilatory system. In addition, the time of the ventilatory cycle components has been employed to describe the respiratory control mechanisms (as opposed to the actual output).[11,12]

Theoretically, two potentially conflicting goals may determine the response to respirator loads. On the one hand, the body naturally tries to maintain chemical homeostasis (e.g., stabilize the CO_2 and O_2 tensions) while not exceeding the physical limits of the ventilatory and cardiovascular systems. Most studies appear predicated on considering this goal to minimizing adverse sensations and optimizing the efficiency[13,14] of the physiologic apparatus may also be quite important, particularly under the comparatively mild strains imposed by many modern respirators. Several studies of the basic physiology of respiratory control demonstrate the importance of sensation minimization and ventilatory work optimization in respiratory control.[13,14] The timing and intensity of inspiration, which is generally the phase involving active ventilatory work, appear to reflect sensation. An empiric study of respirator type loads[15] also showed a relationship between sensation and timing parameters.

Cardiac Effects

Nearly all respirator studies have measured heart rate as a cardiac effect. Many have shown that respirator use does not in itself increase the heart rate, except as a consequence of carrying the weight of a heavy device such as a self-contained breathing apparatus (SCBA).

Arborelius et al[16] conducted more detailed studies including right heart catheterization during exercise. They found that even positive pressure respirators, which would be expected a priori to have the greatest effect, did not adversely affect cardiac output.

Work Performance

Numerous studies have looked at work performance as the outcome measure. Van de Linde[17] performed one of the few studies in which this was directly measured in a nonlaboratory setting. Laboratory studies tend to use maximal work performance as the outcome measure. Methods have included measuring how long it takes for subjects to reach exhaustion or, conversely, determining the peak exercise level obtainable with and without a respirator. It remains to be determined whether impact of respirator use upon maximal achievable work rate or upon tolerance to submaximal work (typical of most industrial uses) is most relevant.

Many studies have shown that use of respirators decreases the peak work that may be performed, whether assessed as the maximal attainable work rate or the duration of very heavy intensity work.[5,8,9,18,19]

Respirator Use in Nonexperimental Situations

Nuutinen et al[20] showed that powered air helmets are subjectively acceptable for use by farmers. Measurement of physiologic effects in the workplace, however, has been limited by two problems: the first is the technical inability to measure ventilation outside an experimental laboratory setting and the second is the difficulty in separating the effect of the respirator from that of the work situation necessitating respirator use.

Newer measurement techniques have made worksite physiologic measurements possible, although still difficult. In particular, respiratory inductive plethysmography permits ventilation measurement without any connection to the mouth or nose.[21-23] Respiratory inductive plethysmography is, however, technically demanding and not as accurate as routine techniques.[21,23] In a workplace study, Hodous et al[22] were successful in collecting useful data in only 50% of workers. Nevertheless, they demonstrated consistent effects upon ventilation and respiratory timing in a pattern which validated that found in several laboratory studies.

Assessment of the level of exercise during which respirators are used in "real life" situations can guide the choice of relevant experimental conditions. For example, respirators are used in escape from mine incidents, and Kamon et al[24] found a very high work rate (approximately 75% of maximal). Louhevaara et al[25] studied the exertion level of several jobs requiring respirator use and found that firefighting was among the most physicall demanding.

NIOSH collects "case reports" of respirator-related problems from actual worksites. The 35 problems reported in the course of a year emphasized mechanical rather than physiologic problems, however.[26]

Wilson et al[10] raise the important consideration that ventilation may determine the "service time," the length of time an SCBA can permit work by supplying air. This practical consideration, that worker and respirator characteristics may significantly affect service time, obviously requires more attention.

Physiologic Adaptation - Time Course

There has been very limited assessment of whether adaptation to respirator use occurs or, conversely, if the adverse effect increases with time. Short term accommodation was suggested by an experimental study of Harber et al,[12] which showed that psychophysical sensitivity to resistance declined with time. Van de Linde[17] demonstrated that adverse effects of respirators or respirators combined with chemical protective clothing did not increase over a one-day period of continuous use. Deno et al[7] developed an empiric equation showing that the ability to work with a respirator may decline as duration of exercise increases.

In an interesting study, Epstein et al[27] noted that several consecutive days of use improved the characteristic physiologic response. Unfortunately, it is not completely clear whether this represented beneficial adaptation to respirator use or reflected the benefit of the exercise per se.

Subjective Outcomes

Until recently, relatively few studies measured subjective outcomes, and those that did employed relatively imprecise methods. Subjective measurements have included symptom inventories, lists of subjective symptoms volunteered by actual or experimental users, and formal rating schemes (such as Borg and visual analog scales).

Borg scales use discrete ordered categories, with verbal descriptions assigned to each category. One study[28] used a high respiratory Borg scale score combined with symptom inventory to operationally define "respiratory distress."

Unlike Borg scales, visual analog scales[15,29] produce a continuous scale by having the subject mark a point along a line which is "anchored" at both ends (e.g., "no effect" and "extremely severe"). Using this method, Harber et al[15] and Shimozaki et al[29] have shown that respirator users may separate a descriptive sensation (current respiratory discomfort) from a predictive assessment (estimated limitation of exercise duration). Thus, subjective tolerance may not be explained only by exercise limitation, at least at submaximal exercise levels.

The specific components of respirator use which produce subjective effects have been studied. Shimozaki et al[29] examined the effect of individual respirator loads and found resistance to have greater subjective effect than dead space. Harber et al[30] showed that there may be divergence of subjective from physiologic effects. Morgan and Raven[28] showed that both respirator mask use and exercise both affected the perception of breathing. Their data suggest that use of an SCBA was equivalent in magnitude to an increase in exercise of 15% of maximal oxygen consumption.

The relationship between subjective effect and physiologic effect has been evaluated in a few studies. Harber et al[15] found a relationship between the magnitude of the subjective response and physiologic factors, including respiratory timing. Wilson and Raven[8] found a weaker correlation of subjective and more limited physiologic measures.

Protective Value for Inhalation Disease

The goal of respirator use is to protect the worker from inhalation of toxic materials. Therefore, measurement of efficacy in preventing disease (while not interfering with work) is an appropriate outcome measure.

Nuutinen et al[20] studied a small group of farmers with farmer's lung disease. They demonstrated that use of a powered air helmet prevented disease progression. Unfortunately, there was no control group with continued exposure but no progression. Similarly, Slovak et al[31] found air helmets to be useful for workers with laboratory animal asthma or rhinitis. By using laboratory provocation challenges to carefully monitor effectiveness, Hendrick et al[32] showed that dust respirators protected against acute extrinsic allergic alveolitis in four of six cases tested.

Positive pressure respirators are used in very hazardous situations to prevent any exposure by maintaining a constant positive pressure inside the mask so that no inward movement of a toxin would occur even in the absence of a perfect facial seal. Laboratory-based studies of pressure-demand respirators raise the disturbing possibility that the pressure inside the facepiece may become negative due to the high inspiratory airflows associated with heavy exercise.[33,34]

Compliance with Proper Use

Proper use is an ultimately important outcome. In an empiric study, White et al[39] demonstrated that subjective discomfort was the major determinant of whether spray painters actually used respirators. This study underscores the importance of considering subjective as well as physiologic measures. Additional studies of compliance are discussed below.

COMPARISON OF RESPIRATOR STRESSORS

Although many studies describe the effects of different respirator loads, surprisingly few attempt to compare directly the significance of different types of loads. Table 2 summarizes types of loads studied. Babb et al[36] present data suggesting that resistance was more limiting of exercise than was CO_2 inhalation. On the other hand, James et al[37] felt that dead space was particularly important, largely based upon heart rate responses. Several studies of Harber et al[29,38] suggest that inspiratory resistance is of greater significance than dead space both in terms of physiologic loading and subjective response. This is consistent with theoretical considerations that dyspnea sensation is related to the disproportion between the work of breathing and the actual ventilation produced; with dead space, ventilation increases concomitantly with the increased work of the ventilatory muscles, but this is not true with inspiratory resistive loading. Larger breathing areas (the actual available surface area of the mask) are associated with

TABLE 2
Stresses Studied

Respirator
Inhaled carbon dioxide (CO_2)
Laboratory exercise
Maximal
Submaximal
Field exercise
Actual work
Thermal loads
Inspired air
Whole body

lower resistances but higher dead space. In a simple study of dust mask use, Andrew[39] found that larger "breathing area" masks had better subjective response, thereby suggesting that resistance rather than dead space should be minimized. Lerman et al[6] also concluded that inspiratory resistance was of primary importance.

Because respirators are generally used at work rather than rest, studies uniformly use exercise as an additional concomitant physiologic load. Studies have applied exercise loads in two disparate ways. In some, each subject's maximum attainable exercise level is predetermined, and then respirator effects are studied at an exercise level which is a fixed percentage of this maximum level. Alternatively, other studies have employed a constant exercise level (e.g., 3 mph @ 5% grade) for all subjects.

Combined Heat and Respirator Stresses

Heat stress may combine with respirator stress for two reasons: First, the respirator itself may impose heat stress by preventing heat elimination via the respiratory tract, particularly with rebreathing closed circuit systems. Second, many work situations, such as firefighting or hazardous waste site work, requiring respirator use also mandate the use of protective clothing which adds heat stress.

Testing of specific respirators under ambient heat stress situations was performed in several studies.[37,40,41] In addition, studies of combined respirator and protective clothing ensembles have been accomplished.[42] White et al[43] noted that the effect of clothing plus an SCBA respirator load was much more significant than either alone. For example, heart rate failed to plateau with clothing plus respirator but with neither alone. Subjective responses were also found to be significant. SCBA's using liquid air or oxygen appeared preferable to compressed air systems because they absorbed more heat.[40,41]

Recent work has suggested another very important interaction between temperature and respirator use. The thermal and humidity conditions of the air within the mask may affect the "acceptability" of the respirator directly. This was suggested in 1955 by Lind[40] who found that inspired air temperature was a major determinant of tolerance. In a series of carefully planned studies, Gwodsow et al[44] and Nielson et al[45] evaluated the interaction of mask air thermal conditions and ambient conditions at rest[44] and at exercise.[45] Their major outcome measure was the "acceptability" of the work conditions, and their work emphasized the sensations rather than the physiologic stresses associated with respirator and thermal loads. Humid air was more poorly tolerated than dry air. Interestingly, mask air conditions affected acceptability of the whole body conditions, so that breathing warm air decreased the subjective tolerance of work overall. Furthermore, they showed that whole body ambient exposures conditioned the degree to which respirator air temperatures were tolerated, such that under extreme ambient conditions, respirator temperature became a more significant adverse factor. Even without actual changes in the added work of breathing, hot air increased the sensation of the work of breathing.

EFFECT OF PERSONAL CHARACTERISTICS ON THE PHYSIOLOGIC RESPONSE

Only a minority of respirator users seem to be adversely affected. Unfortunately, relatively few studies have assessed which worker characteristics determine the response. Such personal factors that may affect respirator use are listed in Table 3. A number of these factors were reviewed by Beckett and Billings.[46]

Disease

Subjects with disease have also been studied, focusing upon relatively mild respirator impairments. Respiratory response patterns were generally qualitatively similar to that of normals, both in terms of respiratory volumes and flows[47] and respiratory timing.[30] In a study of mild-moderately obstructive lung disease subjects, Hodous et al[47] concluded that workers who could do the job without a respirator could also do it while wearing one. However, this study only looked at basic ventilatory parameters and ability to do the work, rather than assessing the actual impact on tolerance per se. Raven et al[48] found that patterns of responses of patients with mild obstructive abnormalities were similar to normals; however, these patients used a greater portion of their ventilatory reserve during exercise.

Restrictive disease subjects were included in the study group of Harber et al[30] and had responses that were qualitatively similar to those of obstructive disease subjects. In a larger study, Hodous et al[49] found that, with high resistance loads, restrictive disease subjects tended to have less increase in tidal volume, but greater increase in oral pressure than did normals. This is consistent with the idea that restrictive disease makes todal volume increases more difficult.

TABLE 3
Worker Personal Determinants of Respirator Use and Effect

Personal characteristics
Smoking
Disease
Age
Personal physiologic and psychophysical characteristics
Trait anxiety
CO_2 sensitivity
Social factors
Training
Attitudes and beliefs
Acceptability
Fear of health consequences
Availability
Worker experience

Age

Age itself does not appear to be an important factor determining acceptability of resistances.[50]

Psychophysiologic and Physiologic Characteristics

Persons differ in the degree to which they perceive added loads such as resistances. Magnitude estimation techniques measure the growth in sensation with increasing loads rather than subjective report per se. This personal psychophysical characteristic appears to help determine the pattern of breathing adopted in response to a respirator load,[15] and is correlated with subjective effect. This leads to the postulate that a person's innate psychophysical load sensitivity affects the pattern adopted, and that this in turn affects the sensation of breathing.[30]

Certain other personal physical factors affect the fit (leakage of facial seal) of respirators. For example, a recent review concludes that facial hair affects both the magnitude and the variability of the leak.[51]

Although respirators provide significant dead space, Babb et al[36] found that a person's sensitivity to CO_2 does not determine the effect of respirator use. Shershow et al[52] showed that, in general, individuals with relatively depressed sensitivity to inhaled CO_2, as would occur with dead space, had elevation of many scales on the Minnesota Multiphasic Personality Inventory, suggesting the need to consider psychologic factors.

Personal Psychologic Factors

Personal psychologic factors may decrease the likelihood of compliance with proper respirator use. In addition, they may cause changes in respiratory pattern which in turn may lead to physiologic effects.

In a series of papers, Morgan[53-55]: 1) reasoned that psychologic intolerance to respirators may be similar to the hyperventilation syndrome,[53] (2) summarized data showing that psychologic disturbances affect respiration,[54] and 3) surmised that psychologic factors per se account for respirator problems in 10% of potential users.[55] This 10% estimate was based upon studies showing that 10% of people have psychologic problems, that 10% perceive resistance poorly, and that 90% of Bentley et al[56] research subjects were comfortable with a pressure swing less than 17 cm H_2O. Morgan's work postulates that hyperventilation is the mediator of psychologic intolerance by the following mechanism: anxiety + respirator → hyperventilation → disturbed sensation of breathing or increased work → poor tolerance. The studies of CO_2 responsiveness[36,52] suggest that CO_2 loading induced by the respirator dead space is unlikely to be the direct mediator.

In an experimental study, Morgan and Raven[28] found that trait anxiety, a psychologic characteristic of individual subjects, was moderately predictive of stopping exercise with a respirator due to "respiratory distress."

Trait anxiety showed surprisingly good sensitivity (five of six) and specificity (38 of 39) for prediction. (However, the test set and validation set were the same, and, therefore, the predictive value may be overestimated).[57] Hodous et al,[22] on the other hand, found that trait anxiety was not related to respiratory comfort. Morgan[58] previously showed that persons who were neurotic, anxious, or depressed had difficulty in accurately rating work levels, suggesting the possibility of an aberrant link between sensation and the actual loads.

Effect of Social Factors

A common assumption is that the tolerance of respirators is conditioned largely by physiologic or psychophysical factors. However, the willingness to use a respirator may be affected by the personal beliefs of the worker and worksite social factors as well.

Virolainen et al[59] found that the major determinant of respirator use among farmers was participation in the "occupational health experiment," a Finnish program to encourage good practices. This group also found that male farmers were more likely than females to use respirators. Social and psychosocial factors were shown to be important determinants of respirator use by White et al.[35] Personal beliefs about the health consequences of not using respirators and the perceived attitudes of coworkers toward respirator use were shown to be quite important. This suggests that worker training should address attitudes in addition to simply teaching "how to use a respirator." Smokers tended to use respirators less than nonsmokers.

Effect of Worker Experience

Most research is conducted on laboratory volunteers, yet "real" industrial users may be different. Only a small number of studies evaluated the effect of actual respirator experience.

One group[28] suggested that at low exercise levels, experienced users may have less subjective effect than inexperienced users, but that this difference disappears at higher exercise levels. In a series of studies, Wilson et al[9] found that the physiologic response of experienced users was similar to that of novices. (However, novices who volunteer for research studies may not truly reflect novices in the workplace population.)

Conclusions

The past decade has produced considerable information about respirator physiologic, psychologic, and subjective effects. In addition, many worker personal characteristics and worksite factors that affect proper and safe use of respirators have been identified. It is clear that tolerance of respirator use represents much more than just the ability to overcome the resistance of the device. Rather, it is affected by :1) the "traditionally determined" ventilatory effects, 2) effects on ventilatory control, and 3) sensation effects (both respiratory and nonrespiratory). It is unlikely that there is a *single* answer to the question, "What is *the* goal of respirator physiology research?" Perhaps a small number of clear questions can be developed to guide the next decade of research in order to ultimately prevent occupational disease through proper respirator use.

In the interim, clinicians evaluating individual workers for respirator medical fitness should consider all of the major categories of effect: ventilatory limitation, change in respiratory pattern, the worker's subjective opinion of discomfort, and the degree to which the respirator interferes with the performance of the job at which it will be used. Furthermore, clinicians should consider the worker's knowledge and beliefs about respirator use. The possibility of temperature-humidity effects producing either heat stress or thermal discomfort should also be considered. Consideration of these several factors does not imply that each needs to be formally tested in every worker. Indeed, recognition that respirator tolerance appears to be so multifactorial suggests that it is inappropriate to mandate a single "simple" test for all users because this would overemphasize the one factor measured and might imply false reassurance if other factors are not measured. There is a need to use good clinical judgment rather than reliance upon any one test. There is also a research need to delineate the most important question(s) for assessing respirator effects.

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