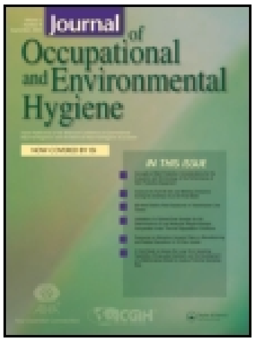

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Respirator Physiological Effects under Simulated Work Conditions

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This study compared the physiological impacts of two respirator types in simulated work conditions. Fifty-six subjects included normal volunteers and persons with mild respiratory impairments (chronic rhinitis, mild COPD, and mild asthma). Respiratory parameters and electrocardiogram were measured using respiratory inductive plethysmography while performing eight work tasks involving low to moderate exertion using two respirators: (1) a dual cartridge half face mask (HFM) respirator, and (2) the N95. Mixed model regression analyses evaluating the effect of task and respirator type showed that task affected tidal volume, minute ventilation, breathing frequency and heart rate; all were greater in heavier tasks. Although respirator type did not affect respiratory volume parameters and flow rates, the HFM led to increase in the inspiratory time, reduction of the expiratory time, and increase in the duty cycle in comparison with the N95. The magnitude of differences was relatively small. The results suggest that most individuals, including persons with mild respiratory impairments, will physiologically tolerate either type of respirator at low to moderate exertion tasks. However, because effective protection depends on proper use, differences in subjective effect may have greater impact than physiological differences. Using respirators may be feasible on a widespread basis if necessary for maintaining essential services in the face of widespread concern about an infectious or terrorist threat.

Keywords physiology, plethysmography, pulmonary ventilation, respirator, terrorism

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INTRODUCTION

Respirators (personal respiratory protective devices) have an important role when other exposure control measures cannot be implemented effectively. These are widely used. In 2002, 3.3 million American workers used respirators.[(1)] The physiological effects of respirators such as the effects of breathing through resistances and dead space have been subjected to research by pulmonary physiologists.[(2–5)]

Nevertheless, most of the available information is not directly applicable to workplace conditions because it was obtained under laboratory settings that are not comparable to actual workplace conditions. The challenge of measuring respiratory parameters under field conditions probably accounts for the paucity of assessment under actual work conditions. Unlike other physiological systems (e.g., cardiac), respiratory parameters assessment typically requires a connection of the mouth or nose via hoses to measuring equipment; any such connection might bias the results.

Only a limited number of studies have considered the physiological measurements during work.[(6,7)] The current study directly measures numerous respiratory physiological parameters non-invasively during simulated work activities. The approach was facilitated by using respiratory inductive plethysmography.

This study compared two types of respirators that might be widely used in the event of bioterrorism threat[(8)] or in the face of an infectious epidemic (e.g., avian influenza or SARS).[(9–11)] The study therefore differs from many others for which the focus has been on more highly protective devices that are, however, unlikely to be widely employed (e.g., self-contained breathing apparatus, complex full face mask respirators, etc.). In addition, the study focused on activities that are semi-sedentary or with moderate exertion level, whereas the majority of prior studies were conducted at very high exertion levels exemplifying the activities done by workers such as firefighters and military personnel.[(12–14)]

METHODS

The study was approved by the Institutional Review Boards of UCLA and of the VA Greater Los Angeles Healthcare Center. Subjects were recruited from newspaper advertisements, posters, and referrals from clinicians. The subjects included normal individuals as well as persons with three types of mild respiratory impairments (chronic rhinitis, mild COPD, and mild asthma). For analysis, each subject was assigned to a single disease category. Subjects with multiple disorders were assigned according to the following hierarchy: COPD > asthma > rhinitis > normal; for example, a person with both asthma and rhinitis would be classified as "asthma."

All subjects underwent a screening interview. After detailed explanation and signed consent, they underwent limited physical examination and spirometry testing. Exclusion criteria included forced expiratory volume in one second (FEV_1)$<$50% predicted for COPD subjects, recent hospitalization, history of chest pain, use of psychiatric medication, or significant musculoskeletal disorder. (Due to an initial misclassification of one subject, one subject with COPD and an $FEV_1$$<$50% predicted was included.)

Each subject participated on three days: (i) Exercise laboratory; (ii) HFM: Work stimulation with a dual cartridge half face mask respirator (Comfo-Elite, Mine Safety Appliance Co, Pittsburgh Pa.); (iii) N95: Work stimulation with N95 single-use type respirator (8210, 3M, St. Paul, Minn.). This article describes the results of the physiological studies during work simulation.

For work stimulation, the subjects completed a series of tasks; some were done while seated, whereas others required standing or walking. The tasks were selected to include different body positions (seated vs. upright), different exertion levels (sedentary to moderate), and different levels of concentration. The tasks were (i) sedentary: familiarize subject with rating procedures (lern); sort bolts into bins (bolt); simulate driving (driv); produce towers with plastic blocks following prescribed instructions (lego); (ii) mild exertion: walk across room, obtain paper, and place into proper bins (case); place magnets on boards at proper coordinates based on oral instructions (mags); walk across the room and place magnets on boards at proper coordinates based on oral instruction (magw); (iii) moderate exertion: stock store shelves with cereal boxes and juice jugs (stor); stock store shelves with rice buckets (carr). Each task was approximately 8–10 min in length. Subjects were permitted breaks between the tasks as required. The order of days and the order of tasks within days were randomized.

Measurement Methods

Respiratory parameters and electrocardiogram/heart rate were measured using a respiratory inductive plethysmograph (Vivometrics Life Shirt, models 200 and 100; Ventura, Calif.), which consists of a pair of elastic bands worn around the chest and the abdomen. Each band contains a series of parallel conductor wires through which a high frequency signal is passed. Expansion of the elastic band (e.g., by inspiration) changes the configuration and the inductance of the coils; the signal is then recorded on a small solid-state recorder or transmitted by WiFi directly to a computer recording system. The signal continuously reflects the circumference of the two body components (abdomen and chest).[15]

The volume of air inhaled or exhaled was determined by a linear combination of the changes in the two components — chest and abdomen (i.e., volume = b1 × chest circumference + b2 × abdomen circumference). The coefficients b1 and b2 were calculated for each individual by the "fixed volume" calibration procedure. In this procedure, the subject repetitively inhales a known fixed volume from a calibrated bag using different flow rates in different configurations of chest and abdomen motion. Calibration was performed on each experimental date both at the beginning and the end of the experiments.

Software provided by the equipment manufacturer demodulates the signal and provides graphical display and calculated respiratory parameters. Software developed in our laboratory was then used to index the plethysmograph output to the work activity, thereby allowing identification of the work simulation or experimental exercise laboratory condition. Graphical results were displayed and selected. Sections free of notable artifact were included for analysis. Special software developed in our laboratory was used for data processing using Microsoft Access and Visual Basic for applications.

The parameters that were measured are summarized in Table I. Total minute ventilation (Ve), tidal volume (Vt), and respiratory frequency (Fb) were measured by the plethysmograph; they were also measured by spirometer during exercise laboratory sessions, which was used to help validate and optimize the plethysmograph calibration methodology. In addition, respiratory time parameters were determined from the plethysmograph. These included inspiratory time (Ti), expiratory time (Te) and duty cycle (Ti:Tt) (proportion of the total respiratory cycle during which inspiratory effort is made).

Statistical Analysis

Data were managed using a relational database (Microsoft Access); statistical analyses were conducted using SAS for PC (v. 9.1). Descriptive measures included means, standard deviations, and counts as appropriate. Mixed model regression analyses were employed to evaluate major effects of respirator

TABLE I. Physiological Variables Evaluated

Code	Dependent Variable	Units
Vt	Inspiratory Tidal Volume	Liters
Ve	Minute Ventilation	Liters/Min
Fb	Respiratory Rate	Breaths/Min
HR	Heart Rate	Beats/Min
Ti	Inspiratory Time	Seconds
Te	Expiratory Time	Seconds
Tt	Total Breath Time	Seconds
Ti/Tt	Fractional Inspiratory Time	Ratio
Vt/Ti	Mean Inspiratory Flow	Liters/Sec
PifVt	Peak Inspiratory Flow	Liters/Sec
PefVt	Peak Expiratory Flow of Vt	Liters/Sec
PifTTi	Time to Reach Peak Inspiratory Flow	% of Time
PefTTe	Time to Reach Peak Expiratory Flow	% of Time

TABLE II. Subject Characteristics

Primary Disease	n	Gender (% males)	Age (years) Mean	SD	Range Low	Range High	FEV1 (% predicted) Mean	SD	Range Low	Range High	FEV1/FVC ratio (actual value) Mean	SD	Range Low	Range High
Asthma	17	65%	47.7	12.0	21.0	62.0	89%	20%	36%	128%	75%	13%	49%	94%
Chronic Rhinitis	8	75%	53.6	3.8	46.0	58.0	87%	16%	57%	117%	70%	5%	64%	78%
COPD	15	93%	52.9	5.5	43.0	61.0	74%	12%	43%	89%	69%	6%	56%	78%
Normal	16	50%	39.2	11.7	21.0	57.0	100%	11%	82%	125%	82%	4%	77%	88%

Notes: Subject characteristics are shown. Mean, standard deviation (SD), and ranges are shown above. COPD = chronic obstructive pulmonary disease.

and task and to evaluate their interactions. Each physiological parameter was separately analyzed as the outcome variable using respirator type, task and their interaction as predictor variables; the covariance structure was specified as CS (compound symmetry), and the model recognized repeated measures within subject. The primary model for analysis included respirator type, task, and the respirator * task interaction as predictor variables. Two additional models were employed: in one, FEV_1 percentage predicted was added as a predictor; in the second, disease category was added as a categorical variable predictor. A $p < 0.05$ was considered statistically significant. In addition, the mixed regression model was employed to calculate least squares mean values for each task-respirator type dyad.

RESULTS

The 56 subjects included 39 men and 17 women. The average age was 47.5 years with a range of 21 to 62 years. The FEV_1, expressed as percentage of predicted[16] had a mean value of 87.1% with a standard deviation of 18.0%. FEV_1% predicted ranged from 36.4% predicted to 127.9% predicted. The group included 16 healthy subjects, 8 with chronic rhinitis, 17 with asthma, and 15 subjects with COPD. All subjects successfully completed the work simulation studies, and none removed the mask because of inadequate tolerance. Characteristics of the subjects are shown in Table II.

Several measures of the respiratory function are summarized in Table III. The table includes the least squares adjusted mean for each task and respirator type. In addition, the p values for the effects of respirator type and task are shown. Unless otherwise specified, results are based on the mixed regression model, including task and respirator type as the predictor variables; an interaction term was also used.

Task type had significant effect on tidal volume, minute ventilation, breathing frequency, and heart rate; these effects were greater in those tasks involving heavier exertion (e.g., carrying, store stocking) than those that were more sedentary (e.g.,

TABLE III. Respirator and Task Effects During Simulated Work

Variables	Respirator HFM	N95	Task bolt	driv	lego	mags	magw	case	carr	stor	p Value Respirator	Task	R*T
Vt	0.92	0.91	0.77	0.72	0.80	0.76	0.91	1.21	1.02	1.12	ns	<.0001	ns
Ve	23.39	23.25	18.18	15.76	19.08	17.51	25.22	30.32	29.22	31.28	ns	<.0001	ns
Fb	28	28	26	23	26	25	31	31	33	33	ns	<.0001	ns
HR	86	86	80	80	80	82	88	88	94	96	ns	<.0001	ns
Ti	1.14	1.10	1.17	1.22	1.17	1.21	1.06	1.10	1.01	1.02	<.0001	<.0001	ns
Te	1.39	1.44	1.57	1.71	1.53	1.56	1.28	1.31	1.18	1.16	0.0018	<.0001	ns
Tt	2.53	2.54	2.74	2.93	2.69	2.78	2.34	2.42	2.19	2.18	ns	<.0001	ns
Ti/Tt	0.46	0.45	0.44	0.43	0.44	0.44	0.46	0.46	0.47	0.47	<.0001	<.0001	ns
Vt_Ti	0.85	0.88	0.69	0.61	0.72	0.66	0.91	1.12	1.06	1.14	ns	<.0001	ns
PifVt	1.50	1.53	1.19	1.00	1.26	1.15	1.58	2.08	1.83	1.99	ns	<.0001	ns
PefVt	1.39	1.35	1.05	0.83	1.12	1.03	1.44	1.90	1.69	1.88	ns	<.0001	ns
PifTTi	50.26	50.46	51.13	49.03	50.63	50.76	50.26	50.77	50.17	50.11	ns	<.0001	ns
PefTTe	46.71	46.32	45.44	43.10	46.53	45.21	47.66	47.20	48.52	48.47	ns	<.0001	ns

[A] Values shown are least squares adjusted means according to respirator type and task. Tasks are defined in Methods, and variables are defined in Table I.
[B] HFM = half face mask dual cartridge respirator; N95 = N95 single use respirator. R*T = Interaction of Respirator and Task.
[C] The p values for effects of respirator type, task, and interaction are shown in right 3 columns. ns = "not significant."

driving, sorting bolts). Respiratory times decreased, while duty cycle increased with increasing levels of exertion. Respiratory volume parameters did not differ according to the type of respirator (perhaps surprising in view of the greater dead space of the larger mask). However, significant differences in the respiratory control timing were noted between the HFM respirator and the N95 respirator. The HFM led to prolongation of the inspiratory time ($p < 0.0001$), reduction of the expiratory time ($p=0.0018$), and increase in the duty cycle ($p < 0.0001$). Peak flow rates in inspiration and expiration were evaluated and showed a significant change with type of activity but did not differ significantly between the respirator types. Neither the model employing FEV_1% predicted nor the model employing disease status showed results that differed from the primary model. Furthermore, neither the FEV_1% predicted nor the disease status was statistically significantly related to any of the outcome variables.

Figure 1 shows the average values for each task. Results are shown for several physiological variables, including tidal volume, minute ventilation, and respiratory frequency. In addition, several parameters reflecting respiratory control are illustrated in Figure 2; these include inspiratory time, expiratory time, and duty cycle (Ti:Ttot).

DISCUSSION

Respirators impose several types of physiological loads. These include inspiratory airflow resistance, expiratory airflow resistance, and dead space (rebreathing of exhaled air).[4,17–22] In addition, certain designs impose a respiratory threshold load (pressure necessary to open a valve) and thermal/humidity stress.[23–25] Others, particularly self-contained breathing apparatuses (SCBA), may be quite heavy and require considerable energy expenditure simply to carry. Finally, many reduce the ability to communicate or interfere with vision.[26]

The study compared the physiological impact of two common types of respirators during simulated work activities rather than comparing respirator use vs. no respirator use. We included a diverse group, including both healthy volunteers and individuals with mild respiratory impairments. N95 and dual cartridge half face mask respirator types were selected because they are the most commonly used and are likely to be employed by workers in settings that do not have comprehensive occupational health programs.

The effects were studied under circumstances comparable to "real life" rather than under artificial laboratory conditions. Among the limited number of studies during realistic work situations many have relied on subjective ratings rather than measuring physiological effects. For example, respirator users have been assessed in the SARS epidemic,[9] automobile assembly plants,[27] military medical operations,[12] emergency setting,[7] and an anatomy laboratory.[6] Studies evaluated physiological response during simulated work (e.g., limited respiratory parameters were determined during simulated fire fighting work using an SCBA).[13]

Study tasks were selected to reflect the increasingly diverse settings in which respirators are used. A 2001 survey by the Bureau of Labor Statistics[1] showed that respirators are used in approximately 10% of private industry workplaces. The study estimated that more workers in the services sector than in manufacturing use respirators, and more than twice as many workers in the retail trade than in mining use respirators.

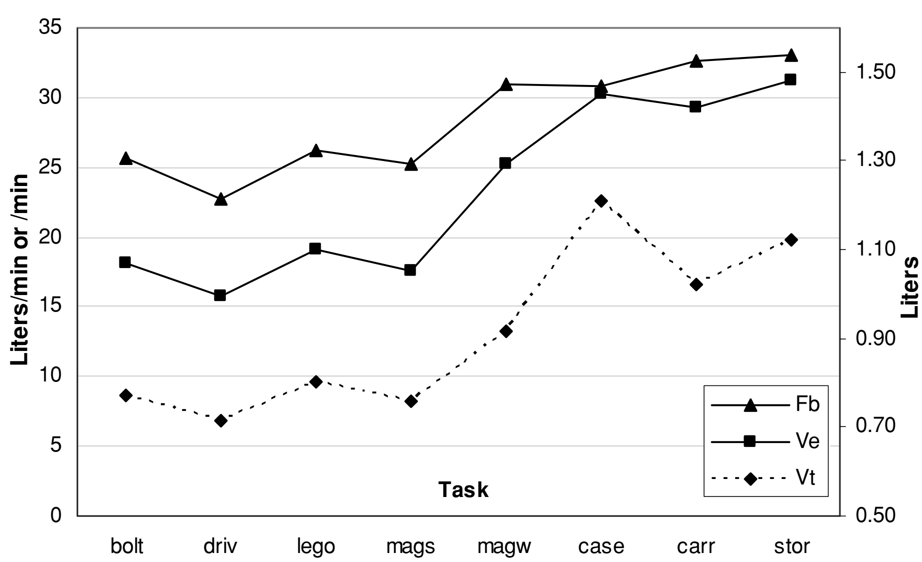

FIGURE 1. Effect of task on respiratory volume parameters and frequency. Vt = tidal volume (liters); Ve = minute ventilation (liters/min); Fb = frequency of breathing (per min); Vt is on secondary axis to the right of graph. Tasks are described in Methods section.

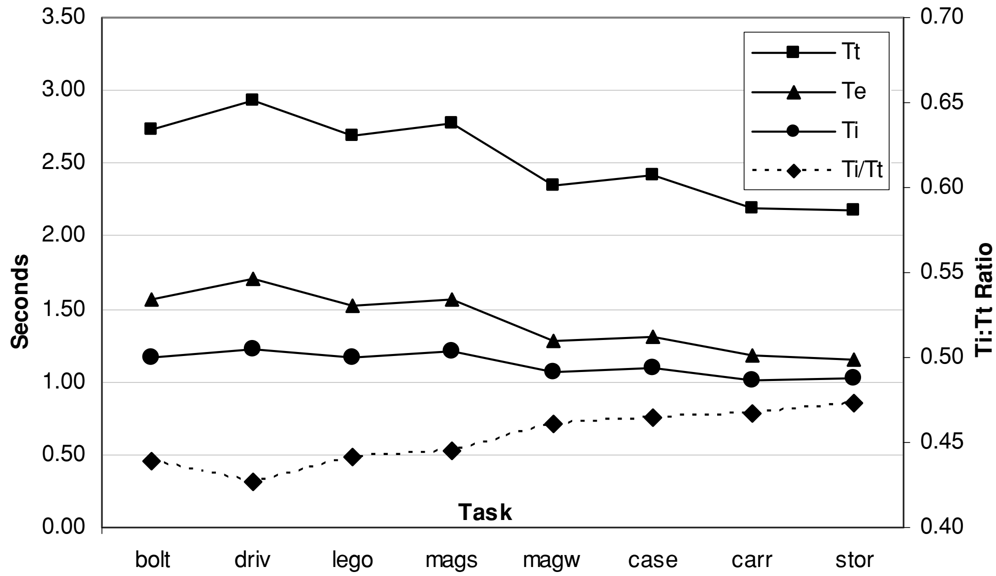

FIGURE 2. Effect of task on respiratory time parameters. Ti = inspiratory time (sec); Te = expiratory time (sec); Tt = total time (sec); Ti/Tt = duty cycle (ratio); Ti/Tt is on secondary axis to the right of graph. Tasks are described in Methods section.

Furthermore, over half the use was described as voluntary. An empirical study of respirator users[(28)] found that exertion in many jobs was typically in the low to moderate range rather than at near peak performance. Low to moderate exertion tasks were emphasized.

Most studies of physiological effects were conducted in healthy workers, such as members of the military services, firefighters, and healthy volunteers. The current study, however, uses a group comparable to the general population. Mild respiratory impairments are common in the general population. For example, 5% of the general population has asthma,[(29)] 20–25% have rhinitis,[(30–32)] and 6% have COPD.[(33)] These health conditions are frequently not diagnosed; one study showed that 12% of the general population has undiagnosed airflow obstruction.[(34)]

A few studies have focused on persons with obstructive or restrictive abnormalities, generally focusing on moderately to severely impaired patients.[(21,35–38)] In general, it was found that respirator use had limited effect. Study of a group including impaired persons complements prior studies in several ways. First, it assesses if impaired individuals have very aberrant responses that differ significantly from the persons with normal respiratory systems. Second, because respirators are used in an increasingly diverse array of workplaces, respirator users are likely to include persons with impairments who would not normally be found in heavy jobs in traditional manufacturing/mining industry sectors.

Third, respirators may suddenly be used by many unselected workers and community members to maintain daily and vocational activities in the face of an epidemic or terrorist threat concerns.

Therefore, the results of this study are likely to be applicable to the majority of current respirator applications that are characterized by intermittent, voluntary, limited use by workers who are not particularly screened for being medically fit.

Physiological Effects

Results were analyzed to evaluate the effects of task type and to compare the two respirator types. As shown in Table III and Figures 1 and 2, there were statistically significant effects of task type on each of the physiological variables studied. Conversely, statistically significant differences between the two respirator types were noted only for the respiratory timing parameters (inspiratory time, expiratory time, and duty cycle), and the magnitude of differences was relatively small.

The adjusted mean values for both tidal volume and minute ventilation were so similar that the absence of statistical significance is unlikely to be due simply to measurement variability or an inadequate sample size. The results complement findings of studies of respirator effects during maximal or near-maximal exercise. In many of those studies, minute ventilation and tidal volume were affected by respirator use, showing in some that the maximal attainable ventilation was reduced.

The results suggest that hypoventilation is unlikely to be a significant concern with the respirator types and exertion levels studied. In particular, the N95 respirator has low resistance and low dead space. Therefore, although this study compared two respirator types rather than a respirator to a no-respirator condition, it is not likely that the physiological loading of either is sufficient to cause significant hypoventilation.

Dead space is the volume of air breathed during every breath that does not contact gas-exchanging alveolar surfaces and, therefore, does not contribute to CO_2 elimination. Dead space includes both the anatomical dead space (e.g., trachea) and the dead space of the respirator. Although the physical size of the mask was greater in the half face mask respirator than the

N95 device, the tidal volume and ventilation were comparable. This suggests that the "dynamic" dead space (representing the functional effect of dead space) is considerably lower than the static physical volume within the respirator, possibly due to preferential air streaming within the respirator. A study using a physiological lung simulator (with 19 masks used for noninvasive medical ventilation) demonstrated that the functional effect of dead space was typically about a quarter of the "static" dead space.(39)

However, in contrast to effects on ventilation, effects on respiratory control were notable. The half face mask respirator reduced expiratory time, prolonged inspiratory time, and increased the proportion of time during which active ventilatory muscle activity was needed. The resistance to airflow during inspiration imposed by the respirator cartridges leads to prolongation of the inspiratory time. This is consistent with prior controlled laboratory studies using respirators or respirator surrogates by our group and others.(4,40,41) By prolonging the inspiratory time, users are able to avoid markedly increasing the peak pressures that are necessary. The increased resistance is likely to come from two sources. First, the resistance of the cartridge devices themselves is significant (measured at 2.1 cm of water per liter per minute for each cartridge). Second, the size of the entry orifice between the cartridge and the half face mask is considerably smaller than the total surface area available for airflow in the N95.

In contrast to the effect of respirator types, characteristics of the tasks clearly induced changes in all of the respiratory parameters studied. The tidal volume, minute ventilation, and breathing frequency were greater in those tasks involving heavier exertion than those that were more sedentary. Inspiratory, expiratory, and total time decreased, while duty cycle increased with increasing levels of exertion. Normally, the need for increased oxygen uptake is met by increasing minute ventilation, which can be a result of increased tidal volume, increased frequency of breathing, or both. In the study, the response to the greater exercise exertion appears to have included a combination of the increased frequency of breathing and increased tidal volume (volume per breath).

The heart rate also significantly increased with higher exertion tasks. The relationship between heart rate and ventilation is generally linear at exertion levels below the anaerobic threshold. In this study, a linear relationship was also seen during respirator use.

METHODOLOGY

The study demonstrated that it is feasible to make meaningful respiratory measurements noninvasively during work activities. The method depends on a respiratory inductive plethysmograph and does not require any connection between the measuring apparatus and the mouth or nose. Respiratory inductive plethysmographs have been used extensively in clinical sleep laboratories to evaluate breathing during sleep; such clinical testing typically seeks to determine whether breathing intermittently stops and, therefore, does not require accurate measurements of flows and volumes. Nevertheless, this study and others have demonstrated that these methods may be used effectively for respirator research.(42–44) Results obtained using actual respirators may differ from those using surrogate loads in laboratory settings.

CONCLUSION

Overall, the results suggest that for most individuals, including persons with mild respiratory impairments, either type of respirator may be tolerated from the physiological standpoint. However, effective protection against inhaled materials depends on proper utilization; differences in subjective responses among respirator types(45) may, therefore, have greater impact than physiological differences.

Furthermore, although the study analyzed the average responses, it is possible that there are a small number of individuals who will have particularly adverse physiological impacts. The average magnitude of several demonstrated differences between the two respirator types was small yet statistically significant. This may provide useful insight into mechanisms of adaptation. Nevertheless, the study supports the feasibility of using respirators on a widespread basis if necessary for maintaining essential services in the face of widespread concern about an infectious or terrorist threat.

ACKNOWLEDGMENTS

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REFERENCES

1. "Respirator Use and Practices." [Online] Available at http://www.bls.gov/iif/oshwc/osh/os/osnr0014.pdf (Accessed December 5, 2008).
2. **Raven, P.B., A.T. Dodson, and T.O. Davis:** The physiological consequences of wearing industrial respirators: A review. *Am. Ind. Hyg. Assoc. J. 40:*517–534 (1979).
3. **Louhevaara, V.A.:** Physiological effects associated with the use of respiratory protective devices. A review. *Scand. J. Work Environ. Health 10:*275–281 (1984).
4. **Harber, P., S. Shimozaki, T. Barrett, P. Losides, and G. Fine:** Effects of respirator dead space, inspiratory resistance, and expiratory resistance ventilatory loads. *Am. J. Ind. Med. 16:*189–198 (1989).
5. **Harber, P., K. SooHoo and M. Lew:** Effects of industrial respirators on respiratory timing and psychophysiologic load sensitivity. *J. Occup. Med. 30:*256–262 (1988).
6. **Akbar-Khanzadeh, F., and E.V. Pulido:** Using respirators and goggles to control exposure to air pollutants in an anatomy laboratory. *Am. J. Ind. Med. 43:*326–331 (2003).
7. **Coates, M.J., A.S. Jundi, and M.R. James:** Chemical protective clothing; a study into the ability of staff to perform lifesaving procedures. *J. Accid. Emerg. Med. 17:*115–118 (2000).
8. **Golan, E., M. Arad, J. Atsmon, J. Shemer, and H. Nehama:** Medical limitations of gas masks for civilian populations: The 1991 experience. *Mil. Med. 157:*444–446 (1992).
9. **Khoo, K.L., P.H. Leng, I.B. Ibrahim, and T.K. Lim:** The changing face of healthcare worker perceptions on powered air-purifying respirators during the SARS outbreak. *Respirology 10:*107–110 (2005).

10. **Loeb, M., A. McGeer, B. Henry, et al.:** SARS among critical care nurses, Toronto. *Emerg. Infect. Dis. 10:*251–255 (2004).
11. **Mitka, M.:** Face masks, respirators might help during pandemic flu outbreak. *JAMA 297(21):*2338 (2007).
12. **Luria, S., S. Givoni, and M. Alcalay:** Evaluation of a novel protective gas mask during medical unit activity. *Mil. Med. 164:*707–709 (1999).
13. **Donovan, K.J., and A.K. McConnell:** Do fire-fighters develop specific ventilatory responses in order to cope with exercise whilst wearing self-contained breathing apparatus? *Eur. J. Appl. Physiol. Occup. Physiol. 80:*107–112 (1999).
14. **Louhevaara, V., T. Tuomi, O. Korhonen, and J. Jaakkola:** Cardiorespiratory effects of respiratory protective devices during exercise in well-trained men. *Eur. J. Appl. Physiol. Occup. Physiol. 52:*340–345 (1984).
15. **Sackner, J.D., A.J. Nixon, B. Davis, N. Atkins, and M.A. Sackner:** Non-invasive measurement of ventilation during exercise using a respiratory inductive plethysmograph. I. *Am. Rev. Respir. Dis. 122:*867–871 (1980).
16. **Hankinson, J.L., J.R. Odencrantz, and K.B. Fedan:** Spirometric reference values from a sample of the general U.S. population. *Am. J. Respir. Crit. Care Med. 159*:179–187 (1999).
17. **Caretti, D.M., W.H. Scott, A.T. Johnson, K.M. Coyne, and F. Koh:** Work performance when breathing through different respirator exhalation resistances. *AIHAJ 62(4):*411–415 (2001).
18. **Caretti, D.M., and J.A. Whitley:** Exercise performance during inspiratory resistance breathing under exhaustive constant load work. *Ergonomics 41:*501–511 (1998).
19. **Johnson, A.T., W.H. Scott, C.G. Lausted, et al.:** Effect of respirator inspiratory resistance level on constant load treadmill work performance. *Am. Ind. Hyg. Assoc. J. 60:*474–479. (1999).
20. **Love, R.G., D.C. Muir, K.F. Sweetland, R.A. Bentley, and O.G. Griffin:** Acceptable levels for the breathing resistance of respiratory apparatus: Results for men over the age of 45. *Br. J. Ind. Med. 34:*126–129 (1977).
21. **Raven, P.B., A.W. Jackson, K. Page, R.F. Moss, O. Bradley, and B. Skaggs:** The physiological responses of mild pulmonary impaired subjects while using a "demand" respirator during rest and work. *Am. Ind. Hyg. Assoc. J. 42:*247–257 (1981).
22. **Thompson, S.H., and B.J. Sharkey:** Physiological cost and air flow resistance of respiratory protective devices. *Ergonomics 9:*495–499 (1966).
23. **Jones, J.G.:** The physiological cost of wearing a disposable respirator. *Am. Ind. Hyg. Assoc. J. 52:*219–225 (1991).
24. **Nielsen, R., A.R. Gwosdow, L.G. Berglund, and A.B. DuBois:** The effect of temperature and humidity levels in a protective mask on user acceptability during exercise. *Am. Ind. Hyg. Assoc. J. 48:*639–645 (1987).
25. **Gwosdow, A.R., R. Nielsen, L.G. Berglund, A.B. DuBois, and P.G. Tremml:** Effect of thermal conditions on the acceptability of respiratory protective devices on humans at rest. *Am. Ind. Hyg. Assoc. J. 50:*188–195 (1989).
26. **Johnson, A.T., C.R. Dooly, M.S. Sahota, K.M. Coyne, and M.B. Benjamin:** Effect of altered vision on constant load exercise performance while wearing a respirator. *Am. Ind. Hyg. Assoc. J. 58:*578–582 (1997).
27. **Akbar-Khanzadeh, F., M.S. Bisesi, and R.D. Rivas:** Comfort of personal protective equipment. *Appl. Ergon. 26:*195–198 (1995).
28. **Laird, I.S., R. Goldsmith, R.J. Pack, and A. Vitalis:** The effect on heart rate and facial skin temperature of wearing respiratory protection at work. *Ann. Occup. Hyg. 46(2):*143–148 (2002).
29. **Arif, A.A., G.L. Delclos, E.S. Lee, S.R. Tortolero, and L.W. Whitehead:** Prevalence and risk factors of asthma and wheezing among US adults: An analysis of the NHANES III data. *Eur. Respir. J. 21:*827–833 (2003).
30. **Sly, R.M.:** Changing prevalence of allergic rhinitis and asthma. *Ann. Allergy Asthma Immunol. 82:*233–248; quiz 248–252 (1999).
31. **Turkeltaub, P.C., and P.J. Gergen:** Prevalence of upper and lower respiratory conditions in the US population by social and environmental factors: Data from the second National Health and Nutrition Examination Survey, 1976 to 1980 (NHANES II). *Ann. Allergy 67:*147–154 (1991).
32. **Jessen, M., and L. Janzon:** Prevalence of non-allergic nasal complaints in an urban and a rural population in Sweden. *Allergy 44:*582–587 (1989).
33. **Mannino, D.M.:** COPD: Epidemiology, prevalence, morbidity and mortality, and disease heterogeneity. *Chest 121:*121S–126S (2002).
34. **Coultas, D.B., D. Mapel, R. Gagnon, and E. Lydick:** The health impact of undiagnosed airflow obstruction in a national sample of United States adults. *Am. J. Respir. Crit. Care. Med. 164:*372–377 (2001).
35. **Hodous, T.K., C. Boyles, and J. Hankinson:** Effects of industrial respirator wear during exercise in subjects with restrictive lung disease. *Am. Ind. Hyg. Assoc. J. 47:*176–180 (1986).
36. **Hodous, T.K., L. Petsonk, C. Boyles, J. Hankinson, and H. Amandus:** Effects of added resistance to breathing during exercise in obstructive lung disease. *Am. Rev. Respir. Dis. 128:*943–948 (1983).
37. **Wilson, J.R., P.B. Raven, W.P. Morgan, S.A. Zinkgraf, R.G. Garmon. and A.W. Jackson:** Effects of pressure-demand respirator wear on physiological and perceptual variables during progressive exercise to maximal levels. *Am. Ind. Hyg. Assoc. J. 50:*85–94 (1989).
38. **Harber, P., T. Barrett, S. Shimozaki, and R. Kanter:** Respirator effect in pulmonary impaired subjects. *Am. Rev. Respir. Dis. 139:*A491 (1989).
39. **Saatci, E., D.M. Miller, I.M. Stell, K.C. Lee, and J. Moxham:** Dynamic dead space in face masks used with noninvasive ventilators: A lung model study. *Eur. Respir. J. 23:*129–135 (2004).
40. **Coyne, K., D. Caretti, W. Scott, A. Johnson, and F. Koh:** Inspiratory flow rates during hard work when breathing through different respirator inhalation and exhalation resistances. *J. Occup. Environ. Hyg. 3:*490–500 (2006).
41. **Harber, P., J. Beck, C. Brown, and J. Luo:** Physiologic and subjective effects of respirator mask type. *Am Ind Hyg Assoc J*. 52:357–362 (1991).
42. **Caretti, D.M., P.V. Pullen, L.A. Premo and W.D. Kuhlmann:** Reliability of respiratory inductive plethysmography for measuring tidal volume during exercise. *Am. Ind. Hyg. Assoc. J. 55:*918–923 (1994).
43. **Harber, P., M. Lew, S. Shimozaki, and B. Thomas:** Noninvasive measurement of respirator effect at rest and during exercise. *Am. Ind. Hyg. Assoc. J. 50:*428–433 (1989).
44. **Stark, G.P., T.K. Hodous, and J.L. Hankinson:** The use of inductive plethysmography in the study of the ventilatory effects of respirator wear. *Am. Ind. Hyg. Assoc. J. 49:*401–408 (1988).
45. **Harber, P., S. Bansal, S. Santiago, et al.:** Multidomain subjective response to respirator use during simulated work. *J. Occup. Environ. Med. 51*: 38–45 (2009).