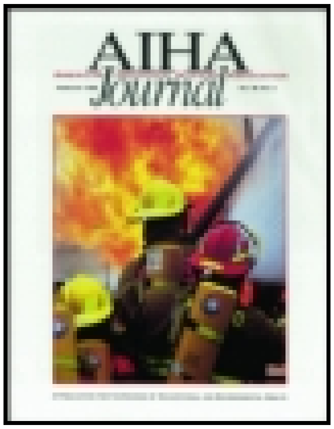

American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

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Published online: 04 Jun 2010.

Am. Ind. Hyg. Assoc. J. 50(7):372-378 (1989)

Workplace Measurement of Respirator Effects Using Respiratory Inductive Plethysmography*

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A useful system to study the cardiopulmonary effects of respirators in the workplace would be reliable, portable, and lightweight and would not encumber the nose or mouth or require modification to the respirator. Twenty men using such a system (which measured ventilatory parameters by respiratory inductive plethysmography [RIP]) were studied. The subjects all performed their usual jobs which involved some work with and some without a respirator. Twelve subjects used airline respirators and eight used air-purifying respirators. The RIP equipment measurements included respiratory frequency, tidal volume (V_T), minute ventilation ($\dot{V}$), and heart rate (HR). The RIP data from 20 other subjects was lost because of equipment malfunction, primarily lead separation in those whose jobs involved climbing around large workpieces. In general, the workers' cardiopulmonary parameters increased during respirator wear, probably because of a combination of factors, including the increased exercise of most respirator-requiring tasks and the weight and heat stress associated with the respirator and protective clothing. When the ventilatory parameters with and without a respirator were compared at the same heart rates, no significant differences were noted in V_T for the entire group. Respiratory frequency, however, and $\dot{V}$ increased with respirator wear. The effects of respirators alone were found to be commonly confounded in the workplace by changes in protective clothing, exercise requirements, and ambient heat stress. Further improvements in the portable RIP system are needed before it can be accepted as a reliable ventilatory measurement device in the workplace.

Introduction

An extensive literature exists regarding the physiological and psychological effects of respiratory protective masks (respirators).[1-3] Studies have been primarily laboratory-based, although a number of field studies exist.[4-7] Although the experimental conditions often cannot be controlled in workplace studies, these studies should provide the most realistic data on actual respirator effects. These studies, however, have been limited by the lack of a portable ventilatory measurement system that does not encumber the nose or mouth or require modification of the respirator. Reported here is the authors' experience with such a system which measures ventilatory parameters by respiratory inductive plethysmography (RIP).

Experimental Materials and Methods

Forty male volunteers were recruited from a steel mill, two equipment repair plants, and one university maintenance department. Of these, 20 were excluded because of incomplete data (see below), leaving 20 subjects in the study. The three steel mill employees worked at a blast furnace and wore long shirts, pants, and work boots. When working with the molten ore, they also wore a dual cartridge, half-face respirator (Scott Comfo II, Scott Aviation, Lancaster, N.Y.) and an aluminum-coated hooded garment. The respirator work periods lasted approximately 30 min. Work both with and without a respirator was performed standing. The employees from the two equipment repair plants were eight sandblasters, six spray painters, and two other workers. When sandblasting, employees wore coveralls with an airline respirator hood (Bullard 77-0, E.D. Bullard Co., Sausalito, Calif.) with cooled inspired air in a large enclosed bay. Large workpieces required that employees do climbing and bending. Work without a respirator consisted of coiling lines and cleanup activities. Four spray painters used airline respirators (3M Airline, St. Paul, Minn.) and two wore dual cartridge, full-face respirators (Scott). Activities were similar to those of the sandblasters. In both groups, respirator work periods lasted from 5 to 40 min. The two other industrial plant subjects wore half-face, dual cartridge respirators (SURVIVEAIR, Division of U.S.D. Corp., Santa Ana, Calif.) in sanding or cleaning activities, almost all done in the standing position. The university employee used a dual cartridge respirator in outside sidewalk work.

In the data analysis, the subjects were grouped into the following five categories: (1) blast furnace workers (n = 3); (2) other workers using air-purifying respirators (n = 5); (3) air purifying—total (n = 8, Groups 1 and 2 combined); (4) airline respirator workers (n = 12); (5) all respirator wearers (n = 20), total group. Anthropometric data on the subjects by group are presented in Table I.

The studies were performed during summer months, and the blast furnace and equipment repair plants (hangars) were largely open to the outside environment. Dry bulb temperatures in the working areas generally ranged from 25° to 30°C, and wet bulb temperatures ranged from 15° to 19°C.

Each subject read and signed an informed consent form approved by the National Institute for Occupational Safety and Health (NIOSH) Human Subjects Review Board. Spi-

*Mention of brand names does not constitute endorsement by DHHS, CDC, or NIOSH.

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TABLE I
Anthropometric Data[A]

Respirator Worn	No.	Age (yr)	Height (cm)	Weight (kg)	$\frac{FEV}{FVC}$, %	FVC % Predicted
Air-purifying (AP) with suit	3	36.7 (7.6)	175.3 (10.7)	82.1 (8.6)	80.5 (6.1)	99.3 (10.1)
AP: other	5	36.0 (5.3)	178.6 (4.3)	98.2 (20.4)	80.1 (5.0)	106.7 (16.0)
AP: total	8	36.3 (5.8)	177.4 (6.8)	92.2 (18.1)	80.3 (5.0)	103.9 (13.8)
Airline	12	36.4 (7.3)	171.5 (6.4)	77.4 (11.0)	78.0 (5.4)	107.5 (18.0)
All respirators	20	36.4 (6.6)	173.9 (7.0)	83.3 (15.7)	78.9 (5.2)	106.1 (16.1)

[A]Means (± SD)

rometry following American Thoracic Society guidelines[8] and a modified British Research Council questionnaire[9] then was administered. The RIP equipment then was put on the subjects and calibrated. Briefly, the equipment consisted of a wired elastic band around the chest and another around the abdomen to measure changes in their circumference by means of changes in the bands' inductances. These changes in the rib cage and abdomen during respiration reflect the subject's tidal volume,[10] once they are calibrated with a spirometer. Because most of the anticipated work was done in the standing position, this position was used during the calibration.[11] Calibration, as previously described,[12] consisted of measuring inspired volume with the spirometer during multiple breaths and simultaneously recording both the rib cage and chest RIP signals. A least squares analysis[13] yielded appropriate average gain factors for the RIP signals. The two average gain factors then could be used to calculate the tidal volume during calibration and this volume compared to that measured by spirometry. The percent error was calculated as follows:

$$\frac{V_{T,RIP} - V_{T,SP}}{V_{T,SP}} \times 100$$

where $V_{T,SP}$ = tidal volume as measured by the spirometer and

$V_{T,RIP}$ = tidal volume as calculated from the RIP.

Since the initial spirometrically measured volumes were used to derive these average gain factors, one would expect a relatively low error. To determine if band slippage occurred during work, the calibration procedure was repeated after work. The initial gain factors were used to calculate the $V_{T,RIP}$ at the postwork calibration. These values were compared with the spirometrically measured tidal volumes obtained at the postwork calibration, and a second percent error was generated. If the RIP bands had moved during work, a larger postwork error, as compared with the prework error, would be expected.

A heart rate monitor also was used (ExerSentry, Respironics Co., Monroeville, Pa.), and RIP and heart rate data were recorded on a small tape cassette worn in a pouch around the waist. The total weight of all the equipment was 1.6 kg.

After the equipment was calibrated, the employee returned to his work station and carried out his usual activities for at least 30 min, about half of which involved respirator use. An observer with a stop watch recorded all activities, noting carefully when the respirator was and was not worn. In every case, subjects were monitored both before and after at least one respirator-wearing work session.

After the physiological monitoring, subjects were asked several questions regarding respirator wear. They first were requested to grade the degree of comfort of the respirator during the work shift as (1) fairly comfortable, (2) somewhat uncomfortable, (3) moderately uncomfortable, or (4) very uncomfortable. The answers were given a number for analysis purposes. Another question was, "Which of the following aspects of wearing a respirator bothers you the most?" Subjects were asked to indicate a first and second choice from the following list: face or head irritation; trouble breathing; excessive heat; added weight; other. (The response "other" was followed by a blank for the subject to fill in his response.) Finally, subjects were asked to complete a brief, commercially available anxiety trait questionnaire.[14]

Extensive software programs for a VAX 11/780 computer (Digital Equipment Corp., Maynard, Mass.) were written to digitize all data at 20-Hz intervals; to assist in visual review, editing, and labeling of RIP segments with excessive artifact; to compute breath-by-breath analysis; and to create a summary file for each different test segment. Before digitization, the RIP signals were filtered with a low-pass filter to remove unwanted high frequency noise.

The effects of respirator wear on cardiopulmonary parameters were evaluated using paired, two-tailed t-tests at a significance level of 0.05. Respirator effects when controlling for work rate as represented by heart rate were evaluated by using least squares regression lines for each parameter with heart rate and calculating the parameter value at an arbitrary heart rate of 100.

Results

The reasons for excluding 20 subjects are given in Table II. A number of these problems, such as broken contact, should be easily rectified. Changes in the equipment and electrical contacts were made, however, to increase durability between a prior laboratory study[12] and the present one. It is believed that climbing, crawling, and similar activities of the subjects in this study were important causes of the excessive artifacts. Examples of usable data and unusable data caused by excessive artifact are shown in Figure 1. It should be recognized that excessive artifact was based on the reviewer's judgment that valid end-inspiratory and end-expiratory points could not be determined. The same reviewer was used for all 40 subjects entering the study.

Calibration data for the 20 subjects with acceptable data are shown in Table III, in which the mean tidal volumes as measured by the spirometer and RIP are listed both before and after the work session. For the group as a whole, the RIP system produced tidal volumes within 2% of those measured by spirometry. The percent error (absolute values) was greater than 10% in one subject in the prework calibration and in three subjects in the postwork calibration. The change over the work period in calibration factors is best illustrated in the last column of Table III, in which 5 subjects' absolute percent error changes were greater than 10%. In the prework calibration, for example, Subject 9's RIP-measured tidal volume was 6.4% higher than the simultaneously measured ("true") spirometer V_T. After working, however, his RIP-measured V_T was 4.4% lower than the spirometer V_T. It was not possible in the present protocol to determine when these changes occurred, and all subsequent data is based on the initial calibration factors.

The comparison of mean cardiopulmonary parameters with and without respirator use is shown in Table IV. In general, all groups showed similar changes while wearing respirators, although some changes were not statistically significant. The respirator-work condition was associated with an increase in heart rate, respiratory rate, V_T, and time of the inspiratory time fraction of each respiration (T_I/T_{TOT}). The rib cage fraction of V_T (VOL RC/V_T) did not change significantly in any group with respirator use.

TABLE II
Reasons for Excluding Data

Reason	Number of Subjects
Excessive artifact in RIP signals (one or both)	11
Inadequate calibration	3
RIP signal over-ranging	2
RIP or heart rate lead separation (lost data)	2
Other (one technician error, one cassette damaged)	2
Total	20

When controlling for work rate as represented by heart rate, the group as a whole still had significant increases in respiratory frequency (f), $\dot{V}$, and T_I/TOT when wearing a respirator (Table V). Several other differences noted in Table IV became nonsignificant, however, when parameters were compared at the same heart rate. It should be noted that it was the opinion among the five observers that the subjects' work while wearing a respirator was, in general, more strenuous than that while not wearing one.

Only 2 of the 20 subjects reported chronic cough and phlegm (both were cigarette smokers). Both the air-purifying and the airline respirator wearers graded the degree of respirator comfort as 1.9 (mean value), that is, close to a "somewhat uncomfortable" rating. The first and second most bothersome aspects of respirator wear were excessive heat (14 responses) and added weight (12 responses), as shown in Table VI. Trouble breathing was noted only among those using air-purifying respirators. On the other hand, complaints of added weight were more common among the airline respirator users.

The group mean on the anxiety trait questionnaire was 35.2, within the reported range of 34–36 for a standard population.[14] The test has a minimum possible score of 20 and a maximum of 80. No correlation was found between the reported degree of respirator comfort and the anxiety trait scores. Those with respirator comfort scores of 1, 2, 3, and 4 had a mean anxiety score of 34.3 (n = 9), 35.3 (n = 6), 39.7 (n = 3), and 31.5 (n = 2), respectively.

Discussion

The study of respirator effects in the workplace presents several problems. One is the technical difficulty in measuring pulmonary parameters without altering the function or effects of the respirator itself. A second difficulty arises when one attempts to measure physiological parameters while not disrupting the employee's normal work activity. A third problem is the inability to control for confounding factors which also may affect the physiological parameters of interest. The respiratory inductive plethysmography (RIP) equipment used in this study can overcome the first two problems. It is portable, relatively light, and does not encumber the mouth or nose. At present, however, in this study this equipment itself has a number of problems. A large loss of data (20 subjects) was caused by equipment failure. Accuracy is much less than that which can be obtained in a laboratory setting, and the problem of band slippage in bending, sweating subjects remains.

As Table III illustrates, the overall RIP accuracy in the subjects with usable data was good. Of the 20 subjects, however, 5 had a calibration change of 10% or greater, which theoretically could obscure any true differences in V_T and $\dot{V}$ caused by the respirator-work condition. A change in calibration also might produce differences between respirator and nonrespirator work data that did not, in fact, exist. In this study, however, the monitoring of subjects both before and after their respirator work should have reduced this possible error. Tighter taping and strapping might reduce

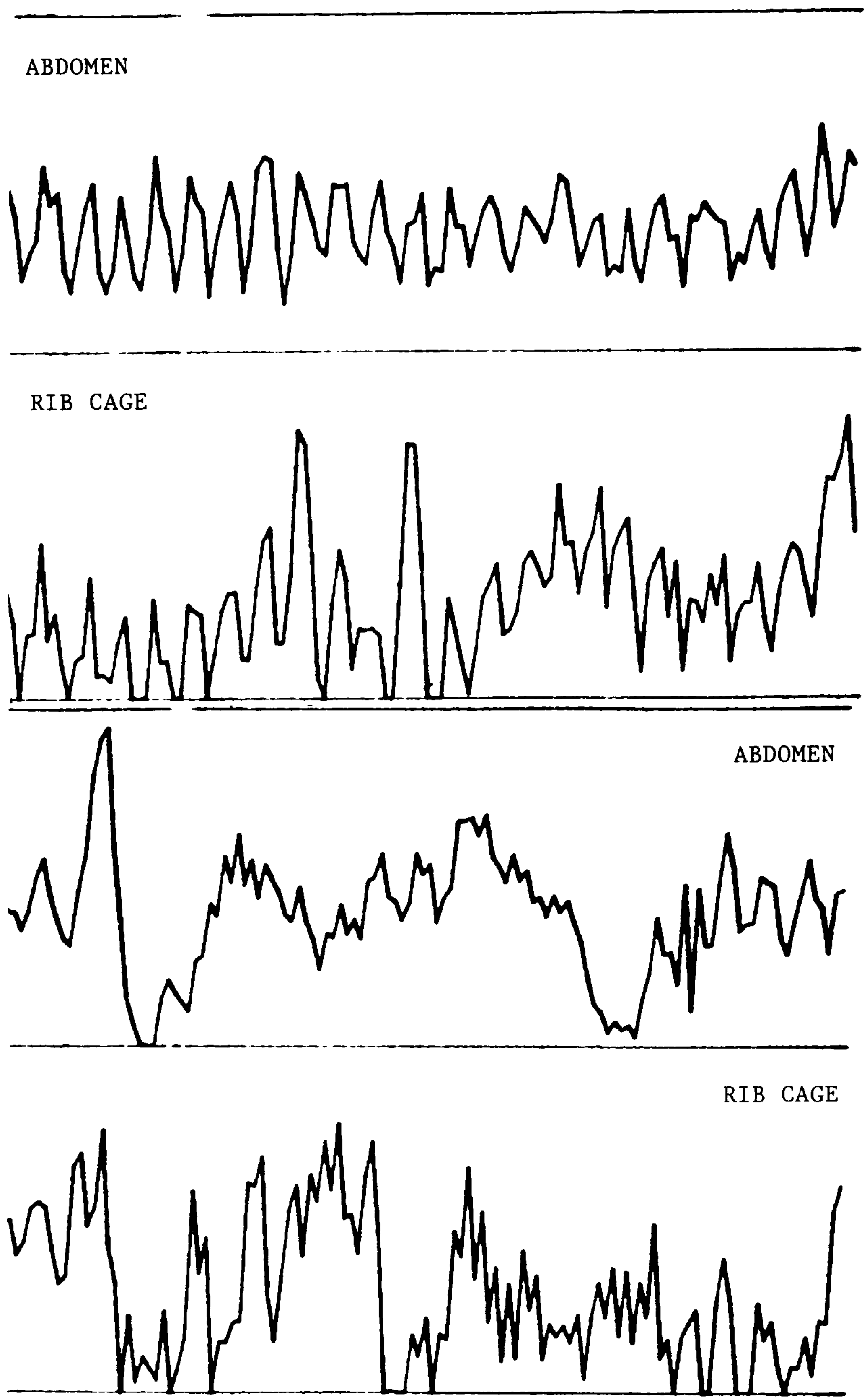

Figure 1—Example of (mostly) usable RIP data. Bottom: Example of unusable RIP data because of excessive artifact. Both sets were collected during exercise. Horizontal axis represents a time interval of 38 sec. Vertical axis represents volume signal.

TABLE III
Comparison of Pre- and Postwork Calibration[A]

Subject	Prework Calibration $V_{T,SP}$[B] (mL)	Prework Calibration $V_{T,RIP}$[C] (mL)	Prework Calibration Percent Error	Postwork Calibration $V_{T,SP}$ (mL)	Postwork Calibration $V_{T,RIP}$ (mL)	Postwork Calibration Percent Error	Percent Error Change[D]
1	358	360	0.6	393	538	36.9	36.3
2	407	409	0.5	399	420	5.3	4.8
3	716	708	- 1.1	718	740	3.1	4.2
4	532	525	- 1.3	692	697	0.7	2.0
5	1272	1272	0.0	1361	1379	1.3	1.3
6	475	452	- 4.8	624	619	- 0.8	4.0
7	1556	1572	1.0	1398	1383	- 1.1	- 2.1
8	862	833	- 3.4	919	898	- 2.3	1.1
9	544	579	6.4	712	681	- 4.4	-10.8
10	528	470	-11.0	483	503	4.1	15.1
11	1089	1142	4.9	1195	1410	18.0	13.1
12	813	786	- 3.3	902	887	- 1.7	1.7
13	533	516	- 3.2	371	372	0.3	3.5
14	1163	1263	8.6	1397	1172	-16.1	-24.7
15	955	952	- 0.3	932	986	5.8	6.1
16	545	543	- 0.4	554	550	- 0.7	- 0.4
17	810	795	- 1.9	781	718	- 8.1	- 6.2
18	1055	1153	9.3	1296	1380	6.5	- 2.8
19	719	719	0.0	811	884	9.0	9.0
20	751	731	- 2.7	834	788	- 5.5	- 2.9
Mean	784	789	0.6	839	850	1.4	0.8
SD	310	329	4.6	330	328	10.4	11.3

[A]See text for explanation
[B]$V_{T,SP}$ = tidal volume measured by spirometry.
[C]$V_{T,RIP}$ = tidal volume measured by respiratory inductive plethysmography.
[D]Postwork percent error minus prework percent error.

TABLE IV
Comparison of Mean (± SD) Cardiopulmonary Parameters with and without Respirator Wear

Resp. Group	Resp. Cond.	HR (Bpm)	f (/min)	V_T (mL)	$\dot{V}$ (L/min)	T_I/T_{TOT}	VOL RC/V_T
Air-purifying with suit (n = 3)	off	114.2 (13.5)	28.0 (1.7)	[A]480 (115)	14.24 (3.52)	[A]0.33 (0.02)	0.33 (0.07)
	on	125.3 (20.3)	32.2 (3.0)	595 (151)	19.26 (6.25)	0.36 (0.02)	0.37 (0.05)
Air-purifying other (n = 5)	off	[A] 95.5 (8.8)	23.0 (2.1)	[A]580 (157)	[A]12.64 (2.64)	[B]0.32 (0.02)	0.37 (0.17)
	on	105.2 (6.3)	26.7 (7.1)	927 (345)	22.90 (8.14)	0.39 (0.05)	0.40 (0.15)
Air-purifying total (n = 8)	off	[A]102.5 (13.8)	24.9 (3.2)	[B]544 (143)	[B]12.87 (2.76)	[B]0.33 (0.02)	0.36 (0.14)
	on	112.8 (13.8)	28.8 (6.3)	803 (322)	21.53 (7.25)	0.38 (0.04)	0.39 (0.12)
Airline (n = 12)	off	[B]102.7 (16.6)	[B]26.2 (3.2)	585 (171)	[A]14.48 (3.99)	[B]0.33 (0.02)	0.51 (0.23)
	on	114.3 (16.6)	29.9 (5.2)	636 (223)	17.76 (5.60)	0.36 (0.02)	0.49 (0.22)
All resp. (n = 20)	off	[B]102.6 (15.1)	[B]25.7 (3.2)	[B]568 (158)	[B]13.83 (3.56)	[B]0.33 (0.02)	0.45 (0.21)
	on	113.7 (15.9)	29.4 (5.5)	703 (272)	19.27 (6.41)	0.37 (0.03)	0.45 (0.19)

[A]$p < 0.05$
[B]$p < 0.01$

TABLE V
Comparison of Mean (± SD) Ventilatory Parameters Calculated at a Heart Rate of 100 with and without Respirator Wear

Resp. Group	Resp. Cond.	f (/min)	V_T (mL)	$\dot{V}$ (L/min)	T_I/T_{TOT}	VOL RC/V_T
Air-purifying with suit (n = 3)	off	25.4 (1.1)	435 (79)	10.38 (0.94)	0.30 (0.01)	0.33 (0.07)
	on	25.9 (4.7)	408 (112)	9.66 (5.13)	0.31 (0.04)	0.39 (0.08)
Air-purifying other (n = 5)	off	23.7 (1.9)	[A]644 (250)	14.46 (5.17)	[A]0.34 (0.02)	0.38 (0.16)
	on	26.6 (7.0)	925 (346)	22.87 (8.50)	0.39 (0.05)	0.40 (0.15)
Air-purifying total (n = 8)	off	24.3 (1.8)	566 (222)	12.93 (4.47)	0.33 (0.03)	0.36 (0.13)
	on	26.3 (5.9)	731 (379)	17.92 (9.78)	0.36 (0.06)	0.40 (0.12)
Airline (n = 12)	off	[B]26.2 (3.4)	596 (186)	14.88 (5.27)	0.34 (0.03)	0.49 (0.22)
	on	29.9 (5.4)	594 (222)	16.98 (7.08)	0.35 (0.03)	0.47 (0.22)
All resp. (n = 20)	off	[B]25.4 (2.9)	584 (196)	[A]14.10 (4.94)	[A]0.34 (0.03)	0.44 (0.19)
	on	28.5 (5.7)	649 (294)	17.35 (8.03)	0.36 (0.04)	0.44 (0.18)

[A]$p < 0.05$
[B]$p < 0.01$

this problem, but chest strapping is known to alter pulmonary mechanics,[15] thus modifying the pulmonary parameters of interest. A fuller discussion of calibration techniques and RIP accuracy has been published previously.[12]

The third problem of confounding factors is not easy to resolve. It is believed that the changes observed with respirator use (Table IV) are partly caused by the different work conditions during their use as opposed to the respirator effects alone. This is based partly on the observation of the workers and on studies which show that most lightweight respirators have minimal heart rate effect.[16-18] Except for the "other air-purifying" respirator group, all respirator use also was associated with extra protective clothing that would add weight and contribute to heat stress. These factors would account for some increase in heart rate even if work load was otherwise unchanged.

When heart rate was controlled, fewer differences were noted between respirator wear and no respirator wear (Tables IV and V). An independent stress from respirator wear, however, was observed at least in the total group. One should note that body temperature, a potential confounder in the relationship between ventilatory parameters and heart rate, was not measured in this study. Because of this and the large variability noted, one must interpret these data with caution. It also should be noted that all workers in this study essentially did "batch work" and did not have to wear their respirators for more than approximately 40 min at a time. Greater physiological and psychological stress would be expected in workers whose jobs require continuous respirator use for hours at a time.

Because the RIP system records data on a breath-by-breath basis, analysis of the various timed components of breathing is possible.[19] As expected, the addition of an air-purifying respirator increased T_I/T_{TOT} as V_T increased (Table V). Since the reduction in expiratory time during exercise is limited by several factors, including the lungs' elastic and resistive properties, a marked increase in inspiratory time (from added inspiratory resistance) could unduly stress some subjects.[20]

The RIP system also yields separate data for rib cage (RC) and abdominal (AB) volumes. The RC component primarily reflects thorax volume change while the AB reflects diaphragm contraction.[21] Study of these factors has substantially increased understanding of respiratory mechanisms in health and disease.[22-25] Research into different patterns of breathing also may yield useful information regarding fitness to wear respirators. No significant changes were found in the present study, which tested only low inspiratory resistances.

The anxiety trait questionnaire was used because of earlier research suggesting that high scores correlated with difficulty in adapting to respirator use.[26] The negative findings perhaps are not surprising in this group, most of whom had

TABLE VI
Reported First and Second Most Bothersome Aspects of Respirator Wear

Complaint	Air-Purifying (n = 8) 1st	Air-Purifying (n = 8) 2d	Airline (n = 12) 1st	Airline (n = 12) 2d	Total
Face or head irritation	1	3	1	1	6
Trouble breathing	4	0	0	0	4
Excessive heat	3	3	6	2	14
Added weight	0	2	2	8	12
Other[A]	0	0	3	1	4
Total	8	8	12	12	40

[A]One "dry mouth," one "visual impairment," and one subject with no first or second complaints at all.

normal spirometry (Table I) and years of respirator experience. The other subjective data were not obtained with a validated questionnaire, but they do suggest some discomfort with respirator wear. The common complaints of excessive heat and added respirator weight (Table VI) are not unexpected given the respirators worn and the warm working conditions.

The results of this study suggest that during respirator-requiring work, changes in work level, protective clothing, and ambient heat stress are important stress factors in addition to the respirator's effects, per se. This emphasizes the need to consider all aspects of the respirator-work situation in assessing the physiological and subjective stress to employees. The data also suggest that further improvements in the portable monitoring of cardiopulmonary parameters are needed to accurately evaluate respirator-work effects in the workplace.

Acknowledgment

The authors gratefully thank Jeff Rushford for his technical assistance and Helen Michael for manuscript preparation.

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2 May 1988; Revised 29 December 1988