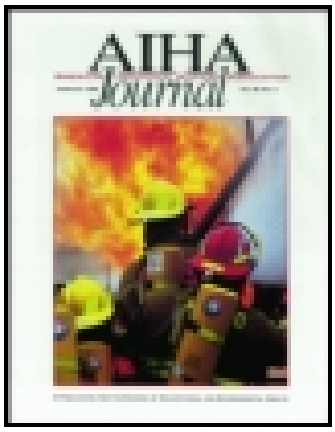

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The Use of Inductive Plethysmography in the Study of the Ventilatory Effects of Respirator Wear*

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The authors recently developed an ambulatory system, in which a self-contained respiratory inductive plethysmograph (RIP) was used, to measure noninvasively the volume and time components of breathing. Since it does not use nasal or oral devices, such a system is particularly suitable for use in studying the effects of respiratory protective masks on respiratory parameters. In order to validate this portable system, 22 healthy subjects were exercised on a treadmill; RIP and pneumotachographic minute ventilation measurements were compared. A short, graded submaximal exercise protocol was run 3 times by each subject under each of the following conditions: no oral mouthpiece; oral mouthpiece with pneumotachograph; and wearing an industrial protective mask (half facepiece, twin cartridge). Chest and abdominal RIP signals, a time signal and either a pneumotachograph or heart-rate signal were recorded on a small cassette recorder worn at the belt. The data tapes were later edited and analyzed by computer. Data from 5 subjects were excluded because of equipment malfunction. The average error in RIP-measured ventilation compared to values simultaneously measured by a pneumotachograph in the 17 remaining subjects over all exercise levels was -3.16%. Marked variability (SD = 11.26%), however, was found in individuals at different exercise levels and especially between subjects. Use of a respirator was associated with a decreased respiratory frequency, an increased tidal volume and minute ventilation, and an unchanged heart rate. At present, the portable RIP system has substantial variability that limits its ability to measure ventilation accurately.

Introduction

Federal regulations require that workers be provided with respiratory protective devices (respirators) when atmospheric contamination by hazardous substances cannot be prevented by engineering controls.[1] There are, currently, many thousands of workers who utilize respirators on a daily basis. This number may increase if federal regulations are revised to "permit increased reliance on respirators."[2] As more persons utilize respirators, the medical screening of workers for fitness to wear a respirator will become more important. Federal regulations also state: "Persons should not be assigned to tasks requiring use of respirators unless it has been determined that they are physically able to perform the work and use the equipment. The local physician shall determine what health and physical conditions are pertinent."[1] The physiological effects of respirator wear thus are important considerations, both when evaluating specific workers for respirator use and when contemplating changes in regulations that might result in many more workers being required to use respirators.

There have been many studies that have investigated the effects of a variety of respiratory protective devices on the ventilation and exercise tolerance of young, healthy persons. There have been relatively few studies on subjects who are older[3] or who have some degree of pulmonary impairment.[4-6] The vast majority of studies have been done in the laboratory by using either the treadmill or bicycle ergometer, although some studies have involved either simulated work exposures[7] or actual field conditions.[8] Rarely have there been studies of the ventilatory effects of respirators in a sample of workers actually performing their jobs, even though these studies would provide the most realistic data. One of the major reasons such ventilatory studies have not been performed is the lack of a suitable method for measuring parameters (other than respiratory rate) in freely ambulatory respirator-wearing subjects. The authors' initial experiences with a portable form of a respiratory inductive plethysmograph (RIP) are reported here. This equipment allows pulmonary monitoring of ambulatory subjects without oro-nasal encumbrance.

Methods

Subjects

Male subjects (N = 22)—predominately office and laboratory personnel—were studied, but analysis was performed only on the 17 with complete data (see "Results"). Mean values (SD) for age, height, and weight were 31.3 (3.7) years, 177 (10.4) cm, and 81.6 (11.6) kg, respectively. All subjects gave informed consent, and the project was reviewed and approved by the National Institute of Occupational Safety and Health's (NIOSH) Human Subjects Review Board. Subjects were screened before entry into the study by a questionnaire, physical examination and a resting electrocardiogram.

Equipment

A commercially available DC-coupled respiratory inductive plethysmograph (Respitrace Non-Invasive Monitoring Systems, Inc., Ardsley, N.Y.) was used. It is described in detail

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

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elsewhere.[9,10] RIP allows for measurement of volume and time components of respiration non-invasively with no physical connection to the airway. Briefly, an insulated wire is sewn into an elastic belt in a zig-zag pattern. Two belts are used: one encircles the rib cage (RC); the second encircles the abdomen (AB). An oscillating current is passed through the wires. Volume changes in the RC and AB can be calculated from changes in the self-inductance of the coil induced by changes in the cross-sectional area of the belt after calibration with a spirometer.

Data were recorded on a four-channel miniature analog tape recorder (Medilog, Ambulatory Monitoring, Inc., Ardsley, N.Y.). The first channel received the RIP-RC signal. The second channel recorded the RIP-AB signal. The third channel recorded the spirometer volume signal during calibration, or a heart rate or pneumotachograph signal during exercise. The fourth channel received a time reference signal from a crystal controlled clock to allow for correction of any variations in tape speed.

The heart-rate signal was provided by an ambulatory heart-rate monitor (Exer Sentry, Respitronics, Inc., Monroeville, Pa.) modified to deliver a recordable electronic pulse with each cardiac cycle.

The RIP-RC and -AB bands were positioned over the chest wall and upper abdomen. The heart-rate sensors were contained in a third band that was placed around the lower chest, between the two RIP bands. The RIP oscillator (4.6 × 4 × 2 cm, 60 g) was taped to the skin and secured by the belt containing the heart-rate sensors. The 3 bands and the oscillator then were wrapped by four 6-in. elastic bandages that, in turn, were covered by an elastic net, stress test t-shirt (BandNet Western Medical, Limited, Reseda, Calif.). The signal from the RIP bands was fed through a Medilog Respitrace Interface, then to the 4-channel recorder. The heart-rate signal passed through the modified heart-rate monitor and then to the 4-channel recorder. The 4-channel recorder (11.1 × 8.8 × 3.6 cm), the interface (12 × 6.5 × 4 cm), and the heart-rate monitor (10.2 × 6.0 × 2.1 cm) were stored in a leather pouch (18 × 18 × 4.5 cm) that was worn on a belt around the waist. The complete system weighed 1.6 kg.

Calibration

At the time of calibration, the heart-rate signal was disconnected from the 4-channel recorder, and this channel was used to record the volume signal from an Ohio No. 840 spirometer (Ohio Instruments, Madison, Wis.). A 1.5-L calibration syringe was used to enter a signal of known volume onto the tape. Then the subjects were asked to engage in normal tidal breathing from the spirometer for three 30-sec periods. They then were asked to breathe normal tidal volumes with only their chest for three 30-sec periods and then with only their abdomen for three 30-sec periods. The spirometer was flushed between each period. These 9 periods of 3 different patterns of tidal breathing, in a standing position, then were used to calibrate the RIP by the least squares method.[11] The pneumotachograph was calibrated with a 1.5-L syringe.

RIP calibration was performed both before and after exercise. RC and AB gain factors generated from the initial calibration were used in two analyses. They first were used to compare the initial RIP values with the simultaneously spirometrically measured tidal volumes recorded during the initial calibration. 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;
$V_{T,RIP}$ = tidal volume as calculated from the RIP.

Since the initial spirometrically measured volumes were used to derive these gain factors, one would expect a relatively low error. These same initial gain factors then were used to calculate the $V_{T,RIP}$ at the postexercise calibration. These values were compared with the spirometrically measured tidal volumes obtained at the postexercise calibration, and a second percent error was generated. If the RIP bands had moved during exercise, a much larger postexercise error, as compared with the preexercise error, would be expected.

Protocol

The test subjects were outfitted with the equipment, and the RIP was calibrated as just described. The subjects then performed a graded treadmill exercise protocol while wearing RIP under three conditions of oro-nasal covering: 1) No oro-nasal encumbrance (designated RIP alone); 2) Breathing through a mouthpiece connected to a Fleisch pneumotachograph (Fleisch, Lausanne, Switzerland) and; 3) Wearing a half-face, twin-cartridge respirator (Survivair air purifying respirator with organic vapor cartridge 1001-00, USD, Corp, Santa Ana, Calif.). The Fleisch pneumotachograph and associated equipment permitted calculation of reference tidal volume and minute ventilation values. The order in which the 3 oro-nasal coverings were tested was assigned randomly. Exercise consisted of standing in place, then walking at 4.8 km/hr (3 mph) at 0%, 4%, 8% and 12% grades. Each level of exercise, including standing, lasted 5 min, except the 12% grade that lasted 3 min. There was 5 min of seated rest after each exercise series. The first 15 sec of data of each exercise level was assumed to be nonsteady state and was excluded from analysis.

The RIP-RC, -AB, and time signals were recorded during all three oro-nasal conditions. The heart rate was recorded, beat-by-beat, under conditions of RIP alone and while wearing the respirator. The heart-rate signal was replaced by the pneumotachograph signal while the subjects were connected to it.

Data Analysis

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;

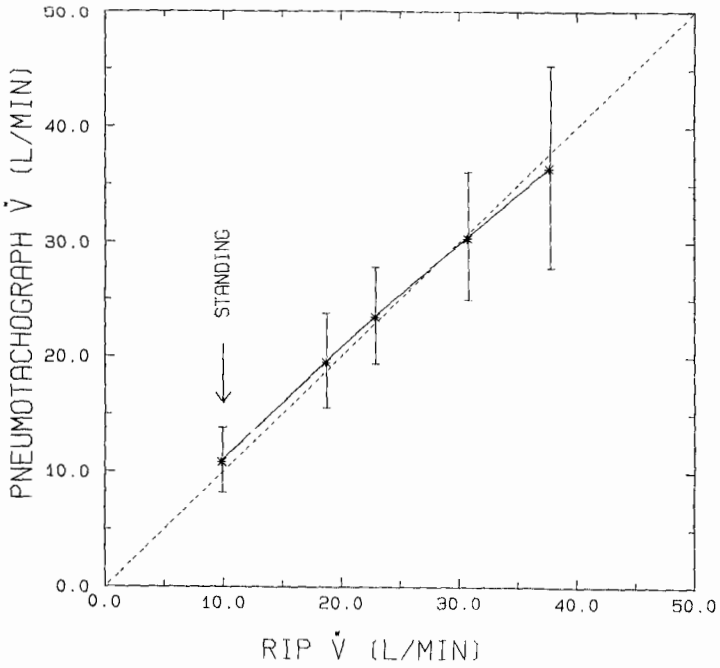

Figure 1—Comparison of group mean ventilation ($\dot{V}$) while standing and at four levels of exercise as measured simultaneously by a pneumotachograph and by respiratory inductive plethysmography (RIP). Dashed line is line of identity. Bars represent ± 1 SD.

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. Statistical comparisons used standard and paired t-testing.

Results

Data from 5 of the 22 subjects were excluded. In 1 case, the test was halted before completion because of premature cardiac beats. In the other 4 subjects, equipment malfunctions resulted in the loss of data. In 2 of the 4, the malfunction was in the RIP apparatus. In the other 2, there was loss of the pneumotachograph signal.

The comparison of the minute ventilation measured by the RIP ($\dot{V}_{RIP}$) and that measured by the reference pneumotachograph ($\dot{V}_P$) is shown in Figure 1. This provided a measure of accuracy of the RIP. The percent error was calculated as follows:

$$\frac{\dot{V}_{RIP} - \dot{V}_P}{\dot{V}_P} \times 100$$

The overall mean percent error for all individuals at all exercise levels was -3.16%, SD 11.26. As reflected in the standard deviation, however, there was marked variability when the errors for each individual at each work level were examined (Table I).

Results of the comparison of pre- and postexercise calibration are shown in Table II. The mean percent error changed from -1.2% to 6.0%, or 7.2%. The absolute value of the percent error change was 10% or more in 10 subjects, and was less than 5% in only 2 subjects.

The subjects' mean values for minute ventilation ($\dot{V}$), respiratory frequency (f), tidal volume (V_T), ratio of inspiratory

TABLE I
Percent Error (SD) in Respiratory Inductive Plethysmography-Measured Minute Ventilation at Each Level of Exercise

Subject	Standing	4.8 km/hr (3.0 mph)				Mean Percent Error (SD) for Each Subject
		0% Grade	4% Grade	8% Grade	12% Grade	
1	- 6.5 (0.88)	0.0 (1.10)	- 1.7 (1.44)	2.0 (3.10)	5.5 (2.57)	- 0.14 (4.45)
2	-11.9 (4.63)	- 2.0 (2.52)	- 2.8 (4.98)	- 1.3 (2.43)	0.5 (1.12)	- 3.50 (4.85)
3	-20.9 (5.45)	-17.7 (2.41)	-18.9 (1.89)	-15.2 (2.10)	-14.4 (4.21)	-17.42 (2.67)
4	-18.5 (2.55)	- 6.8 (8.86)	- 3.1 (3.85)	18.9 (4.71)	19.4 (1.61)	1.98 (16.67)
5	7.2 (3.34)	5.4 (3.44)	7.1 (3.30)	9.1 (3.35)	9.9 (2.33)	7.74 (1.78)
6	5.0 (0.53)	4.7 (2.59)	8.1 (4.12)	10.3 (1.92)	11.6 (1.68)	7.94 (3.09)
7	-24.2 (1.27)	-23.0 (2.51)	-20.0 (1.00)	-16.1 (0.99)	-14.6 (1.07)	-19.58 (4.19)
8	-13.3 (6.09)	- 3.9 (4.88)	- 4.0 (1.66)	- 5.1 (1.90)	- 6.9 (1.75)	- 6.64 (3.91)
9	-21.5 (2.83)	- 7.5 (0.90)	- 6.4 (2.13)	- 3.4 (3.57)	- 0.3 (1.81)	- 7.82 (8.14)
10	16.6 (2.12)	7.9 (1.82)	5.2 (1.93)	9.0 (2.35)	15.9 (0.42)	9.72 (6.21)
11	-10.7 (4.56)	0.0 (3.46)	- 1.9 (0.83)	- 1.1 (2.60)	1.8 (2.97)	- 1.94 (5.09)
12	-15.6 (2.49)	- 9.2 (2.76)	21.2 (4.47)	19.5 (2.04)	25.3 (4.69)	8.24 (19.09)
13	-19.0 (2.11)	-16.7 (4.80)	-14.0 (5.26)	-10.8 (4.61)	-10.8 (5.31)	-14.26 (3.62)
14	-19.6 (2.07)	- 6.2 (4.29)	- 3.8 (4.31)	- 5.0 (3.88)	11.7 (10.44)	- 4.58 (11.11)
15	-10.5 (3.13)	2.8 (4.07)	3.9 (2.00)	3.7 (2.11)	4.2 (2.81)	0.82 (6.35)
16	- 1.8 (4.59)	- 2.3 (4.98)	- 0.8 (1.46)	- 0.8 (2.20)	0.5 (1.95)	- 1.04 (1.08)
17	-22.0 (5.17)	-12.9 (2.22)	-10.0 (1.73)	-10.6 (0.92)	- 7.9 (0.56)	-12.68 (7.79)
Mean	-11.0 (11.67)	- 5.1 (8.71)	- 2.5 (10.16)	0.2 (10.64)	3.0 (11.67)	- 3.16 (11.26)

TABLE II
Comparison of Pre- and Postexercise Calibration[A]

Subject	Preexercise Calibration			Postexercise Calibration			Percent Error Change[D]
	$V_{T,SP}$[B] (mL)	$V_{T,RIP}$[C] (mL)	Percent Error	$V_{T,SP}$ (mL)	$V_{T,RIP}$ (mL)	Percent Error	
1	1191	1188	-0.3	1325	1527	15.2	15.5
2	490	493	0.6	543	587	8.1	7.5
3	394	462	17.3	488	474	-2.9	-21.2
4	620	620	0.0	927	921	-0.6	-0.6
5	953	904	5.1	807	948	17.5	12.4
6	1142	1153	1.0	1081	1207	11.7	10.7
7	566	529	-6.5	629	641	1.9	8.4
8	530	528	-0.4	407	473	16.2	16.6
9	559	496	-11.3	595	627	5.4	16.7
10	1593	1606	0.8	1435	1578	10.0	9.2
11	833	821	-1.4	858	1002	16.8	18.4
12	1547	1633	5.6	1876	1568	-16.4	-22.0
13	790	753	-4.7	1038	904	-12.9	-8.2
14	374	375	0.3	606	643	6.1	5.8
15	496	510	2.8	818	954	16.6	13.8
16	833	809	-2.9	975	1070	9.7	12.6
17	680	669	-1.6	823	808	-1.8	-0.2
Mean	767	758	-1.2	851	902	6.0	7.2

[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]Postexercise percent error minus preexercise percent error.

time to total respiratory cycle duration (T_I/T_{TOT}), mean inspiratory flow rate (V_T/T_I), fractional rib cage contribution to tidal volume (VOL RC/V_T), and heart rate at rest and exercise under the 3 conditions of oro-nasal covering are presented in Table III. The exercise values were taken at steady state at 4.8 km/hr (3 mph) at an 8% grade. The differences in the parameters from rest to exercise were analyzed in a paired fashion, with each individual serving as his own control. Every measured parameter was significantly different during exercise than at rest ($p < 0.001$ for all except VOL RC/V_T, where $p < 0.005$).

The differences between the measured parameters under the three conditions (N = RIP alone, P = RIP + breathing through the pneumotachograph, and R = RIP + wearing the respirator) are given in Table IV. N–P indicates that the values obtained while the subject was breathing through the pneumotachograph were subtracted from those obtained while wearing the RIP apparatus alone. The other notations follow the same format. Statistically significant differences were found in several ventilatory parameters when either a pneumotachograph or respirator was used. The frequency of respiration fell and the V_T increased, both at rest and during exercise. Breathing through the pneumotachograph and wearing the respirator both significantly increased $\dot{V}$ over RIP alone while at rest. Only when the respirator was used was $\dot{V}$ increased—compared with RIP alone—during exercise. There were no significant differences in any of these parameters between the conditions of pneumotachograph and respirator use.

At rest, use of the pneumotachograph or respirator increased T_I/T_{TOT} compared with RIP alone. With exercise, the use of the respirator increased T_I/T_{TOT} when compared with RIP alone or the pneumotachograph. There was no significant difference between RIP alone and RIP plus the pneumotachograph during exercise. The fraction of tidal volume accounted for by the RC volume (VOL RC/V_T) was significantly lower during exercise when using RIP plus respirator compared to RIP plus pneumotachograph.

There were no significant differences found in V_T/T_I induced by either the pneumotachograph or respirator. The heart rate was not increased by the respirator and was not measured during use of the pneumotachograph.

Discussion

Respiratory inductive plethysmography (RIP) has several theoretical advantages over more traditional methods in studying the respiratory effects of respirator wear. Methods that involve mouthpieces and/or noseclips have been shown, in themselves, to alter respiration.[12,13] They also are difficult to adapt to use with a respirator without modifying the respirator. It then can be difficult to ascribe any changes seen to the respirator alone, rather than the modifications. Additionally, actual workplace conditions involve activities and

postures often not simulated by usual laboratory exercise testing because subjects are wired to measuring equipment. RIP does not require a physical connection to the airway, it involves no mouthpiece or noseclips, it does not interfere with respirator wear, and it is not heavy and will not add a significant burden to the test subject. For these reasons it seemed that, if a completely self-contained system could be developed and shown to be accurate, RIP would be ideal for examining the ventilatory effects of respirators in the workplace. Such a system also could find much broader application.

The present study was designed to test if this self-contained RIP was accurate and reproducible. The subjects also wore a respirator as an initial trial to see if any alterations in respiratory function could be found with treadmill exercise or if any problems would be encountered.

A least-squares method of calibration was used. The calibration of the RIP has been the subject of many previous papers.[11,14-18] Since the subjects would be upright throughout the test, a single-position calibration with the subject standing was performed. The subjects were asked to vary their respiratory pattern, first by breathing normally, then by breathing using predominantly their chest, and finally by using predominantly their abdomen. This precise method of calibration has not been described previously. It is similar to published methods and does appear to be relatively accurate. The authors' mean percent error for the initial calibration was 1.2%. Only 2 of the 17 subjects showed errors of over 10%. Other investigators would reposition the RIP bands in these subjects and recalibrate the system until the initial calibration error was under 10% before proceeding.[11] This was not done. Since the authors were designing a system for use in the field, the calibration data would not be available until the tape was analyzed, after the study was completed. This may be one of the weaknesses of this system. Because of band slippage, however, it is not obvious that initial repositioning of the bands would make a significant difference in the overall accuracy of RIP compared with the pneumotachograph.

The calibration of the RIP against the pneumotachograph was disappointing. For the group as a whole, the mean percent error was -3.16%, a very acceptable number. There was, however, much variability with the mean percent error (ranging from 9.72% to -19.58%) for individual subjects (Table I). As noted, the standard deviation of the mean percent error was 11.26%.

For most subjects, the errors became less negative, or more positive as the minute ventilation increased, as can be seen in Table I and Figure 1. This may represent a combined fixed ventilatory error with a percent error in the system. More than one error pattern was seen as the minute ventilation increased, however. Some persons began with a low error and maintained this, such as Subject 16. Others had a large initial error that remained large and in the same direction, such as Subject 13. These subjects might yield more accurate data if the bands were repositioned after the initial calibration. Other subjects, however, began with large

TABLE III
Mean Values (SD) for RIP-Measured Parameters at Rest and During Exercise at 4.8 km/hr (3 mph) at an 8% Grade

	RIP[A] Alone (No Oro-nasal Encumbrance)		RIP and Pneumotachograph		RIP and Respirator	
Parameter	Rest	Exercise	Rest	Exercise	Rest	Exercise
f (resp/min)[B]	18.3 (5.6)	28.2 (5.5)	14.9 (5.4)	24.6 (6.0)	15.7 (4.4)	24.6 (4.9)
V_T (L)[C]	0.495 (0.307)	1.074 (0.337)	0.741 (0.325)	1.329 (0.477)	0.655 (0.223)	1.337 (0.501)
$\dot{V}$ (L/min)[D]	8.1 (3.0)	29.3 (6.9)	9.9 (3.3)	30.8 (7.6)	9.5 (2.9)	31.3 (7.8)
T_I/T_{TOT}[E]	0.30 (0.04)	0.40 (0.02)	0.35 (0.06)	0.40 (0.03)	0.34 (0.03)	0.42 (0.02)
V_T/T_I (L/sec)	0.444 (0.107)	1.278 (0.303)	0.495 (0.124)	1.332 (0.358)	0.489 (0.118)	1.282 (0.311)
VOL RC/V_T[F]	0.41 (0.16)	0.47 (0.15)	0.39 (0.13)	0.46 (0.15)	0.41 (0.14)	0.47 (0.14)
Heart rate (beats/min)	82.3 (16.0)	122.1 (22.8)	(not measured)		83.7 (11.7)	124.1 (17.8)

[A]RIP = respiratory inductive plethysmography.
[B]f = respiratory frequency.
[C]V_T = tidal volume.
[D]V = ventilation.
[E]T_I/T_{TOT} = inspiratory time/total conspiratory and expiratory time.
[F]VOL RC/V_T = fraction of V_T accounted for by rib-cage volume.

TABLE IV
Differences (SD) in RIP-Measured Parameters Between Test Conditions[A,B]

Parameter	Rest			Exercise		
	N-P	N-R	P-R	N-P	N-R	P-R
f (resp/min)	3.4[C] (5.4)	2.6[D] (3.3)	-0.8 (4.9)	3.7[E] (3.0)	3.6[E] (3.0)	0.06 (3.0)
V_T (L)	-0.246[E] (0.184)	-0.160[E] (0.140)	0.087 (0.184)	-0.255[E] (0.227)	-0.263[E] (0.197)	-0.008 (0.188)
$\dot{V}$ (L/min)	-1.81[D] (1.9)	-1.43[C] (2.09)	0.38 (2.51)	-1.54 (3.53)	-2.03[C] (3.91)	-0.50 (3.37)
T_I/T_{TOT}	-0.05[E] (0.05)	-0.03[D] (0.04)	0.02 (0.05)	-0.006 (0.03)	-0.03[E] (0.01)	-0.02[D] (0.02)
V_T/T_I (L/sec)	-0.05 (0.10)	-0.04 (0.09)	0.007 (0.09)	-0.05 (0.17)	-0.004 (0.17)	0.05 (0.14)
VOL RC/V_T	-0.019 (0.071)	-0.003 (0.050)	-0.016 (0.064)	-0.017 (0.045)	0.0 (0.037)	0.017[C] (0.028)
Heart rate (beats/min)		-1.3 (14.5)			-1.9 (10.6)	

[A]See text.

[B]N = RIP alone (no oro-nasal encumbrance); P = RIP + Pneumotachograph; R = RIP + Respirator.

[C]$p < 0.05$.

[D]$p < 0.01$.

[E]$p < 0.001$.

negative errors and ended with large positive errors, such as Subject 4. In these subjects, repositioning the band initially would result only in accurate initial values, with probably an increasing error as exercise proceeded. It also should be noted that the mean percent error—taking the arithmetic sign into account as in Table I—will underestimate the individual RIP values' deviations from the reference pneumotachographic value. In Subject 4, for example, the mean percent error using absolute deviations from the reference value (regardless of direction) is 13.34%, not 1.98%. If the absolute deviations are averaged over all exercise levels and all subjects, the mean percent error is 9.53%, not -3.16%.

The preexercise calibration was compared with the postexercise calibration as previously described. If the subjects with the most variability had large discrepancies between the two calibration periods, it might indicate that conditions were changing during the test. For example, this might be caused by movement of the RIP bands. Unfortunately, no relationship was found between the preexercise calibration, the postexercise calibration, or the change in calibration and the difference between the RIP and pneumotachograph. Subject 4, for example, had a preexercise calibration in which the RIP agreed precisely with the spirometer (Table II). The postexercise calibration in which the preexercise coefficients were used (see "Methods") showed only a minimal -0.6% difference between the RIP and the spirometer. During the exercise protocol, however, the difference between the RIP and pneumotachograph varied from -18.5% to 19.4%, a wide range. Subject 7 also showed acceptable pre- and postexercise calibrations, but the percent error varied from -24.2% to -14.6%, with a mean error of -19.6%.

The lack of correlation between the calibration and the error measured during exercise has a number of possible explanations. It could be the pneumotachograph was in error. Two of the subjects whose data were eliminated had problems with the pneumotachograph portion of the data. In one case, the pneumotachograph signal was lost, and the data were not recorded. In the other case, there was a small leak in the pneumotachograph mouthpiece, and the volumes were obviously small. In both cases, however, the errors were detected easily, and the authors have not noted any other irregularities with the system, which was calibrated periodically.

Another possibility is that the RIP system behaves differently during exercise than it does with the subject standing in place (as during calibration). There have been reports of stepping artifacts occurring with treadmill exercise with RIP.[19] The movement and muscular activities of physical work could cause small, transient changes in abdominal and chest girth unrelated to breathing, but these should have minimal net effect when averaged over time. No specific problems have been reported to account for errors of the magnitude that is seen. Other investigators also have reported significant variability when using RIP, however. One group[20] found a difference in the ratio of a reference V_T measured at the mouth divided by $V_{T,RIP}$ of over 20% in single subjects measured 5 min apart. Similarly, others have found a "marked inconsistency of apparently comparable calibrations and a wide variability of results along but independently of the time in steady conditions (ranging up to 30%)."[16] The results of this report are also similar to those of previous authors[16] who found what would be considered acceptable mean errors—

7.6%, SD 7.0 and 7.3%, SD 7.3—for the two calibration techniques used. It is unlikely that the resistance of the pneumotachograph or respirator contributed to the error seen. Others have found the RIP to be relatively accurate at much higher resistive loads than was imposed by the authors' equipment.[21]

In spite of the variability seen with the RIP data, the changes occurring while wearing a respirator and breathing through a mouthpiece while wearing a noseclip are very similar and are generally what would be expected. To the extent that consistent RIP errors occur in any individual at a given exercise level, evaluation of a respirator's effect may have some validity when the work with and without the respirator is similar. Table I also suggests that most subjects' changes in RIP errors tend to be in the same direction across increasing levels of exercise. That is, as exercise level and $\dot{V}$ increased, the percent errors tended to become more positive (or less negative). A correction factor based on $\dot{V}$ thus would seem possible. This study, however, has not evaluated intra-subject variability by repeating calibration tests on different days.

Studies have shown that the presence of a mouthpiece and noseclip alone will increase V_T, decrease respiratory frequency, and either will increase or have a variable effect on minute ventilation.[12,13] Other studies using flow-resistive devices, such as industrial respirators, tend to show a decreased respiratory frequency, increased V_T, decreased minute ventilation, and increased T_I/T_{TOT}.[4-6,22] The authors' data show a decreased respiratory frequency and increased V_T at both rest and exercise induced by both the pneumotachograph and respirator. A significantly increased minute ventilation was found at rest under both conditions but during exercise was increased only significantly with the respirator. Both conditions are associated with added resistance and dead space. T_I/T_{TOT} was increased by both the pneumotachograph and the respirator at rest. Interestingly, T_I/T_{TOT} was not increased significantly by the pneumotachograph during exercise but was by the respirator. Perhaps this was due to the higher airflow resistance found in the respirator.

The fractional contribution of the RC volume to V_T was less than 50% and increased during exercise. It also was noted that the pneumotachograph tended to increase the RC volume during exercise when compared with RIP alone or when wearing the respirator. This possibly could be due to an alteration of posture needed to maintain position on the treadmill while keeping the mouthpiece in place.

Conclusion

The ambulatory RIP apparatus described here was shown to provide an accurate mean value for this population. There was, however, extreme inter- and intra-subject variability in the measurements, which has been reported by other authors. This limits the utility of the system and makes the interpretation of the data difficult, especially in individual cases. Further work is being performed to try to evaluate and reduce this variability. Given these reservations, an analysis of the data did reveal changes in the respiratory variables induced by the pneumotachograph and industrial respirator similar to what previously has been reported.

Major potential advantages of RIP are its portable nature and lack of oro-nasal encumbrance, thus permitting evaluation of respirator wear under actual working conditions in the workplace. At present, however, the portable RIP system has substantial variability that seriously detracts from its ability to measure ventilation accurately.

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