Navy Experimental Diving Unit
321 Bullfinch Rd.
Panama City, FL 32407-7015

LT 07-01
NEDU TR 10-06
MAY 2010

EXERCISE LIMITATION IMPOSED BY AN APPROVED AIR PURIFYING RESPIRATOR (APR)

Authors: B. Shykoff, Ph.D.
D. Warkander, Ph.D.
D. Winters, HM1, USN

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION/DOWNGRADING AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NEDU Technical Report No. TR 10-06	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit 6b. OFFICE SYMBOL (If Applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 321 Bullfinch Road, Panama City, FL 32407-7015	7b. ADDRESS (City, State, and Zip Code)
8a. NAME OF FUNDING SPONSORING ORGANIZATION Defense Threat Reduction Agency 8b. OFFICE SYMBOL (If Applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Defense Threat Reduction Agency 8725 John J. Kingman Rd. Stop 6201 Fort Belvoir VA 22060-6201	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: — PROJECT NO.: — TASK NO.: LT 07-01 WORK UNIT ACCESSION NO.: —

11. TITLE (Include Security Classification) (U) Exercise Limitation Imposed by an Approved Air Purifying Respirator (APR)

12. PERSONAL AUTHOR(S) B. Shykoff, Ph.D.; D. Warkander, Ph.D; D. Winters, HM1 USN

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Report	FROM Apr 2007 TO Dec 2009	2010 May	48

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Respiratory protective device, APR, gas mask, filter, exercise endurance, exercise limitation, breathing resistance, oxygen consumption, work of breathing

19. ABSTRACT: In this IRB-approved study, 31 subjects exercised with and without an approved air purifying respirator (APR). A commonly used gas mask was used in both standard and slightly altered configurations; in Phase1 the filter was “loaded” for a pressure drop simulating dust loading, and in Phase 2 the inlet pathway in the mask was modified. Phase 1 exercises were short (fire hose drag) or long duration (incremental-load treadmill running, ladder climbing, and self-paced box lifting). Phase 2 exercise was incremental and endurance treadmill running. Parameters measured and calculated included breathing frequency, tidal volume, respiratory duty cycle, mask pressure, resistive effort (WOB/V_T), minute ventilation (V_E), peak inspiratory flow ($V_{i\,peak}$), rate of O_2 uptake (VO_2), inhaled and exhaled CO_2, and heart rate. With a standard APR, breathing difficulty caused 22 of 30 subjects to stop incremental running,14 of 15 to stop endurance runs, and 1 of 15 to stop climbing (6 of 15 with the loaded filter). With the standard APR, duration of incremental treadmill running dropped 14% from that with no APR, running endurance time decreased 57%, and climbing endurance dropped by 20%. The standard APR did not affect load lift and transfer or fire hose drag performance, but the number of boxes moved decreased 8% with the loaded filter, and five subjects complained of breathing resistance during recovery from the hose drag. Without an APR, the highest sustained V_E exceeded 150 L/min, and V_i was recorded at 434 L/min. With an APR, V_E decreased 14% to 26% relative to that without an APR at the same workload. Peak attainable VO_2 was reduced 15%, and VO_2 at end running endurance decreased 15 to 18%. Because required inspiratory pressures from laminar and turbulent flow were so high at the necessary V_i, inspiratory WOB/V_T was excessive. V_E inadequate to support VO_2 limited heavy exercise. A mask that could deliver V_i = 360 L/min for a pressure drop of 24 cm H_2O would have allowed 80% of our subjects to breathe as much as the work required, and $WOB_i/V_T \leq 1$ J/L should be acceptable for 80% of subjects.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
[ ] UNCLASSIFIED/UNLIMITED [X] SAME AS RPT. [ ] DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
NEDU Librarian	850-230-3170	

CONTENTS

Page No.

TABLES

FIGURES

ABBREVIATIONS AND DEFINITIONS

APR = air purifying respirator, a conventional gas mask

$F_{ET}CO_2$ = end tidal CO_2 fraction; the fraction of CO_2 measured at the end of a tidal breath and assumed to represent an alveolar gas sample

F_ICO_2 = minimum inspired fraction of CO_2; that measured at the end of inspiration

f_R = respiratory frequency (breaths/min)

HR = heart rate (beats/min)

P_{mask} = instantaneous mask pressure (cm H_2O), measured in the oronasal cup where the speaking disk usually sits and sampled at 100 Hz

P_{exp} = expiratory P_{mask}

$P_{exp\ peak}$ = maximum P_{exp} within a breath (cm H_2O), presented as the average of one minute of breath-by-breath measurements

P_i = inspiratory P_{mask}

$P_{i\ peak}$ = maximum magnitude of P_i within a breath (cm H_2O), presented as the average magnitude of one minute of breath-by-breath measurements

T_I/T_{TOT} = respiratory duty cycle, inspiratory time/period of a breath
For T_I and T_{TOT} expressed in seconds, $T_I/T_{TOT} = T_I \cdot f_R/60$

V_E = respiratory minute ventilation (L/min), the volume of gas exhaled in one minute: $V_E = V_T \cdot f_R$

V_{exp} = instantaneous expiratory flow (L/min), sampled at 25 Hz

$V_{exp\ peak}$ = maximum V_{exp} within a breath, presented as the average of one minute of breath-by-breath measurements

V_i = instantaneous inspiratory flow (L/min), sampled at 100 Hz

$V_{i\ peak}$ = maximum V_i within a breath, presented as the average of one minute of breath-by-breath measurements

VO_2 = rate of oxygen uptake (mL[STPD]/min)

$VO_{2\ max}$ = maximum VO_2 possible for an individual, the measure of aerobic fitness

$VO_{2\ peak}$ = peak VO_2 measured under a particular set of conditions, $\leq VO_{2\ max}$

V_T = tidal volume (L), the total volume exhaled in each breath

WOB_i = inspiratory work of breathing (J), the integral of pressure as a function of volume

WOB_i/V_T = inspiratory work of breathing/tidal volume, also known as inspiratory resistive effort or volume-averaged pressure (J/L = kPa)

:EXECUTIVE SUMMARY

Users of air purifying respirators (APRs), also known as gas masks, frequently complain that the masks impede breathing to an extent that their performance of physically demanding tasks is impaired.[1] We thus know that current standards for the pressure-flow characteristics of APRs are inadequate for heavy work. The goals of this IRB-approved study, were to (1) identify the types of activity in which one currently approved APR limits performance by restricting air flow, (2) determine the extent of the performance limitation, (3) identify the changes in breathing patterns imposed by the APR during exercise, and (4) suggest changes in standards and mask design to reduce the ventilatory impairment created by the APR.

An approved gas mask was used in both standard and slightly altered configurations In two phases of testing, subjects performed tasks with and without an APR for within-subject comparisons. Phase 1 exercises (15 subjects) consisted of treadmill running with incrementally increased slope, continuous ladder climbing, self-paced box lifting, and fire hose dragging. Phase 2 exercises (16 subjects) were incremental and endurance treadmill running at nominally 85% $VO_{2\,max}$. Parameters measured and calculated included breathing frequency (f_R), tidal volume(V_T), respiratory duty cycle (T_I/T_{TOT}), mask pressure, inspiratory resistive effort inspiratory (work of breathing per tidal volume, WOB_i/V_T), minute ventilation (V_E), peak inspiratory flow ($V_{i\,peak}$), rate of O_2 uptake (VO_2), inhaled and exhaled CO_2, and heart rate (HR). The APR was tested in standard configuration and also with minor modifications: in Phase1 the filter was “loaded” for a pressure drop simulating dust loading, and in Phase 2 the inlet pathway in the mask was modified.

With a standard APR, many of the subjects told us that they stopped exercise because of breathing difficulty: 22 of 30 for incremental running, 14 of 15 for endurance runs, and 1 of 15 for ladder climbing-- 6 of 15 with the loaded filter. With the standard APR, duration of incremental treadmill running dropped 15% from that with no APR, running endurance time decreased 57%, and climbing endurance dropped by 20%. The standard APR did not affect load lift and transfer or fire hose drag performance, but the number of boxes moved decreased 8% with the loaded filter, and five subjects complained of breathing resistance during recovery from the hose drag.

Without an APR, the highest sustained V_E exceeded 150 L/min, and $V_{i\,peak}$ was recorded at 434 L/min, or about five times the test flow for current standards. With an APR, V_E decreased 14% to 26% relative to that without an APR at the same workload. Attainable $VO_{2\,peak}$ was reduced 15% by the reduction in V_E. The increase in VO_2 with time during the endurance run was steeper with an APR than without, and VO_2 at the end of endurance runs decreased 15 to 18%. The endurance run often ended with VO_2 apparently at the peak attainable through the mask. For 5 of 15 subjects, the decrease in V_E led to significant CO_2 retention (end tidal CO_2 fraction ≥7%).

V_T changed little with APR use, but f_R decreased. T_I/T_{TOT} did not change systematically from its exercise range of about 0.40 to 0.55. $V_{i\,peak}$ was depressed considerably by APR use despite high inspiratory pressures. Turbulent characteristics of the inspiratory pathways in addition to the mostly laminar filter resistance generate increasingly-high

WOB_i/V_T as $V_{i\,peak}$ increased. The highest WOB_i/V_T calculated with a standard APR was 2.7 J/L, and with a loaded filter, 3.0 J/L, although the average WOB_i/V_T was 1.8 J/L when people stopped running with the standard APR. For comparison, WOB_i/V_T for diving equipment must not exceed 1.5 J/L at 1 atmosphere's pressure.

Subjects vary both in sustainable $P_{i\,peak}$ and in ventilatory requirements for exercise. We examined $P_{i\,peak}$ with an APR and $V_{i\,peak}$ for the same exercise condition without an APR to conclude that a mask that could deliver $V_{i\,peak}$= 360 L/min with $P_{i\,peak}$ = 24 cm H_2O would have allowed 80% of our subjects to breathe as much as the work required. A similar study of WOB_i/V_T and V_E led to the conclusion that $WOB_i/V_T \leq 1$ J/L should be acceptable for 80% of subjects.

Current APR standards for breathing resistance address maximum inspiratory pressure at a constant flow of 85 L/min. That peak flow corresponds to a person at or almost at rest, but not to the usual users of APRs, first responders or war fighters. Standards and testing methods to meet their needs must address the much higher inspiratory flow needs of exercise and the non-laminar flow of gas in the mask inlet pathway. .

INTRODUCTION

Nonpowered air purifying respirators (APRs, or gas masks) cannot provide protection against contaminants without increasing work of breathing. APR performance testing and standards should ensure that the impediment to breathing is within tolerable limits. However, because users report difficulty in breathing through some approved APRs during many activities,[1] we know that current standards are based on inadequate definitions of acceptability. Unmanned testing results appear in Camperman's report for which this is report is an Appendix.[1] The goals of the human testing reported here have been to (1) identify the types of activity in which one currently approved APR limits performance by restricting air flow, (2) determine the extent of the performance limitation, (3) identify the changes in breathing patterns imposed by the APR during exercise, and (4) suggest changes in standards and mask design to reduce the ventilatory impairment created by the APR.

All human performance tests reported here were performed with an APR and filter or with a low-resistance oronasal mask as a control condition. Two phases of testing have provided complementary information. The first phase consisted of four tasks: (1) incremental treadmill running, (2) ladder climbing, (3) load lifting and transferring, and (4) fire hose dragging. The treadmill test in the first phase presented stepwise increases in external work until the subject indicated that he or she could not continue. In the ladder test the subject climbed a continuous ladder exercise machine at a preset rate until he or she could not maintain the pace. Load lift and transfer was a self-paced task with 24 minutes of work. The first phase of testing thus consisted of (1) a short-term test of peak aerobic capacity, with no more than three minutes at any load; (2) an endurance task, but one presented at different fractions of the individual's peak capacity; (3) self-paced heavy work; and (4) a sprint under load. The second phase of testing consisted of two types of treadmill tests: one an incremental test like that in Phase 1, and the other an endurance run at 85% $VO_{2\ max}$.

We have assessed APR-associated performance decrements in all tests and examined the corresponding changes in respiratory parameters. Although the decrements pertain specifically to the test APR, the respiratory requirements of the different tasks are applicable to any passive gas mask.

We also manipulated the APR slightly in each phase to probe the importance of different sources of inspiratory loads. In the first phase of testing, the mask was worn either in its standard configuration with a clean filter or with a loaded filter, that is, one modified to increase its laminar resistance to the maximum level acceptable for dust loading. In the second phase, we did not manipulate the filter resistance. Instead, we compared a mask in its standard configuration to a mask with an altered internal inlet pathway, specifically with the diffuser removed. All mask conditions were matched to tests without APRs.

METHODS

GENERAL

Phase 1 of this project was conducted under Navy Experimental Diving Unit (NEDU) Protocol 07-05/32201, *Human Performance and Respiratory Patterns during Exercise while Wearing an Air Purifying Respirator (APR)*. Phase 2 was conducted under NEDU Protocol 09-12/32223, *Effects of an Air Purifying Respirator (APR) and Inlet Dimensions on Treadmill Endurance*. Both protocols were approved by the NEDU Institutional Review Board, and testing was conducted at NEDU. Subjects, who were recruited from the commands at Naval Support Activity Panama City and at NEDU Reserve Unit Great Lakes, gave written informed consent before participating. If a medical screening at NEDU confirmed that a subject's estimated risks of a cardiovascular event in the next 10 years was less than 5%,[2] he or she was scheduled to begin testing.

The population of interest was a wide cross section of potential APR users — that is, both men and women, and with a large age range. Phase 1 recruiting efforts targeted subjects with either very high or low (for the Navy) physical fitness. Phase 2 recruiting did not attempt to stratify by fitness standards.

<u>Phase 1</u>

Four different exercise tasks — treadmill running, ladder climbing, load lifting and transferring, and fire hose dragging — were chosen. Details of the tasks are provided in "**PROCEDURES**" below.

In general, one-minute averages of breath-by-breath values were used. For the treadmill and load lift tests, the last minute of any exercise condition was taken. For ladder climbs, successive minutes were used from beginning to end. For the hose drag, peak values were examined in addition to the average over the entire exercise period, which was always less than one minute and never a steady state. The end-exercise values listed are seven-breath averages.

The loaded APR filter had a pressure drop of 6.6 cm H_2O at a steady flow of 85 L/min with two layers of material from a standard cotton gauze "4x4." National Institute for Occupational Safety and Health (NIOSH) standards for particulate loading set the limit at 6.5 cm H_2O.

<u>Phase 2</u>

Subjects first completed an incremental treadmill test without APR to estimate $VO_{2\ max}$ and to serve as the baseline for the further incremental tests. Later, in randomized order, subjects completed three endurance runs and two other incremental runs. Subjects ran one endurance and one incremental test for each of the three mask conditions: no APR, unmodified APR, and modified APR. As in Phase 1, data from the last minute of each exercise level were averaged. The treadmill for endurance runs was set to the incline closest to 85% of the peak oxygen consumption.

EXPERIMENTAL DESIGN AND ANALYSIS

Recorded performance variables were rate of oxygen uptake (VO_2) at the end of exercise, time to termination for treadmill testing, time and vertical distance climbed during ladder climbing, number of boxes moved for load lift and transfer, and time and recovery time for the hose drag.

Cardiovascular and ventilatory variables include heart rate (HR), tidal volume (V_T), minute ventilation (V_E), respiratory frequency (f_R), respiratory duty cycle (T_I/T_{TOT}), breath-by-breath VO_2, and end-tidal carbon dioxide fraction ($F_{ET}CO_2$). Mask pressure (P_{mask}), flow signature, inspiratory work of breathing per tidal volume (WOB_i/V_T), and minimum inspired carbon dioxide fraction (F_ICO_2) are also included when the APR was worn on the treadmill or climber.

Variables were compared across the three mask conditions for each phase — namely, no-APR, standard mask with clean filter, and simulated loaded filter for Phase 1, or no-APR, standard mask with clean filter, and modified mask with clean filter for Phase 2 — by repeated measures analysis of variance (ANOVA) with difference contrasts. Stepwise linear regressions were also used to try to explain performance deficit (change in exercise time or fractional change in exercise time) in terms of measured variables. Unless otherwise specified, significance was assessed at $\alpha = 0.05$.

PROCEDURES

General

Each subject completed the series of tests within one month of starting. Except for the hose drag, subjects performed no more than one test per day. Hose drags, done outdoors, were completed with all three mask conditions in random order on the same day to provide consistent environmental conditions.

Subjects wore standard physical training (PT) gear for the treadmill and ladder climb tests, PT gear and boots for the load lift and transfer, and camouflage uniform pants (battle dress uniform), T-shirt, 50-lb weighted vest, boots, and work gloves for the fire hose drag. Because clothing was the same with and without APR, thermal loads were as similar as possible across compared conditions. During all tests each subject wore a chest strap for a HR monitor (Polar Electro; Woodbury, NY) and the harness system holding the COSMED k4b2 cardiovascular measurement equipment (COSMED USA; Chicago, IL). In Phase 1 subjects also wore a blood pressure monitor (Advantage 6016 digital wrist BP monitor, American Diagnostic Corp.; Hauppauge, NY).The turbine flow meter and gas analyzer probe from the k4b2 were attached either to an oronasal mask (Hans-Rudolph; Kansas City, MO) held to the head by a cloth harness (“no-APR”) or to the expiratory port of an APR.

Oronasal masks were available in small, medium, and large sizes, and APRs in small and medium. Each subject used the appropriate size: the subject assessed the APR’s seal by blocking the inspiratory port with his palm and attempting to inhale and then by blocking the expiratory port and trying to exhale.

To test without an APR, we used an oronasal mask with the k4b2 equipment. All inspired gas flowed through the turbine, and the equipment measured inspiratory and expiratory flows and instantaneous oxygen and carbon dioxide fraction at the distal end of the turbine. To test with an APR, we attached the k4b2 turbine assembly to the exhaust port of the APR. On the filter inlet we used a separate flow meter, specifically, a screen pneumotachometer (Collins Microtach, Ferraris Respiratory; Louisville, CO) and a differential pressure transducer (±2 inches H_2O, Honeywell Pressure Sensor Model DC002NDR5, Honeywell Sensing and Control; Golden Valley, MN). During APR use the k2b4 unit measured only expiratory flow and composition of expired gas.

We used two small and two medium APRs. By removing the secondary external eye pieces and the cover from the APR expiratory port, we decreased the total mass by 128 g. We then fitted a rubber coupling over the expiratory port of the APR to hold the k4b2 flow meter assembly (mass 62 g) and added an adaptor to the APR filter (mass 63 g) to hold the inspiratory flow meter (mass 49 g). We replaced the APR speaking disk with a threaded insert having ports for a pressure transducer and a gas sampling line. With the speaking disk replaced and a filter in place, a mask weighed about 1050 g; our other instrumentation added a net 46 g.

Gas composition inside the oronasal cup was measured with a fast-response sector mass spectrometer (MGA 1100; Marquette). P_{mask} was measured with a pressure transducer (±20 inches H_2O, Honeywell Sensor Model DC020NDR5).

Breath-by-breath ventilatory and cardiovascular parameters were recorded in the portable k4b2 unit. For all tests but the hose drag, a cable connection (during treadmill and climber testing) or telemetry (during load lift and transfer testing) transmitted the results to a computer. The cable connection was needed to record breath signature.

A Windows-based portable data acquisition system running LabVIEW version 8.20 (National Instruments; Austin, TX) recorded P_{mask}, inspiratory flow, and mask CO_2 fraction at the mouth at 100 Hz only when the APR was worn on the treadmill or climber and a cable could be attached.

After a subject stopped exercising, he or she continued to wear the APR or metabolic measurements mask for monitoring all variables until HR was <100 beats/min or had been stable near 100 beats/min for two minutes, at which time recovery was deemed complete. After the subject removed the APR, we asked for comments about it. For treadmill and ladder exercise, the tests where the subject ended the test because of inability to continue, we asked the reason for terminating the test.

Phase 1

The first exercise test was always the treadmill run without APR, because peak HR from this test was prescribed as a safety cutoff for further testing; a subject was directed to stop any other test if HR reached the peak value for one minute or exceeded it for more than 30 seconds. The order of all other exercise tests and mask conditions was varied among subjects. To ensure consistent temperature and humidity conditions for the short fire hose drag which was performed outdoors, all three mask conditions were completed in one testing session All other tests were scheduled on separate days to reduce crossover fatigue.

Treadmill

The incremental treadmill test involved stepwise increases in external work up to the subject's $VO_{2\ peak}$. Running speed was individualized on the basis of the subject's Physical Readiness Test (PRT) run time. For a pace that could be sustained, a speed between 3 mph and the average speed recorded for the 1.5-mile run was chosen arbitrarily:

$$\text{Running speed (mph)} = 45/\text{PRT time} + 1.5.$$

Subjects walked on a level treadmill (Precor; Woodinville, WA) at 3 mph for three minutes and then ran for three minutes each on the level and at inclines of 2%, 4%, etc., until they or the investigator terminated testing.

Ladder Climb

Steady state ladder climbing was planned as a submaximal exercise endurance task. The Versa Climber (Heart Rate Inc.; Costa Mesa, CA) allows continuous climbing while hands and feet remain on their supports, but the subject determines the rate of stepping and the height of each step within the equipment's physical limits. The equipment displays vertical feet climbed, time, and cadence.

Subjects climbed with normal arm and leg extension at a steady pace of 60 rungs/min until they could not maintain the pace, they chose to stop, or they were directed to stop. Data were used in one-minute increments.

Load Lift and Transfer

Repeatedly lifting a load and carrying it for a distance involves an intermittent static effort combined with light to moderate dynamic work. We based our task on the American College of Sports Medicine test[3] but adapted it for body weight. We loaded loose weights into three crates with handles. Each subject performed four sets of six-minute duration: the first set with three crates approximately 20% of his or her body weight, the second with 27%, the third with 33%, and the fourth with one crate of each weight. The subject lifted one crate at a time from the floor, carried it 2 meters, and set it on a bench at approximately waist height. When all three loads were on the bench, he or she moved them, one at a time, back to the starting point. The number of transfers in a six-minute set was recorded. Subjects paced themselves but were instructed to work at a rapid but safe, sustainable pace. Between sets, subjects rested seated for one minute while the loads were adjusted for the next set. We arbitrarily decided to use the number of boxes moved during the last six-minutes set to assess performance, and we did not tell the subjects that that set was the primary performance measure.

Fire Hose Drag

The fire hose drag test we used comes from the “International Association of Fire Chiefs Candidate Physical Ability Test.”[4] Hose dragging amounts to a loaded sprint, a situation in which breathing resistance during exercise may be less important than that during recovery.

In keeping with the published test, each subject wore a 50 lb vest to simulate the weight of firefighting gear, and long pants and work gloves to protect the skin from the hose and pavement. Firefighter candidates also wear hard hats, but our subjects did not. While dragging a 200-foot, 1¾-inch fire hose with up to eight feet of marked hose draped across their shoulders, subjects ran 75 feet in a straight line, turned a 90° corner at a stanchion, continued running another 25 feet, and then knelt and hauled in 50 feet of hose. The subjects then rested in the shade until their HRs were <100 beats/min.

The thermal and evaporative resistance of the clothing was identical across tests, though that of the oronasal mask was less than that of the APR. Thermal loads, not a subject of study here, were factored out by comparison of each APR test to its non-APR control.

Phase 2

Incremental treadmill testing was conducted as described for Phase 1, but on a new treadmill (Woodway Pro; Waukesha, WI). For subjects who could not provide a PRT run time (some swim the PRT, and two were civilians), treadmill speed was selected as a moderate pace during the level run of their no-APR incremental test.

Treadmill endurance testing began like the incremental testing. Subjects walked on the level for three minutes at 3 mph and then ran on the level for three minutes as a second warm-up. Next, the treadmill incline was set to the value nearest that for 85% $VO_{2\ max}$ where $VO_{2\ peak}$ from the incremental test with no APR was considered to be $VO_{2\ max}$. Testing stopped when the subject could not continue or reached an abort criterion.

At the end of the test, the treadmill was leveled and the speed decreased to 3 mph until the subject requested a total stop. Subjects were then invited to sit. As in Phase 1, subjects continued to wear the APR or metabolic measurements mask until HR was <100 beats/min or was stable near 100 beats/min for at least 30 seconds.

RESULTS

Data are presented from 15 subjects for Phase 1 and from 16 subjects for Phase 2. However, two Phase 2 subjects became unavailable to complete the entire series; we present data from incremental testing for one and for endurance testing for the other.

Table 1.
Subject characteristics

Phase 1 n = 15: 14 men, 1 woman		**Median**	**(min – max)**
Age	(yr)	33	(19 – 43)
Height	(in)	69	(63 – 73)
Weight	(lb)	170	(146 – 205)
Peak VO_2	($mL \cdot min^{-1} \cdot kg^{-1}$)	50	(35 – 70)

Phase 2 n = 16: 14 men, 2 women		**Median**	**(min – max)**
Age	(yr)	39	(27 – 53)
Height	(in)	69	(62 – 75)
Weight	(lb)	187	(110 – 245)
Peak VO_2	($mL \cdot min^{-1} \cdot kg^{-1}$)	53	(42 – 66)

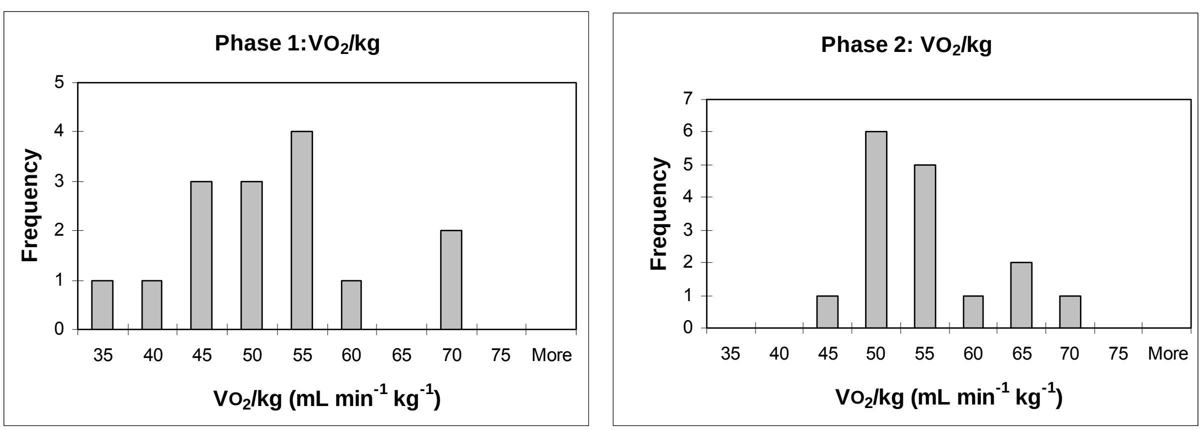


Figure 1. Histograms of $VO_{2\ peak}$ (no APR) normalized by body mass.

Although we attempted to recruit two fitness groups in Phase 1, we did not find two distinct groups. Instead, ten subjects fell into a middle range of fitness, 40 $mL \cdot min^{-1} \cdot kg^{-1} < VO_2/kg \leq 55\ mL \cdot min^{-1} \cdot kg^{-1}$, with two subjects aerobically less fit and three more fit than that middle range (Fig. 1). For Phase 2, when we did not target fitness level during recruitment, we had no subjects below 40 $mL \cdot min^{-1} \cdot kg^{-1}$, twelve subjects between 40 and 55 $mL \cdot min^{-1} \cdot kg^{-1}$, and four subjects above 55 $mL \cdot min^{-1} \cdot kg^{-1}$.

REASONS TO END EXERCISE

Difficulty in breathing, as detailed below by experimental phase, was a dominant reason for cessation of treadmill runs or ladder climbs. Other reasons for stopping included generalized or leg fatigue, shin or knee pain, and even boredom.

Three subjects mentioned feeling almost panicky at the difficulty of breathing at the end of exercise or during hose drag recovery, and two subjects (one in each phase of testing) removed their masks prematurely — that is, before recovery was complete at the end of treadmill exercise. Immediately before one of the subjects removed the mask, $F_{ET}CO_2$ was 7.4%; $F_{ET}CO_2$ had been greater than 7% and end-inspiratory F_ICO_2 had been 0.7% for at least four minutes. The F_ICO_2 would have been that of room air, 0.03%, if the oronasal cup had been completely sealed and the inspiratory valve did not leak.

Phase 1

Of 15 subjects, 11 stated that they stopped running with the APR because they found it too difficult to breathe with increasing external work. One subject wearing the standard APR stopped climbing because of difficulty in breathing, and six using the loaded filter stopped for that reason. Two subjects complained of air hunger or difficulty in breathing during the load lift, and five complained of resistance in breathing during recovery from the fire hose drag.

On the climber, two subjects set themselves time goals and stopped when those were achieved rather than continuing as long as possible. On two occasions a subject's HR exceeded the predetermined safety cutoff, and twice the investigators stopped a subject for other reasons. Climber data for these subjects has been excluded only from analyses of performance and values at the end of exercise. Data from the subjects are included for other exercise modalities.

No subjects stopped early in the load lift and transfer or the hose drag.

Phase 2

After the incremental treadmill test, 11 of 15 subjects stated that they stopped at least partly because of difficulty in breathing with the standard APR, and 12 of 15 stopped for that reason with the modified APR. After the endurance runs, 14 of 15 considered difficulty in breathing to be the primary reason for stopping with the standard mask, and 9 of 15 with the modified mask shared this consideration. Some subjects specifically mentioned that they did not have enough time to inhale, that inspiratory muscles were fatigued, that they got out of rhythm with their breathing and couldn't catch up, or that they were trying to breathe at a higher flow that the mask could deliver ("overbreathing the mask"). One observed that he had felt comfortable with the APR until his legs started to burn, after which he could not keep up with his breathing.

For three subjects after one or both of the incremental runs with an APR, measured $F_{ET}CO_2$ exceeded 7%. Two more subjects, for a total of five, had $F_{ET}CO_2$ in excess of 7% at the end of one or both of the endurance runs with an APR. Only the one subject had F_ICO_2 greater than 0.5%.

PERFORMANCE VARIABLES

Phases 1 and 2

Most performance variables are listed in Table 2, but achievable $VO_{2\ peak}$ is listed in Tables 3a, 3b, and 3c with other cardiovascular variables.

Individual performance with the standard or no APR can be seen in Figs. 2–5 for the treadmill, ladder, and load lifting tasks.

Table 2.
Performance variables

Means (standard deviations)	**No APR**	**Standard APR**	**Loaded or Modified APR**
Treadmill (each set, n = 15)			
Incremental run duration Phase 1 (min)	16.0 (2.7)	14.6 (2.5) ‡	13.4 (1.7) †
Incremental run duration Phase 2 (min)	14.4 (3.3)	11.5 (3.5) ‡	11.8 (3)
Endurance run duration Phase 2 (min)	22.7(13.2)	10.1 (9.8) ‡	10.4 (10.1)
Ladder climb (n given in notes)			
***Climb duration (min)**	12.4 (8.5)	9.9 (6.7) ‡	10.5 (7.8)
****Distance climbed (ft)**	1230 (843)	914 (643)	914 (698)
****Climbing speed (ft/min) (derived)**	100 (14)	94 (16)	91 (18)
Load Lift and Transfer (n = 15)			
Number of boxes in last 6 minutes	60 (9)	60 (9)	55 (7) †
Fire hose Drag (n = 15)			
Hose drag time (s)	34 (16)	32 (15)	32 (16)
Hose drag recovery (min)	1.5 (0.6)	1.8 (1.1)	1.9 (1.0)

Statistical significance ($p<0.05$) from repeated measures ANOVA with difference contrasts: ‡ = different from no-APR condition; † = different from standard APR, not explicitly compared to no-APR condition.
*n = 11 only. Some climbs were stopped before voluntary termination.
**n = 10. Distance climbed not recorded for one subject, no APR.

In both Phases 1 and 2, incremental treadmill run duration was clearly reduced when an APR was worn, but other objective performance variables did not change on the average with APR use (Table 2, Figs. 2–5). (Incremental run time is closely related to treadmill slope by design because the slope was increased every three minutes. Final treadmill slope was therefore not considered to be a separate performance variable.) Incremental run duration decreased from the no-APR condition for all but one subject with a standard APR (Fig. 2), and the average decrease across both phases was 14%. The subject for whom incremental running endurance was greater with APR than without ran at a higher speed treadmill speed for the incremental test with no APR; when data from that subject are ignored, the average decrease becomes 15%. Modification of the mask had no additional effect, but filter loading decreased average incremental run duration a further 7% of the duration with no APR.

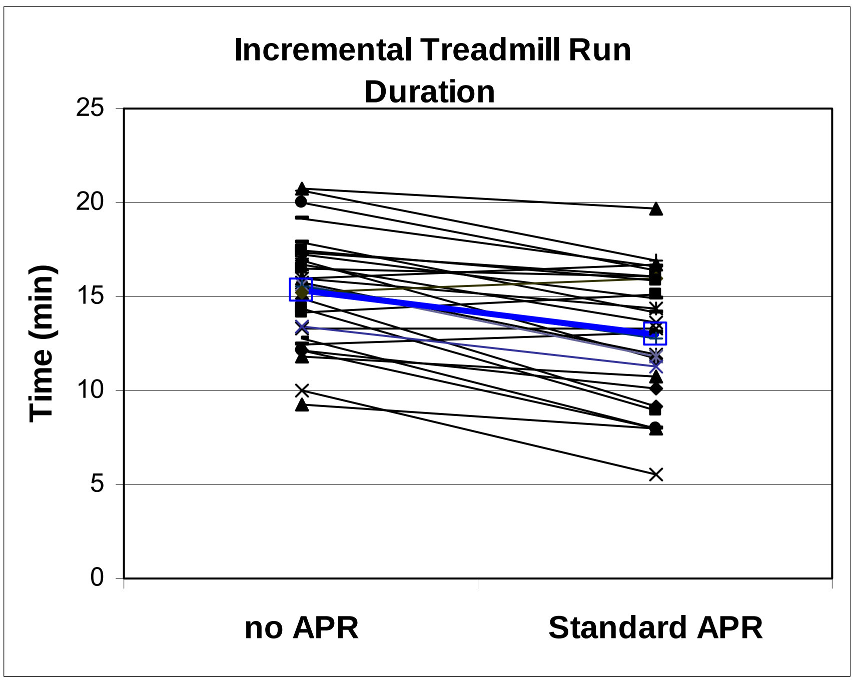


Figure 2. Incremental treadmill run duration, Phases 1 and 2. Each line represents a different subject. The heavy blue line with open box endpoints shows the mean response. Mean decrease = –15%, $p<0.01$.

APR use reduced endurance run duration at 85% $VO_{2\ max}$ even more dramatically — by 57% on the average. Endurance run duration decreased for all subjects (Fig. 3). The subject with high endurance and only a small change in endurance time (from 46 to 41 minutes) may have been running at a percentage of $VO_{2\ max}$ lower than 85%. If those data are removed, the average decrease in endurance time becomes 61%.

Time on the climber showed a mixed response to APR wear, with some subjects apparently unaffected, some improving slightly, and some dramatically impaired (Fig. 4). Filter loading did not alter average climbing duration

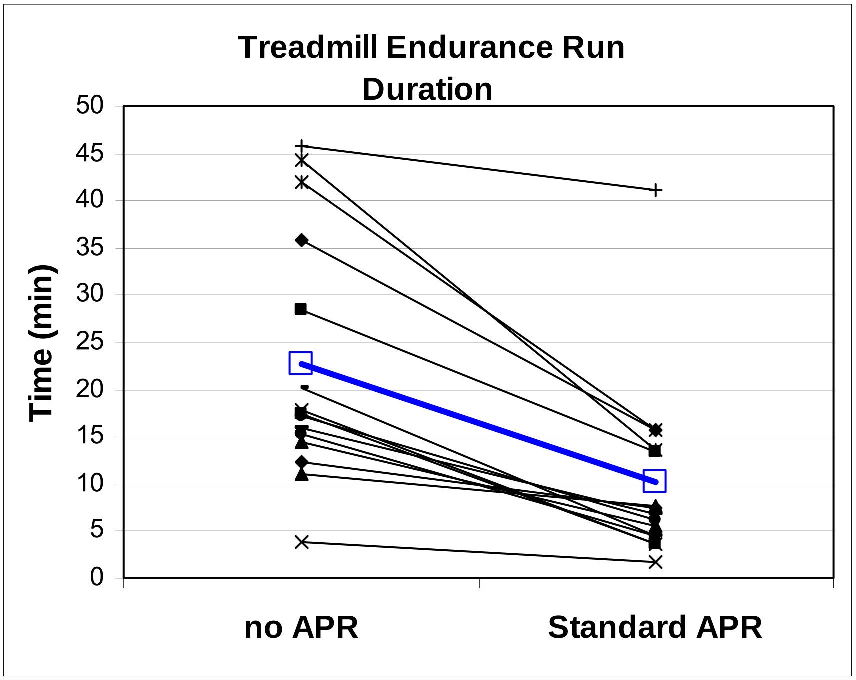


Figure 3. Treadmill endurance run duration at 85% peak VO_2, Phase 2. Each line represents a different subject. The heavy blue line with open box endpoints shows the mean response. Mean decrease = –57%, p<0.01.

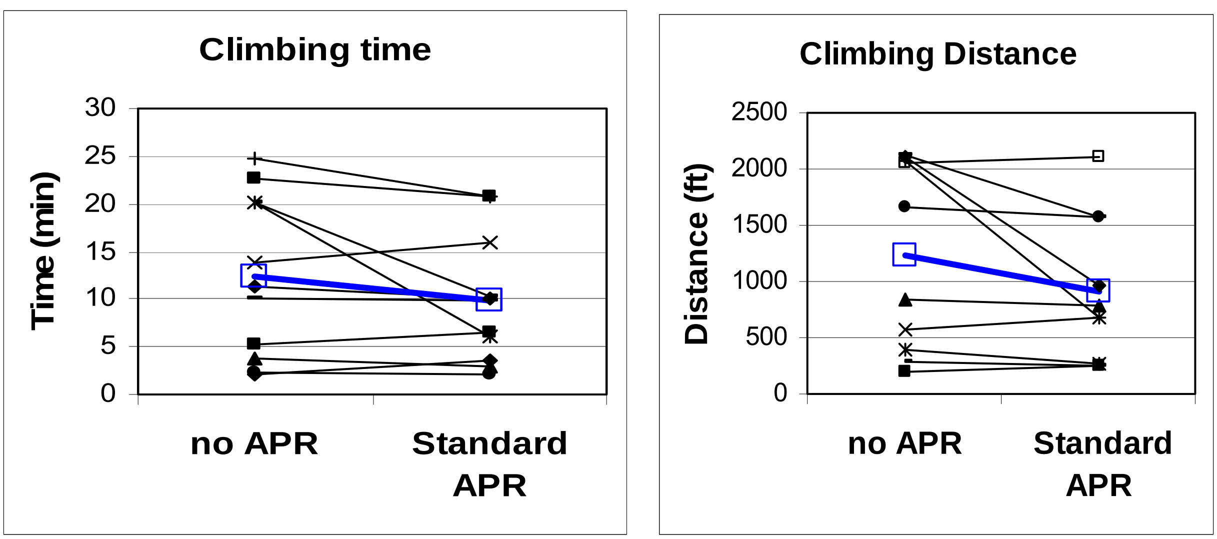


Figure 4. Endurance time on the ladder and vertical distance climbed. Each line represents a different subject. The heavy blue line with open box endpoints shows the mean response. The average changes caused by the APR were not significant (p>0.05).

Performance during the box lift also showed a mixed pattern of response (Fig. 5). Subjects paced themselves at 60% $VO_{2\,max}$ (SD 12%) with no APR, 50% $VO_{2\,max}$ (SD 13%) with standard APR, and 42% $VO_{2\,max}$ (SD 11%) with loaded APR, a significant difference between no APR and standard APR ($p<0.03$), but not between standard and loaded filters. Here, $VO_{2\,peak}$ without APR was used as the estimate of $VO_{2\,max}$. The number of boxes moved in the last minute was reduced 8% with a loaded filter from the number moved with no APR or with a clean filter.

The hose drag, not graphically represented, showed a uniform lack of performance change with APR wear.

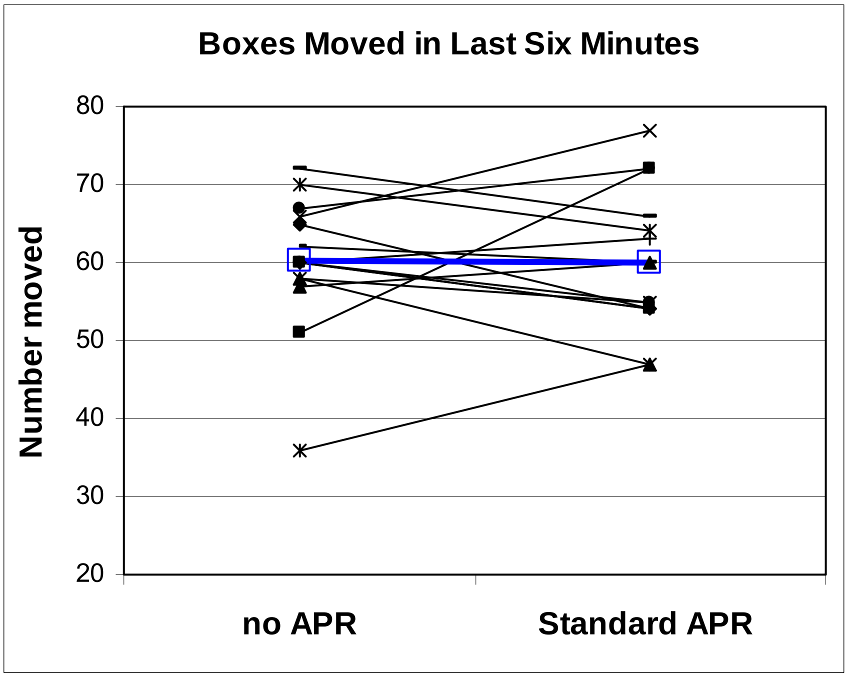


Figure 5. Number of boxes moved in the final six minutes (minutes19–24 of work) of the load lift and transfer test. Each line represents a different subject. The heavy blue line with open box endpoints shows the mean response. The average change caused by the standard APR was not significant ($p>0.05$).

CARDIOVASCULAR AND VENTILATORY VALUES AT END EXERCISE

Values at end exercise with and without an APR are compared in Tables 3a, 3b, and 3c. Values are cross-subject averages of the averages for the last seven breaths of exercise for Phase 1 and the last minute of exercise for Phase 2.

By design, subjects running without an APR exercised to cardiovascular limits during incremental treadmill runs. They were unable to reach those limits when they wore an

APR, as is evident from the lower HR and $\dot{V}O_2$ at the end of incremental exercise (Table 3a).

V_E at end exercise was lower with the APR than without, and associated $F_{ET}CO_2$ was higher. Filter loading increased $F_{ET}CO_2$ beyond that seen with the clean filter, while mask modification had no further effect.

The difference in VO_2 ($\Delta VO_{2\ peak}$), no APR to APR, at end treadmill exercise was significantly related to the associated change in minute ventilation (ΔV_E), as

$$\Delta VO_{2\ peak} = a \cdot \Delta V_E + b.$$

Values of coefficients and their standard errors (SEs) follow. The regression coefficient r^2 represents the fraction of the variance explained by the regression when both *a* and *b* are fitted.

Standard APR (n = 30): a = 0.021 (SE 0.004, p<0.01); b =–0.01 (SE 0.2, n.s.); r^2 = 0.46
Fitted with b = 0: a = 0.021 (SE = 0.002, p<0.01); r^2 = 0.76

Loaded APR (n = 15): a = 0.018 (SE 0.006, p<0.02); b = 0.1 (SE 0.3, n.s.); r^2 = 0.40
Fitted with b = 0: a = 0.019 (SE 0.003, p<0.01); r^2 = 0.81

Modified APR (n = 15): a = 0.02 (SE 0.01, n.s.); b = –0.1 (SE 0.5, n.s.); r^2 = 0.23
Fitted with b = 0: a = 0.021 (SE 0.005, p<0.01); r^2 = 0.56

End endurance, combined standard and modified APR (n=29)
a = 0.022 (SE 0.004, p<0.01); b =0.2 (SE 0.1, p<0.03.); r^2 = 0.58

For any subject running with no APR, VO_2 at end endurance was significantly less (p<0.03) than that at the end of the incremental run. The endurance run was nominally at 85% $VO_{2\ max}$ and the end of the incremental run was our best estimate of $VO_{2\ max}$. However, for subjects wearing an APR, VO_2 at the end of endurance runs was not different from that at the end of the matching incremental run (Table 3a). VO_2 increased gradually during endurance runs whether or not an APR was worn.

The values recorded in Tables 3a, 3b, and 3c are the means and standard deviations across subjects. The values for the individual subjects, though, are also means of breath-by-breath values for the last minute of exercise. The within-subject variability has been ignored here. A quick check for one subject indicated that within-subject coefficients of variation in the last minute of exercise were 3–5% for the variables tabulated.

Only three subjects reached their peak HRs during the ladder climb, and none achieved peak VO_2 as determined on the treadmill (Tables 3a, 3b). For the 11 subjects who stopped climbing because of inability to continue, HR and VO_2 at the end of the ladder climb without an APR were, respectively, 91% (SD, 8%) and 75% (SD, 7%) of the peak treadmill values without an APR.

Table 3a.
Cardiovascular and respiratory variables at end treadmill exercise. Note that the external work (i.e., treadmill incline) may differ at end incremental exercise with and without an APR.

Incremental Treadmill Runs, Phase 1 (n = 15)			
Means (standard deviations)	**No APR End exercise**	**Standard APR**	**Loaded APR**
HR (beats/min)	183 (11)	169 (13) ‡	168 (12)
VO_2 (L/min)	3.9 (0.6)	2.9 (0.7) ‡	3.0 (0.6)
V_E (L/min)	114 (19)	77 (16) ‡	71 (12)
$F_{ET}CO_2$ (%)	5.7 (0.8)	6.2 (0.8) ‡	6.5 (0.7)†
V_E/VO_2	29 (5)	26 (4) ‡	23 (3) †
Incremental Treadmill Runs, Phase 2 (n = 15)			
Means (standard deviations)	**No APR End exercise**	**Standard APR**	**Modified APR**
HR (beats/min)	183 (11)	172 (11) ‡	172 (11)
VO_2 (L/min)	4.1 (0.9)	3.6 (0.9) ‡	3.3 (0.9)
V_E (L/min)	129 (29)	95 (23) ‡	93 (23)
$F_{ET}CO_2$ (%)	5.1 (0.5)	6.2 (0.7) ‡	6.6 (1.5)
Endurance Treadmill Runs, Phase 2 (n = 15)			
HR (beats/min)	176 (11)	163 (12) ‡	161 (21)
VO_2 (L/min)	3.7 (0.7)	3.4 (0.7) ‡	3.5 (1.0)
V_E (L/min)	111 (25)	87 (19) ‡	85 (25)
$F_{ET}CO_2$ (%)	5.1 (0.9)	6.5 (1.0) ‡	6.4 (0.7)

Values are means (and standard deviations) of the last minute of exercise. Statistical significance ($p<0.05$) from repeated measures ANOVA with difference contrasts: ‡ = different from the no-APR condition; † = different from the standard APR, not explicitly compared to the no-APR condition.

Table 3b.
Cardiovascular and respiratory variables at end exercise for Ladder Climb and Load Lift and Transfer. Climb duration generally differed, with and without APR (Table 2), but Load Lift and Transfer involved 24 minutes of lifting in all cases.

Means (standard deviations)	**No APR, end exercise**	**Standard APR**	**Loaded APR**
Ladder Climb (n = 11)			
HR (beats/min)	168 (12)	166 (12)	165 (12)
VO_2 (L/min)	2.9 (0.5)	2.6 (0.5) ‡	2.6 (0.5)
V_E (L/min)	92 (21)	70(16) ‡	73 (13)
$F_{ET}CO_2$ (%)	5.3 (0.7)	6.0 (0.8) ‡	6.0 (0.8)
V_E/VO_2	32 (8)	26 (4) ‡	28 (6)
Load Lift and Transfer (n = 15)			
HR (beats/min)	149 (24)	155 (21)	155 (21)
VO_2 (L/min)	2.5 (0.5)	2.2 (0.5) ‡	2.2 (0.5)
V_E (L/min)	70 (19)	59 (13) ‡	55 (12)
$F_{ET}CO_2$ (%)	5.0 (0.5)	5.2 (0.6)	5.4 (0.6)

Values are seven-breath averages. Statistical significance ($p<0.05$) from repeated measures ANOVA with difference contrasts: ‡ = different from the no-APR condition; † = different from the standard APR, not explicitly compared to the no-APR condition.

Table 3c.
Peak cardiovascular and respiratory variables, fire hose drag. Values are the highest five-breath average during either the hose drag or recovery from it.

Means, 15 subjects (standard deviations)		**No APR, peak**	**Standard APR**	**Loaded APR**
HR (beats/min):	Exercise	171 (31)	180 (24)	177 (25)
	Recovery	158 (20)	165 (12)	164 (13)
V_E (L/min):	Exercise	92 (29)	74 (18)	79 (27)
	Recovery	74 (22)	67 (12)	65 (12)
$F_{ET}CO_2$ (%):	Exercise	5.8 (0.5)	5.2 (0.9)	5.2 (0.6)
	Recovery	6.2 (0.9)	6.0 (0.7)	6.1 (0.7)

None of the measures was significantly different across mask conditions.

The endpoint for endurance during heavy exercise with an APR appears to be the time at which VO_2 reaches the peak achievable with the APR (attainable $VO_{2\ peak}$). VO_2 at the end of treadmill endurance runs and ladder climbing, also an endurance exercise, clusters near the identity line when plotted against $VO_{2\ peak}$ attainable with the APR (Fig. 6). Ladder climbing required work at different fractions of $VO_{2\ max}$ across subjects. Subjects for whom climbing was only moderate exercise and the one runner for whom the endurance load was probably less than the target 85% $VO_{2\ max.}$ show as outliers. Values above the identity line indicate that the incremental $VO_{2\ peak}$ was less than the peak attainable with the APR.

In Figure 6, a value on the x-axis represents the greater of the two measurements of $VO_{2\ peak}$ during the two incremental runs with an APR, for ladder climbing either that with the standard APR or that with the loaded filter, and for endurance running, either that with the standard or that with the modified APR.

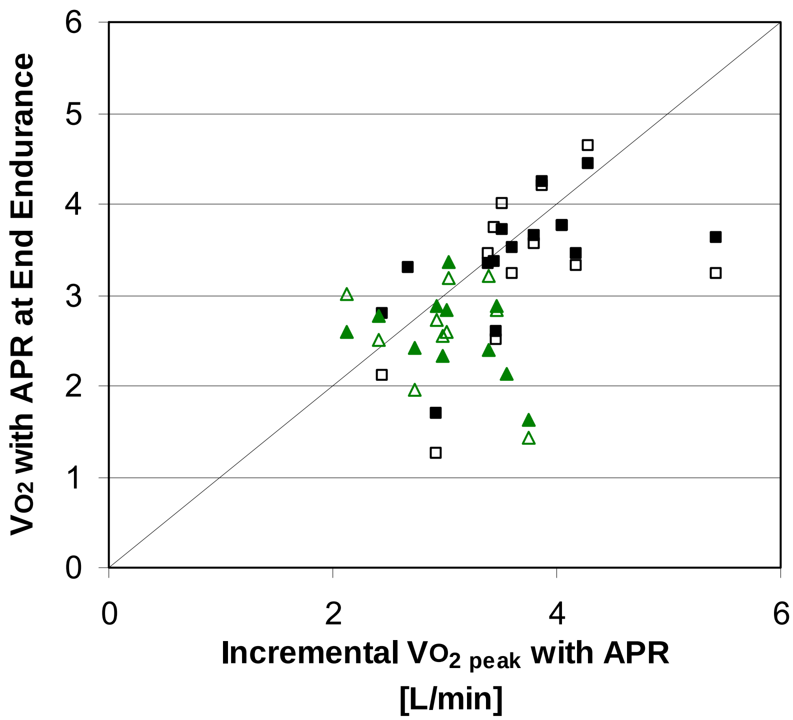


Figure 6. VO_2 with an APR at end endurance running and ladder climbing vs. attainable $VO_{2\ peak}$ during APR use for both mask conditions. VO_2 from endurance exercise is plotted against the higher of the two values for incremental $VO_{2\ peak}$ obtained with an APR. Endurance runs: black squares, solid = standard APR, open = modified APR. Ladder climbing: green triangles, solid = standard APR, open = loaded filter. The identity line is shown.

CARDIOVASCULAR AND VENTILATORY VALUES DURING STEADY EXERCISE

Cardiovascular Variables

Heart Rate

APR use did not change the relation of HR to external work. When HR with the standard APR was plotted against HR without the APR at the same external workload, the slope was between 0.93 and 1.01 for all the exercises tested. HR at the end of treadmill running was lower with an APR than without one (Table 3a) only because the workload at end exercise was lower with the APR than without it; at matched run durations, HR was not different across mask conditions.

Rate of Oxygen Uptake (V_{O_2})

APR use generally reduced V_{O_2} at the same exercise level (Fig. 7). For all tests other than endurance running, the slopes of the correlation plot of values with the APR against those without it lie between 0.82 and 0.85. V_{O_2} with an APR was 15% to 18% less than that without an APR.

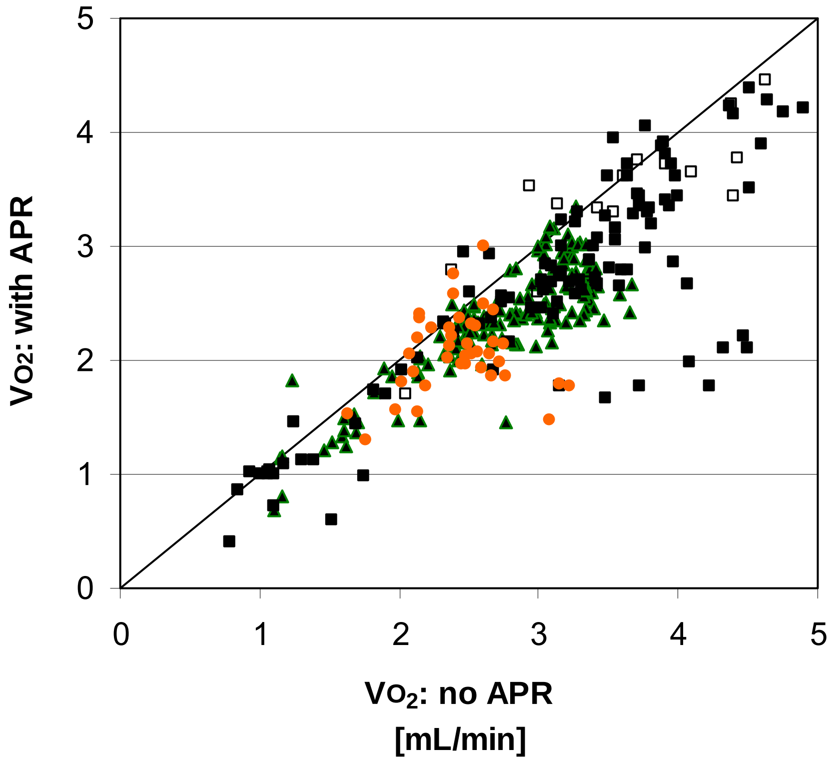


Figure 7. Oxygen uptake during exercise, standard APR vs. no APR at matching workload or exercise duration. Black squares: treadmill running (solid: incremental, open: endurance); green triangles: ladder climb; orange circles: load lift and transfer. The identity line is shown.

The difference in VO_2 with and without an APR was not significant for endurance treadmill runs ($p = 0.14$; slope, 0.95) where only values at end endurance with an APR and the matching time without an APR were considered.

Ventilatory Variables

Minute Ventilation (V_E)

With the same external workload or duration of exercise in each case, V_E with an APR was lower than that without one for almost all steady-state exercise including endurance running (Fig. 8). The slopes of V_E with an APR against V_E without an APR, forced through zero were 0.78 for incremental treadmill running, 0.86 for endurance running, 0.74 for ladder climbing, and 0.84 for load lift and transfer. However, V_E with APR clearly deviates from that without APR only for VE>60 L/min (Fig. 8).

During incremental treadmill running, mean V_E was approximately 25 L/min for walking at 3 miles per hour, 60 L/min for running on the level, 73 L/min on a 2% grade, 85 L/min on a 4% grade, and 100 L/min on a 6% grade. However, V_E at each treadmill incline varied across individuals (as did running speed and VO_2), and maximum values can be much higher; one subject who completed only the incremental run without APR and who therefore is not included in any of the figures or tables had V_E = 41 L/min walking, 89 L/min during level running, 129 L/min on a 4% grade, and 155 L/min on a 6% grade.

V_E generally increases with time during heavy endurance exercise, first rapidly as the body adjusts to the workload, then in a steady, slow climb. For all but two subjects, the slow increase in V_E ($\Delta V_E/\Delta t$) during endurance running was steeper when subjects wore a standard APR than when they ran unencumbered. For those two, V_E with APR decreased with time during APR use, a decrease suggesting fatigue of respiratory muscles. Another two subjects did not continue long enough with APR for the slope $\Delta V_E/\Delta t$ to be estimated. Without those four subjects, the difference between slopes with no APR and with standard APR was significant ($p<0.01$); the mean slope without APR was 0.025 $L \cdot min^{-2}$, SE 0.008 $L \cdot min^{-2}$, and mean slope with standard APR was 0.049 $L \cdot min^{-2}$, SE 0.011 $L \cdot min^{-2}$.

Endurance time ($T_{endurance}$) was inversely proportional to $\Delta V_E/\Delta t$ with or without APR:

$$1/T_{endurance} = c \cdot \Delta V_E/\Delta t + d,$$

where c = 2.1, 95% confidence interval 1.64 to 2.56; and
d = 0.02, 95% confidence interval –0.001 to 0.04; r^2 = 0.81.

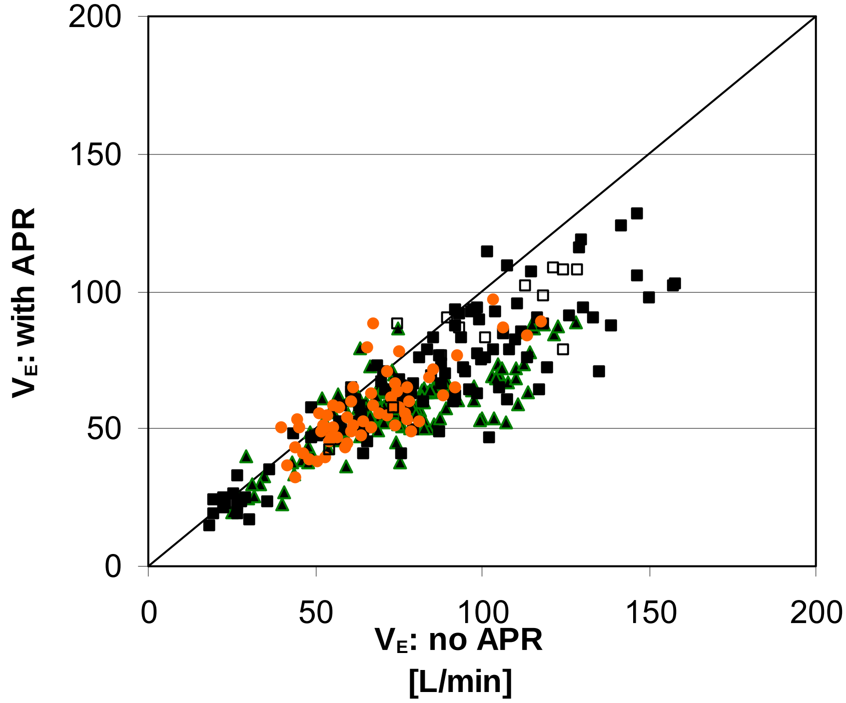


Figure 8. Minute ventilation during exercise, standard APR vs. no APR at matching workload or exercise duration. Black squares: treadmill running (solid: incremental, open: endurance); green triangles: ladder climb; orange circles: load lift and transfer. The identity line is shown.

End tidal CO_2 fraction ($F_{ET}CO_2$)

$F_{ET}CO_2$ provides one measure of ventilatory adequacy, but it changes in a more complex pattern than does the ventilation itself. Examples from one subject on the ladder (Fig. 9a) and during incremental treadmill running (Fig. 9b) illustrate changes in $F_{ET}CO_2$ during these experiments. $F_{ET}CO_2$ generally increases transiently at the start of exercise and then decreases as exercise continues. With APR use, the durations of the different phases sometimes differed from those without an APR, and sometimes $F_{ET}CO_2$ did not decrease after the initial increase.

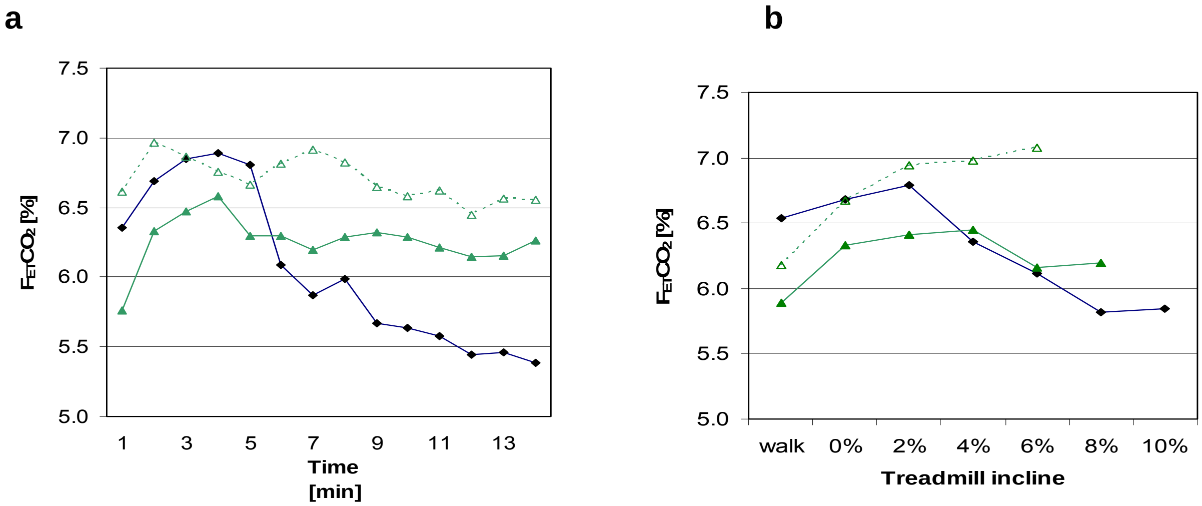


Figure 9. $F_{ET}CO_2$ from one subject as (a) a function of time during the ladder climbing exercise, and (b) a function of exercise level during the incremental treadmill exercise. Although details differ among subjects, these changes in $F_{ET}CO_2$ with time and with exercise intensity show typical patterns. Black diamonds = no APR; solid green triangles = with a standard APR; open green triangles = with a loaded filter.

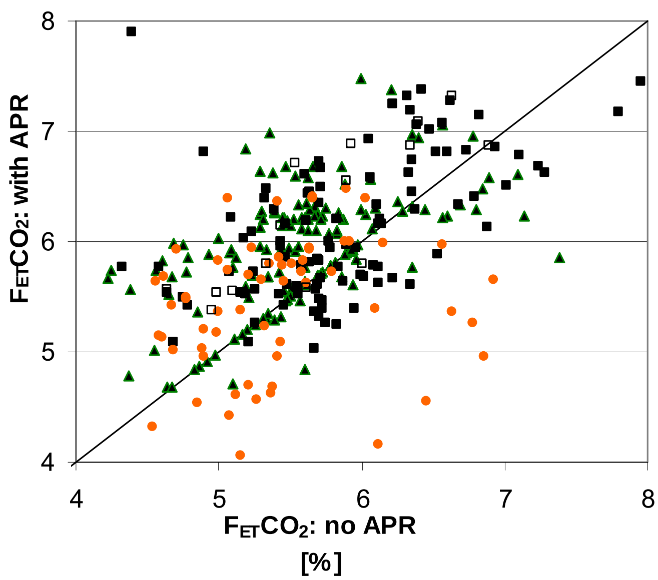


Figure 10. $F_{ET}CO_2$ during exercise, standard APR vs. no APR at matching workload or exercise duration. Black squares: treadmill running (solid: incremental, open: endurance); green triangles: ladder climb; orange circles: load lift and transfer. The identity line is shown.

Average $F_{ET}CO_2$ at end exercise with an APR was significantly higher than that without one, both at the matching time or exercise level and at end exercise (Table 3), but at corresponding intermediate times, the relation sometimes was reversed, as the large scatter in Figure 10 shows.

Tidal Volume (V_T) and Respiratory Frequency (f_R)

During exercise the APR had no effect in general on V_T at matching workload or exercise duration (Fig. 11). Despite the differences in endurance run duration, V_T at the end of endurance runs did not differ across mask conditions. In contrast, V_T at the end of incremental running was reduced by APR use.

APR use decreased f_R during exercise, though with considerable scatter (Fig. 12). At the end of all exercise modalities, f_R was lower with than without an APR.

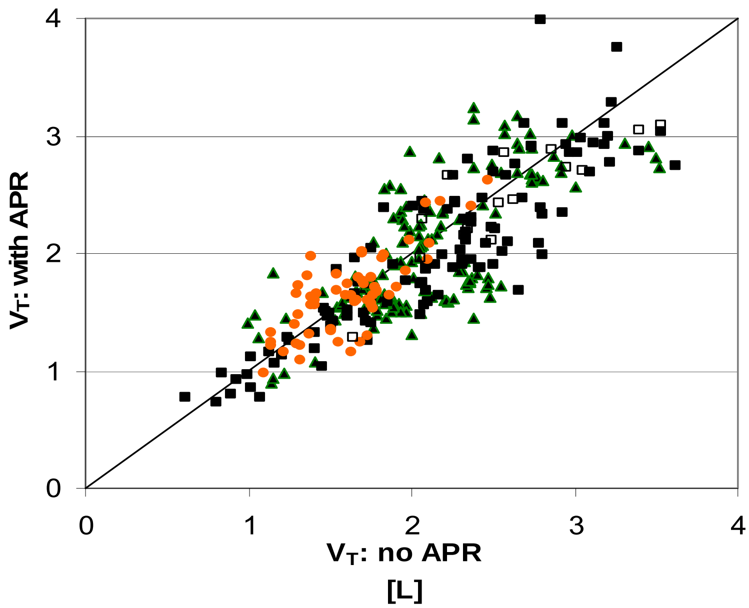


Figure 11. V_T during exercise, standard APR vs. no APR at matching workload or exercise duration. Black squares: treadmill running (solid: incremental, open: endurance); green triangles: ladder climb; orange circles: load lift and transfer. The identity line is shown.

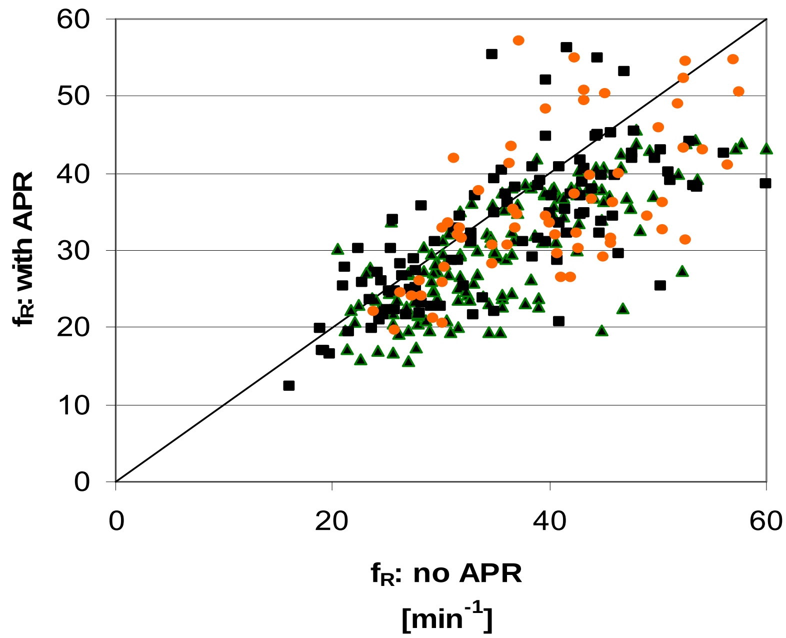


Figure 12. f_R during exercise, standard APR vs. no APR at matching workload or exercise duration. Symbols are as given in Figure 11.

Respiratory Duty Cycle (T_I/T_{TOT})

Although T_I/T_{TOT} without an APR increased during the transition from walking to running, for many but not all subjects it was initially high with an APR and decreased as the ventilatory demands of exercise increased. Surprisingly, T_i/T_{TOT} was *lower* with a standard APR than without one for the load lift and transfer (mean no APR: 0.46, with standard or loaded APR 0.43, $p<0.01$) and for treadmill running exercises, both incremental (mean no APR: 0.47, mean standard APR: 0.45; $p<0.01$) and endurance (mean no APR: 0.48, mean standard APR: 0.45, $p<0.04$) but it was not different across mask conditions for ladder climbing or between loaded filter and no-APR conditions for incremental exercise on the treadmill (Fig. 13).

At peak exertion during Phase 1 treadmill running, mean T_I/T_{TOT} without an APR was 0.47 (SD 0.03), while that with the maximal inspiratory loading, the loaded APR, was 0.45 (SD 0.04). Without an APR, the highest T_I/T_{TOT} for a Phase 1 subject on the treadmill, 0.55, was measured for a subject running on a 4% grade. With an APR, however, the highest values were measured in subjects walking on the level, 0.55 for three subjects using standard APRs and 0.61 for one breathing through a loaded filter. Without an APR, the lowest T_I/T_{TOT}, 0.31, was measured in a subject walking on the level; while with an APR, the lowest values were measured at heavy exercise: with a standard APR, 0.35 on a 6% grade and 0.36 on an 8% grade; and with a loaded APR, 0.38 on a 6% grade.

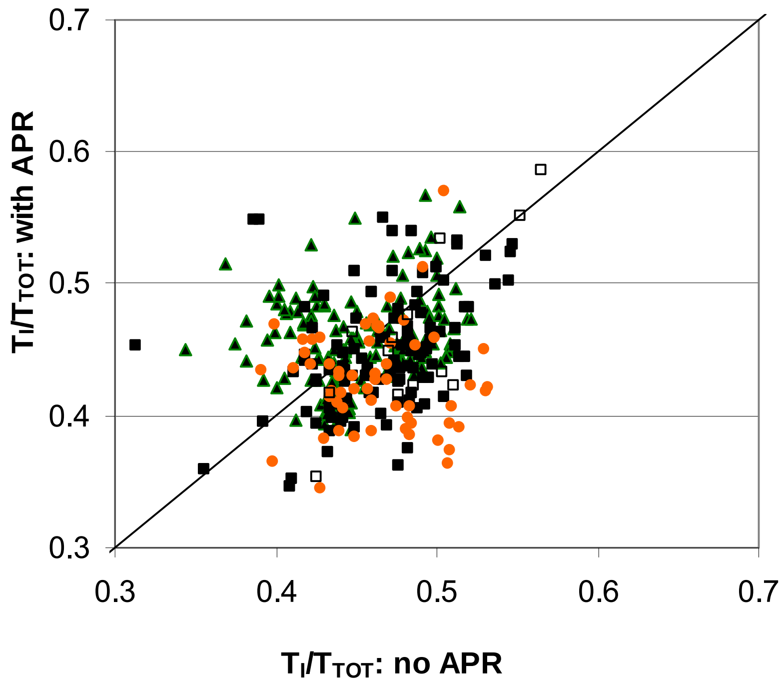


Figure 13. T_I/T_{TOT} during exercise, standard APR vs. no APR at matching workload or exercise duration. Black squares: treadmill running (solid: incremental, open: endurance); green triangles: ladder climb; orange circles: load lift and transfer. The identity line is shown.

Peak inspiratory flow and pressure ($V_{i\ peak}$ and $P_{i\ peak}$)

$V_{i\ peak}$ as defined here is the one-minute average of the breath-by-breath maxima. It was significantly lower ($p<0.01$) with an APR than without one, although the values do not deviate on the average if $V_{i\ peak}$ <200 L/min (Fig. 14). $V_{i\ peak}$ during running was reduced more with the loaded filter than with the standard APR ($p < 0.04$), but unchanged from the standard APR by modification of the inlet pathway.

$P_{i\ peak}$ was significantly greater ($p < 0.01$) with a loaded than with a clean filter, but it was not affected by modification of the mask. At nominally 85% $VO_{2\ max}$, average $P_{i\ peak}$ was –19 cm H_2O, (SD 5 cm H_2O) for the standard APR and –17 cm H_2O (SD 3 cm H_2O) for the modified APR ($p>0.05$).

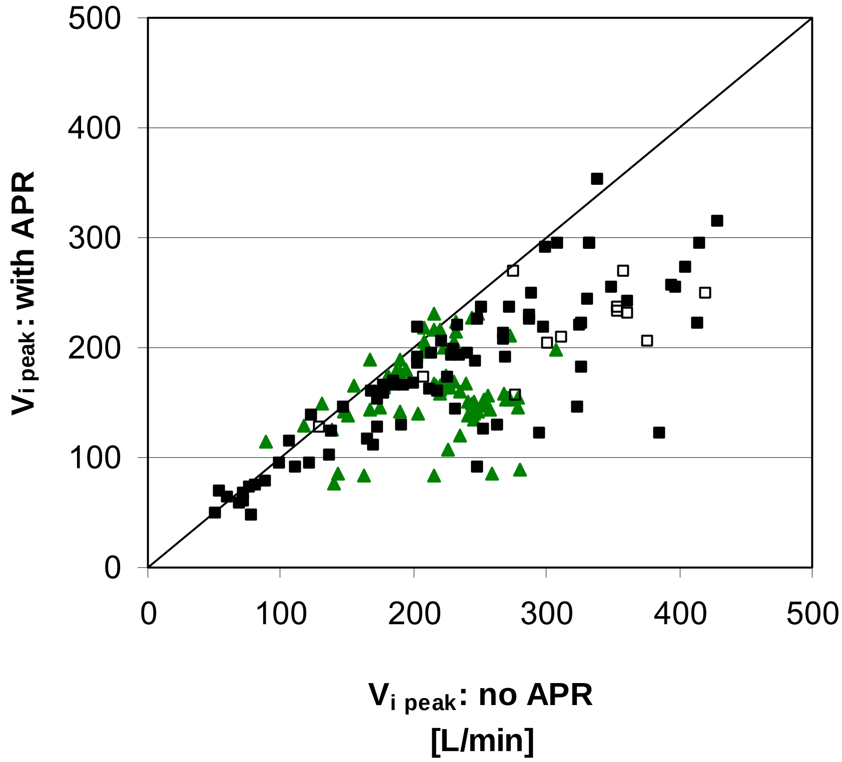
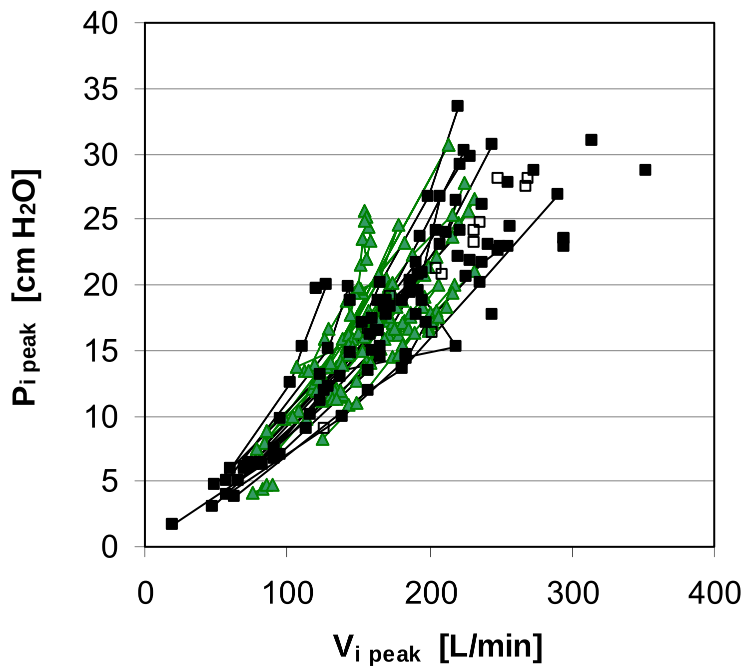
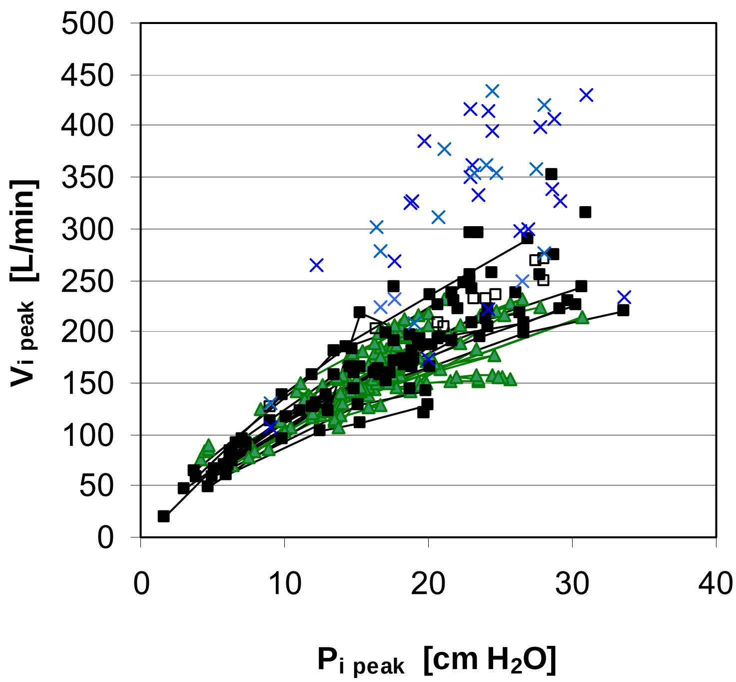


Figure 14. $V_{i\ peak}$ during exercise, standard APR vs. no APR at matching workload or exercise duration. Black squares: treadmill running (solid: incremental, open: endurance); green triangles: ladder climb. The identity line is shown.

The highest $V_{i\ peak}$ measured during incremental treadmill running were 415 L/min unencumbered, 353 L/min with a standard APR, 274 L/min with a loaded filter, and 354 with a modified APR. During endurance running the highest flows were 434 L/min unencumbered, 270 L/min with a standard APR, and 289 with a modified APR — considerably greater than the 85 L/min of the standards. The greatest $P_{i\ peak}$, measured during treadmill running, were 33.6 cm H_2O with a standard APR and 38.4 cm H_2O with a loaded filter.





Figures 15a (top) and 15b (bottom). Relation between $P_{i\ peak}$ and $V_{i\ peak}$, with a standard APR: (a) $P_{i\ peak}$ plotted against $V_{i\ peak}$, and (b) axes reversed. Black squares: treadmill running (solid: incremental, open: endurance); green triangles: ladder climb. Lines connect data from individual subjects. Points without lines show only one value from that individual. Blue x: $V_{i\ peak}$ without the APR at end exercise, running or climbing, for the condition giving the pressure $P_{i\ peak}$ with the standard APR.

The nonlinear (non-laminar) pressure flow relationship for the standard APR during treadmill and climber exercise is shown in Figure 15a. Phase 2 treadmill data fall among those for Phase 1. $P_{i\ mask}$ without APR, not measured, can be assumed to be 0 (not different from atmospheric pressure).

Although the usual pressure-flow relation, used to describe the resistance characteristics of a system, considers pressure to depend on flow (Fig. 15a), subjects wearing an APR generate P_i in order to generate V_i. Figure15b reflects the physiologic independent-dependent relation, $V_{i\ peak}$ vs. $P_{i\ peak}$. $V_{i\ peak}$ without an APR also is shown plotted against the pressure for the same exercise condition but with standard APR; the flow without APR can be considered the target flow for the pressure generated.

$P_{i\ peak}$ has a wide range of values at any V_i (Fig. 15a), perhaps because the interaction of the mask with a subject's facial shape changes the dimensions of the inlet channels. Camperman reports detailed effects of mask fit and position on pressure-flow characteristics on a mannequin head.[1]

The mask modification, removal of an inlet diffuser piece, attempted to address the shape of the one part of the flow pathway. Although the magnitude of $P_{i\ peak}$ at end endurance exercise was lower without the diffuser (modified mask) than with it, neither $P_{i\ peak}$ at the matched treadmill incline nor that at end incremental running differed between the standard and modified APR.

Table 4..
Effect of mask modification on magnitude of peak inspiratory pressures

Magnitude $P_{i\ peak}$, cm H_2O	Standard APR		Modified APR		Probability not different
	Mean	SD	Mean	SD	p
endurance 85% $VO_{2\ max}$	21.3	5.2	19.8	5.4	<0.04
end incremental	23.3	5.6	20.9	5.0	0.10
incremental, 85% $VO_{2\ max}$	19.3	5.1	17.4	3.2	>0.06

Peak expiratory flow ($V_{exp\ peak}$) and pressure ($P_{exp\ peak}$)

$V_{exp\ peak}$ was not affected by APR use (Fig. 16). The expiratory pressure-flow relation, although as variable as that for $V_{i\ peak}$, was linear for the most part (Fig. 17). Expiratory pressures (y-axis of Figure 17) were much lower than inspiratory pressures (y-axis of Figure 15a) and, as expected, were independent of filter condition.

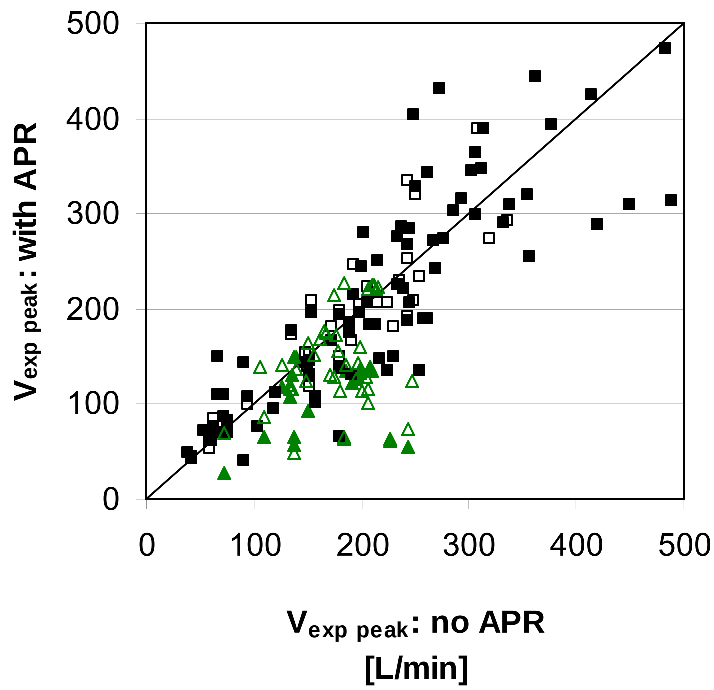


Figure 16. V_{exp} during exercise, APR vs. no APR at matching workload or exercise duration. Black squares: incremental treadmill running; green triangles: ladder climb. Solid: standard APR; open: loaded filter. The identity line is shown.

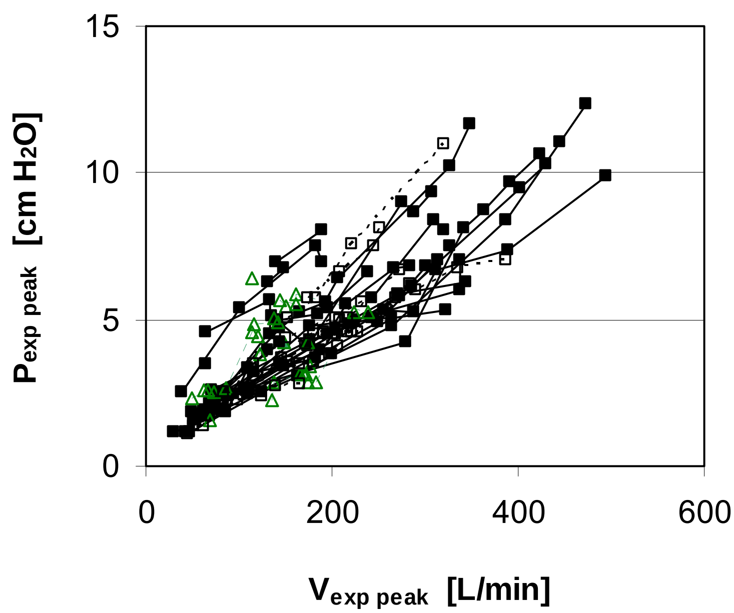


Figure 17. $P_{exp\ mask}$ peak as a function of V_{exp} peak. Black squares: incremental treadmill running; green triangles: ladder climb. Solid: standard APR, open: loaded filter. Lines connect data from individual subjects.

Breathing patterns

Inspiratory waveform shape was assessed by using the ratio of peak inspired to mean inspired flow, the flow profile index. A square wave has a flow index of one and a sine wave has an index of π/2, or about 1.6. On the average, flow profile index did not change with APR use (Fig. 18). The index is not a function of V_E, but all values >1.5 occurred with V_E <60 L/min.

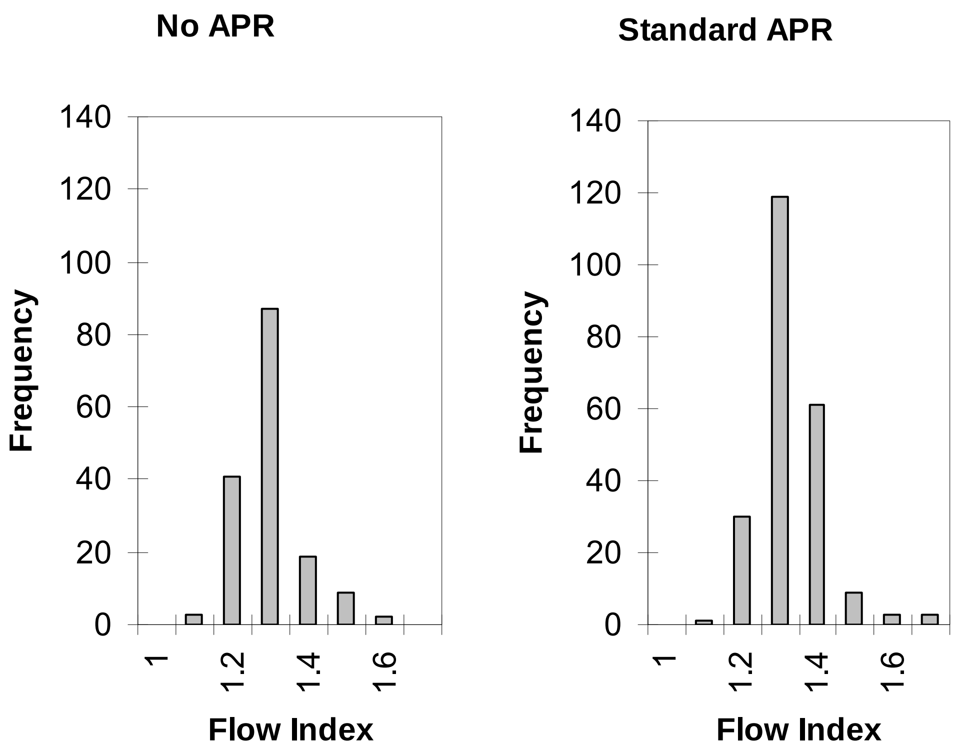


Figure 18. Distribution of inspiratory flow profile index, peak inspired flow/mean inspired flow, with and without a standard APR. Data for all measured intensities of treadmill and climber exercise are pooled. Each measurement condition (treadmill incline or minute of ladder climb) is one count.

Breathing patterns are neither sinusoidal nor square wave and are distinctly different between inspiration and expiration. A sample segment of raw data is given in Figure 19 for one subject during incremental running with a standard APR. Expiration is positive and inspiration negative. The inspiratory waveforms track the pressure waveforms very closely. Because waveforms for inspiratory flow and pressure were gathered separately from those for expiratory flow, we cannot synchronize them perfectly. Expiratory pressure and flow shown here may represent different breaths.

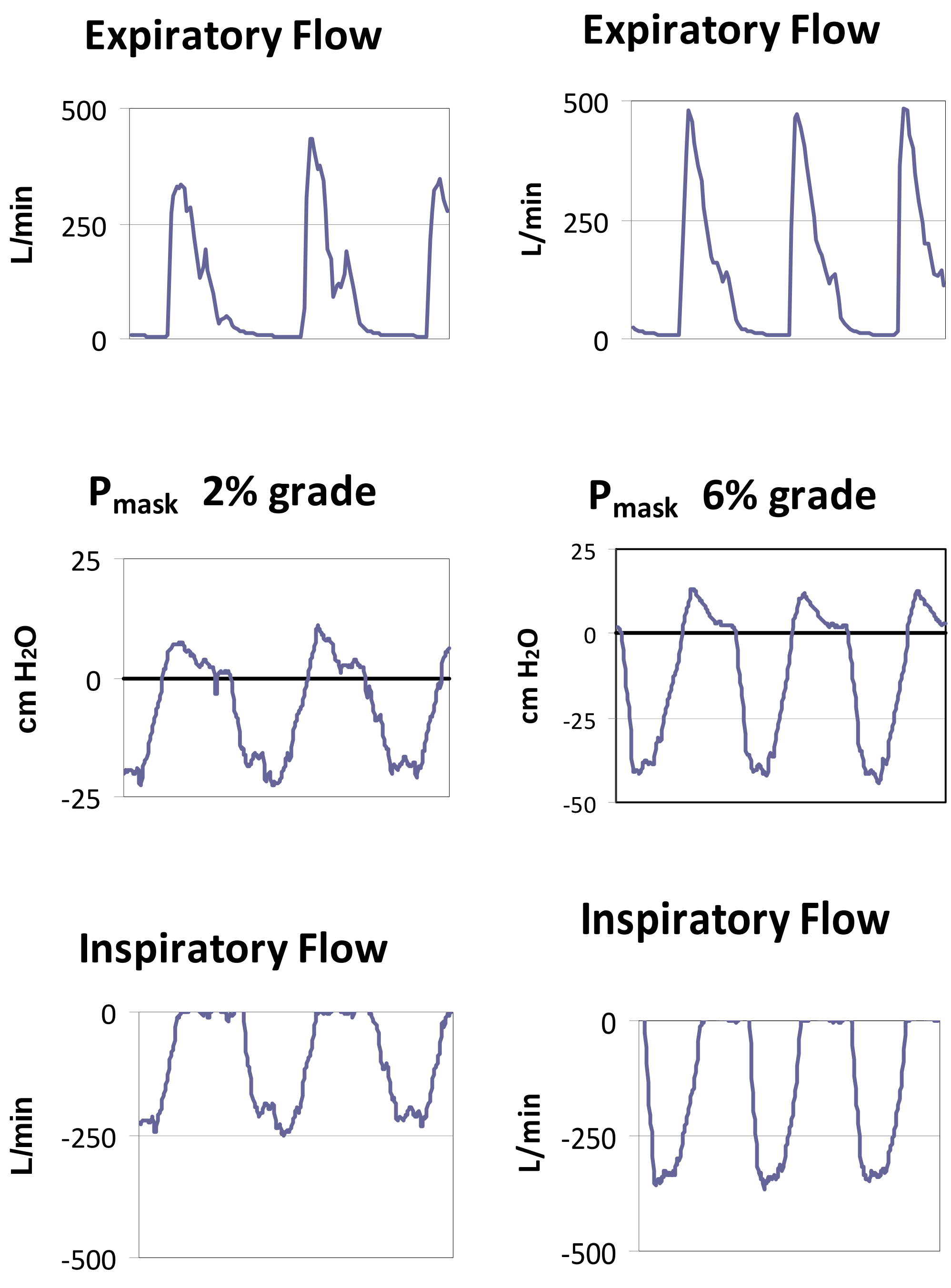


Figure 19. Sample flow and pressure tracings for one subject to illustrate waveform shape. Time scales differ between the data from the 2% grade (left) and those from the 6% grade (right).

Inspiratory Work of Breathing per Tidal Volume (WOB_i/V_T)

Inspiratory work of breathing is the integral of inspiratory pressure with respect to volume — that is, the area between the x-axis and inspiratory pressure-volume curves like those shown in Figure 20. The pressure-volume integral is normalized by tidal volume to yield WOB_i/V_T, a quantity sometimes called inspiratory resistive effort or volume-averaged pressure. WOB_i/V_T has dimensions of pressure.

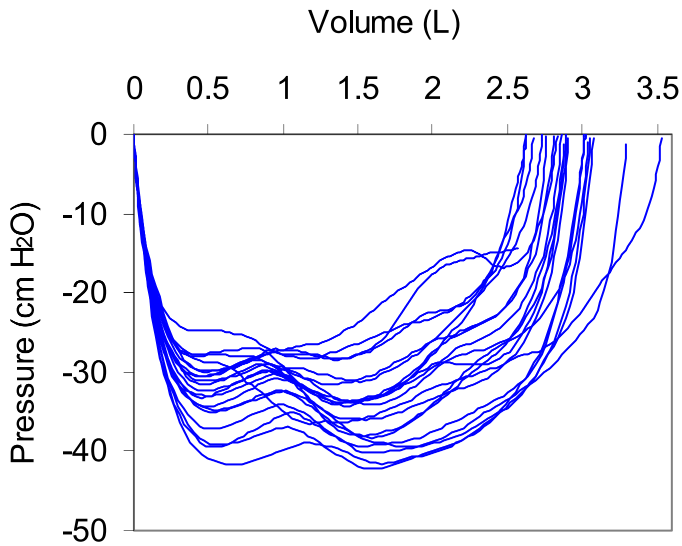


Figure 20. Inspiratory portions of 18 pressure-volume loops for one male subject, $\dot{V}O_2$/kg = 60 mL·min^{-1}·kg^{-1}, running on an 8% treadmill grade. Although exact shapes vary with exercise intensity and across subjects, these can be considered to be typical curves.

WOB_i/V_T was higher with a loaded filter than with a standard APR. After the duration of climbing that corresponded to the final minute with either the standard or the loaded APR, the mean WOB_i/V_T for a loaded APR was 1.9 J/L(SD 0.5 J/L), and that for a standard APR was 1.4 J/L (SD 0.5 J/L), $p<0.01$. At the exercise intensity where incremental running ended with one of the APR conditions, mean WOB_i/V_T with a loaded filter was 2.2 J/L (SD 0.7 J/L) and that with a standard APR was 1.8 J/L (SD 0.5 J/L), $p<0.01$. WOB_i/V_T with the modified APR was not statistically different from that with the standard APR; at the end of incremental running in 10 subjects for whom we have valid data for both conditions, mean WOB_i/V_T was 1.8 J/L (SD 0.5 J/L) with the standard APR and 1.6 J/L (SD 0.4 J/L) with the modified APR, $p>0.1$. Similarly, at the end of endurance running in 11 subjects, mean WOB_i/V_T with the standard APR was 1.7 J/L (SD 0.5 J/L) and with the modified mask was1.5 J/L (SD 0.4 J/L), $p>0.1$. During incremntla runiing at 85% $\dot{V}O_{2\,max}$, mean WOB_i/V_T with the standard APR was 1.4 J/L (SD 0.4 J/L) and with the modified mask was1.3 J/L (SD 0.3 J/L), $p>0.08$.

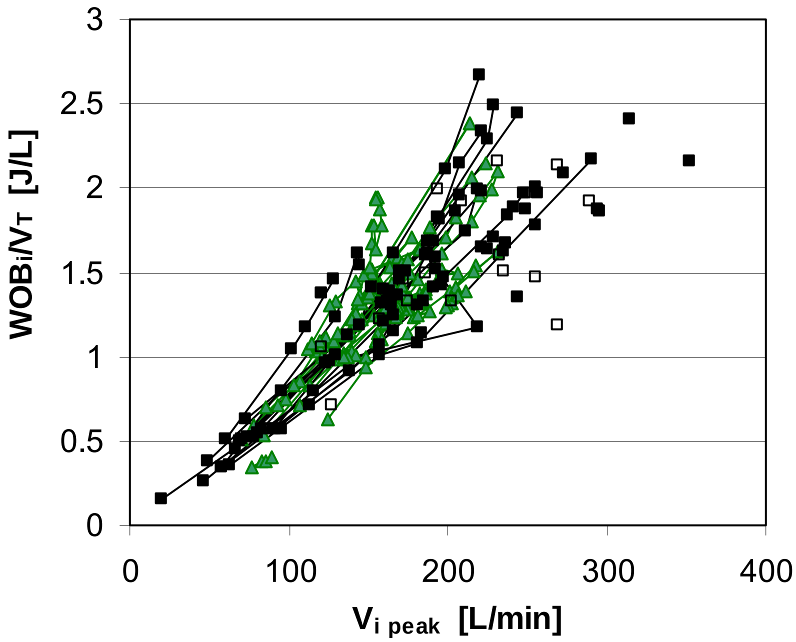


Figure 21. WOB_i/V_T as a function of peak flow. Units of J/L are equivalent to kPa. Green triangles: ladder climb; black squares: treadmill running, solid: incremental running with standard APR, open: endurance running, both mask conditions. Lines connect data from individual subjects when exercise was continuous between measurements.

WOB_i/V_T increased curvilinearly with increasing peak flow (Fig. 21), in a pattern similar to that for P_i peak. Figure 21 shows only values obtained with a standard APR. During climbing, the largest measured values were 2.4 J/L and 2.8 J/L for standard APR and loaded filter, respectively; during incremental running, 2.7 J/L, 3.0 J/L, and 2.2 J/L for standard APR, loaded filter, and modified APR, respectively; and, at the end of endurance running, 2.2 J/L and 2.0 J/L for standard and modified APR, respectively.

V_E obtained for the effort expended is represented in Figure 22. Also shown in that figure are the values of V_E for the matching end exercise conditions, treadmill or ladder, without APR. Those unencumbered V_E values represent the breathing target for each of the exercise conditions.

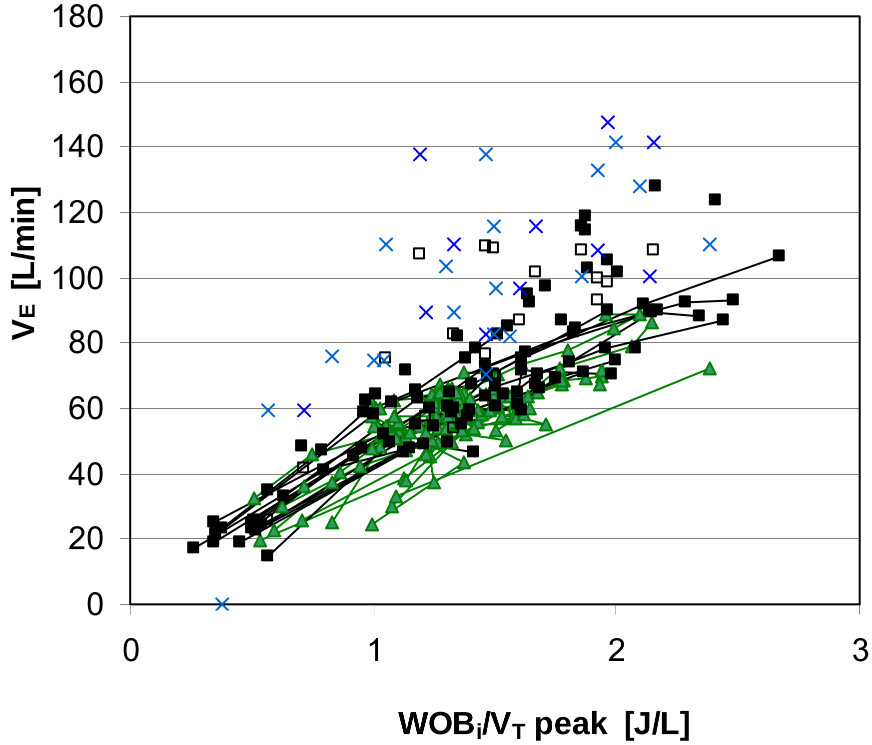


Figure 22. V_E as a function of WOB_i/V_T. Green triangles: ladder climb; black squares: treadmill running, solid: incremental running with standard APR, open: endurance running, both mask conditions. Lines connect data from individual subjects Lines connect data from individual subjects when exercise was continuous between measurements. Blue x: V_E without an APR at end exercise for the condition giving the WOB_i/V_T with a standard APR.

Mask Dead Space

If the oronasal cup seals properly against the face and the one-way valves function properly, at end-inspiration the gas in the APR, both in the eye space and in the oronasal cup, should be atmospheric air (minus any contaminants trapped by the filter). However, minimum inspired CO_2, F_iCO_2 sampled from the oronasal cup at end inspiration, was often somewhat elevated by APR use. We also often saw a small expiratory flow through the inspiratory flow meter. The distributions of end inspiratory F_iCO_2 for ladder climbing and treadmill running are shown in Figure 22. Although most APR uses yielded an end inspiratory F_ICO_2 of about 0.2%, the more elevated end inspiratory F_ICO_2 of many measurements indicates oronasal leaks.

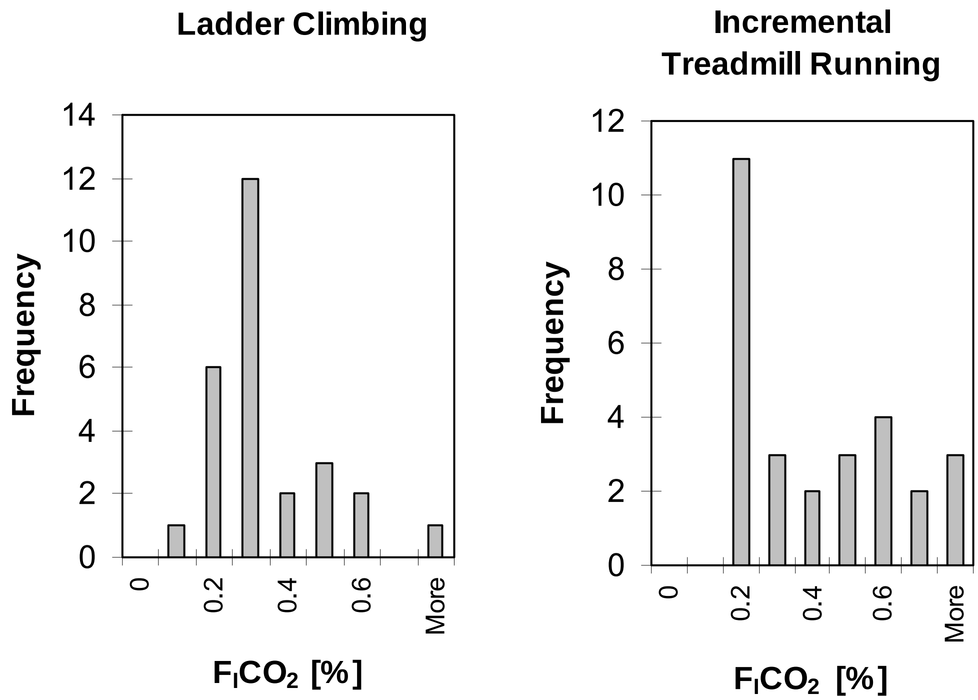


Figure 23. Histogram of minimum F_ICO_2 per breath during ladder climbing and incremental treadmill running. One measurement is represented per subject per mask condition, standard APR and loaded filter. On the x-axis for example, “0.2” labels the frequency of $0.2 \le F_ICO_2 < 0.3\%$

Fire Hose Drag

Cardiovascular variables were not measurably affected by APR use during this loaded sprint. The primary effect of APR on the hose drag was that subjects found the mask difficult to tolerate during recovery. Objective performance, cardiovascular, and ventilatory variables were not sensitive enough to detect the decrement.

DISCUSSION

Performance Limitation — Heavy Exercise

The incremental treadmill runs we conducted measured maximum short-term aerobic work capacity. For subjects without an APR, the maximum VO_2 that we measured, termed $VO_{2\ peak}$, estimated the maximum capacity of the subject, $VO_{2\ max}$. With an APR, however, $VO_{2\ peak}$ was reduced (Table 3a) with no change in subject fitness or disturbance to the usual rate-limiting steps in healthy people: oxygen transfer rate in muscle, distribution of blood flow to the muscle, or peak cardiac output. Rather, the APR introduced a ventilatory limitation to VO_2, a limitation reducing the average attainable $VO_{2\ peak}$ to between 82% and 85% of unencumbered $VO_{2\ max}$ (Fig. 7).

Endurance treadmill runs, set to approximate 85% $VO_{2\,max}$, required subjects with an APR to work near attainable $VO_{2\,peak}$. Ladder climbing, not individualized to a set fraction of $VO_{2\,max}$, also required some, but not all, subjects to work near their attainable $VO_{2\,peak}$ when they wore an APR.

The workload corresponding to 85% $VO_{2\,max}$ was selected based on a three-minute exercise increment. During endurance exercise, VO_2 climbed slowly but steadily. For endurance runs with APR, the final VO_2 was no different from the maximum attainable level measured during incremental running with the same mask. Some subjects also stopped climbing with VO_2 elevated to their peak attainable level (Fig. 6). It appears that heavy endurance exercise with an APR ends when VO_2 climbs to attainable $VO_{2\,peak}$ with the APR. To predict APR-related exercise limitation during an endurance task at heavy exercise, we need to predict (1) the oxygen requirements of a task, (2) the decrement in peak attainable VO_2, and (3) the rate of upward drift of VO_2. Only the oxygen requirement of the task is independent of APR design.

Decrement in Peak Attainable VO_2

During maximal exercise, pulmonary blood flow is greatly increased over that at rest, and the contact time for the blood in the lungs is somewhat reduced. Generally, exercising subjects increase V_E enough to increase alveolar PO_2 and thus the driving force for oxygen transfer to the blood — and thereby to compensate for the reduced pulmonary contact time. Generally, arterial PO_2 remains at resting levels even during maximal exercise. The increased breathing is usually sufficient to reduce alveolar CO_2 partial pressure by 10 to 15 Torr (0.3 to 2%).[5]

The mechanical impediment caused by the APR decreased V_E (Fig. 8) and peak inspiratory flow (Fig. 14) for exercise more intense than running on the level for 3 minutes, and eliminated exercise hyperventilation (Table 3a). Alveolar CO_2, sampled as F_{ET} CO_2, either was unchanged or actually increased from light to heavy exercise, and the achievable VO_2 and thus of external work was compromised (Fig. 7; Tables 2 and 3a). Indeed, the change in achievable $VO_{2\,peak}$ was a linear function of the change in V_E, and the decrement can also be thought of as one in peak attainable V_E.

V_E, the product of V_T and f_R, is limited by respiratory mechanics. The upper bound for V_T is well below vital capacity; end inspiration cannot be extended to total lung capacity without excessive work at the highest lung volumes. Further, if expiration continues to very low lung volumes, dynamic airway closure restricts expiratory flow. Once V_T has reached its maximum value, further increases in V_E can come only from increased f_R — that is, from decreased inspiratory and expiratory durations.

The greatest V_T is obtained in the shortest time for a given peak flow if the average flow equals the peak flow — that is, if airflow during inspiration looks like a square wave. Any other flow profile will yield a larger ratio of peak flow to average inspiratory flow (flow profile index). Sinusoidal inspiratory flow yields a ratio of $\pi/2$, or about 1.6. All measurements for all mask conditions showed flow profile indices between 1.0 and 1.5

(Fig. 18), with most between 1.2 and 1.3 — possibly as close to a square wave as is achievable, and comparable to the flow profile index of Dr. Camperman's trapezium breathing.[1] Subjects appear to have optimized flow profiles to use the entire inspiratory period even at moderate exercise.

During the transition from rest to moderate exercise, T_I/T_{TOT} is known to increase with the elimination of any end-expiratory pause and initial shortening of expiratory time. We did not measure at rest, and our data clustered densely around a duty cycle of 0.45 (Fig. 13). As expiratory time is shortened and active expiration increases expiratory flow, the maximum possible expiratory flow will be reached because of dynamic collapse of airways at low lung volume.[6] This maximum possible flow sets the minimum expiratory time. During mid to late expiration, a higher expiratory pressure for the APR actually could help to keep airways open during forced expiration as pursed lip breathing does for patients with emphysema.

When the minimum expiratory time is reached, the only way to increase V_E is to increase the inhalation rate. The ultimate factor limiting V_E, and thus the maximum attainable V_{O_2} while an APR is being worn, is a person's ability to generate very high inspiratory pressure.[7] If the pressure-flow characteristics of the APR are turbulent (as was the case with the APR we used), the pressure necessary to increase the flow from "high" to "higher" increases in part with the difference of the square of the flows. For example, to go from the highest peak flow seen with an APR, 353 L/min, to the highest seen without an APR, 434 L/min, the turbulent component of the pressure increase would be proportional to $(434)^2 - (353)^2 = 6.8 \times 10^4\ L^2/min^2$. The laminar component of the pressure increase would be proportional to 434 – 353 = 81 L/min.

Intersubject variability in attainable $V_{O_2\,peak}$ with the APR was high. In addition to differences in other factors such as strength of respiratory muscles, tolerance to sensations of dyspnea or CO_2 accumulation, and tolerance to lactic acid accumulation in the legs, subjects had differing APR inspiratory resistance because of interactions between face and APR inlet pathways.[1] We do not have a measure of intrasubject variability, because each subject performed incremental exercise only once with each mask condition.

Rate of upward drift of V_E

For most individuals, the increase of V_E with time during endurance running at a heavy workload, $\Delta V_E/\Delta t$, was steeper with an APR than it was without one, possibly because of gradual acidosis. Even when V_{O_2} was not limited by V_E, V_{O_2} with an APR was lower than that without an APR at the same external workload (Tables 3a and 3b, and Fig. 7). If we assume that the mechanical efficiency of the exercise did not differ with mask condition, more energy must have been produced anaerobically during APR use than without it: anaerobic pathways increase hydrogen ion concentrations and thereby stimulate ventilation if the chemoreceptors are active. The relation between $\Delta V_E/\Delta t$ and endurance time shows that the steeper the increase in V_E with time, the shorter the endurance time. Although the confidence interval for the intercept spans zero, a nonzero intercept suggests that even if $\Delta V_E/\Delta t = 0$, $T_{endurance}$ is finite, and the parameter estimate found puts the limit at just greater than 46 minutes.

During endurance runs at nominally 85% $VO_{2\,max}$, HR at end exercise was lower with an APR than without one, probably because subjects could not run for as long with the APR as without it (Table 2). Thus, the upward drift in HR often seen during prolonged exercise did not progress as far with an APR as without one.

Performance Limitation — Moderate Exercise

For some subjects, the ladder climb represented heavy exercise: for the two subjects with large decrements in climbing time (Fig. 4), the ladder exercise without APR required 83% and 86% of $VO_{2\,max}$ measured during incremental treadmill running. However, for the other subjects, the ladder climb did not heavily tax the cardiovascular system, either because muscular endurance was too low for prolonged climbing (four subjects climbed for less than six minutes without APR [Fig. 4]) or because cardiovascular load was moderate for the individual — i.e., ≤80%$VO_{2\,max}$. For these subjects climbing and for all subjects during the load lift and transfer, the ventilatory limitation of the APR was manifest always as reduced V_E and VO_2 and sometimes in increased $F_{ET}CO_2$ (Table 3b).

Because the hose drag was a short-duration sprint, respiratory limitations of the APR were not perceptible until recovery. The average maximum V_E measured during the drag without APR fell between the average V_E for running on a 4% and a 6% incline, while that during recovery was similar to the average for running on a 2% grade (see "RESULTS, Ventilatory Variables, *Minute Ventilation (V_E)*").

Acceptable Mask Resistance — Heavy Work

APR standards should address acceptable pressure-flow characteristics — for example, nearly linear characteristics for high peak flows. Across subjects with no APR, we measured average sustained peak flows of about 80 L/min for subjects walking, 166 L/min for those running on the level, and 326 L/min for those running on an 8% grade. The highest sustained peak flow we saw without an APR was 434 L/min. Testing with a single steady flow is not an analog for regular breathing, but it does provide single point pressure-flow information. Most certainly, the constant-flow testing at 85 L/min mandated by current standards is inadequate for breathing gear that must support even moderate exercise.

Camperman has shown that the pressure required for inspiratory flow is a summation of laminar conditions in the filter, turbulent entrance effects for the filter, and turbulent flow in the mask itself.[1] Compared to the standard APR tested, a mask with a less tortuous flow path and with fewer constrictions and sudden expansions in the flow pathway could perform better during heavy work; at high flow, the nonlinear increase in pressure with increase in flow, the "upturn" from a straight line in Figure 15a, becomes important.

However, decreased filter resistance, the underlying linear increase in pressure with flow in Figure 15a, would be beneficial at any level of exercise.

The maximum pressure that can be generated repeatedly — that is, the peak P_i at end exercise — differs greatly among individuals (Fig. 15a). An indication of APR pressure-flow characteristics that would permit heavy exercise in many subjects can be gleaned from Figure 15b. That figure shows the highest inspiratory pressures and associated peak flows with which subjects could exercise with an APR. Superimposed on the figure are the peak flows generated by the same subjects during equivalent exercise without an APR (the blue Xs on the figure). A mask that could deliver about 250 L/min with a pressure drop of about 12 cm H_2O and about 450 L/min for a pressure drop of 28 cm H_2O would have allowed all our subjects to breathe as much as the work required, and one that could deliver 360 L/min for a pressure drop of 24 cm H_2O would have been adequate for 80% of our 30 measured cases.

<u>Acceptable Mask Resistance — Self-Paced or Moderate Work</u>

During even low-intensity exercise when subjects could have sustained an increased V_E flow (for example, at the beginning of an incremental treadmill test or throughout the load lift and transfer task at 50% to 60% $VO_{2\ max}$ [Fig. 7 and Table 3b]), APR use reduced V_E from that of the no-APR condition. Indeed, in a different study NEDU has recently seen that ventilatory resistance causes subjects to decrease V_E even if they also inhale CO_2.[8] Other investigators have suggested that respiratory drive is modulated partly by mechanoreceptors tuned to the usual mechanical properties of the respiratory system,[9] receptors that adjust neural output to respiratory muscles on the basis of pressure. A slightly different hypothesis suggests that ventilation is controlled to minimize a cost function that combines work of breathing and CO_2 buildup.[10] Whatever the exact mechanism may be, the result is that even when ventilation is not limited mechanically, pressure generated by an external resistance like an APR reduces ventilation relative to that which optimizes gas exchange.

For the self-paced load lift and transfer, average performance was not changed by the standard APR but was reduced by the APR with loaded filter. The small difference in P_{mask} simulating a dust load in the filter was apparently enough to cross the threshold from generating an unimportant to generating an important decrease in ventilation, unless subjects worked more slowly than they had been working. Unfortunately, we could not measure P_{mask} during that test, but for design and testing of an APR for mild or self-paced exercise, a dose response curve of reduced ventilation as a function of mouth pressure might be informative. D'Urzo et al[11] used an inspiratory resistive load somewhat less than that of the standard APR (Attainable $VO_{2\ peak}$ = 90% $VO_{2\ max}$ vs. 82% to 85% $VO_{2\ max}$ with the APR) and saw no reduction in V_E until mean unencumbered V_E was 75 L/min. We saw a reduction in V_E when the unencumbered V_E was 60 L/min. Preliminary information might be gleaned from Flook's 1973 study,[12] which used laminar resistances. At low flows, the laminar resistance of the filter dominates.

Both steady state (endurance) and incrementally increasing exercise should be considered, because other investigators have noted a difference between the two for a nonlaminar resistance element.[11] Although a difference could arise because of respiratory muscle fatigue, the difference they noted may have been caused by the increase in V_E during endurance exercise. The other investigators compared at matching $\%VO_{2\ max}$. When we compare unencumbered to encumbered V_E for matching exercise duration, we see no distinction between endurance and incremental exercise.

Inspiratory Work of Breathing

Subjects worked hard to generate airflow through the APR. Standards for diving apparatus state that WOB_i/V_T should not exceed 1.5 J/L at sea level,[13] yet subjects exceeded 2 J/L with this dry APR (Figs. 21 and 22). When they breathed with the standard APR, if most subjects were to have stayed within the currently recommended bounds for inspiratory respiratory effort, $V_{i\ peak}$ could not have exceeded about 130 L/min (Fig. 21), and V_E should not have exceeded 55 L/min (Fig. 22) — values that were exceeded with the standard APR by all subjects running on a 2% grade, by all but three subjects climbing, by four subjects during the load lift and transfer, and by all but one subject at some time during the hose drag. With the loaded filter (not shown on Figures 21 and 22), WOB_i/V_T reached 1.5 J/L for some subjects with $V_{i\ peak}$ of 130 L/min or V_E of 50 L/min. Comfort levels for WOB_i/V_T may have influenced pacing in the load lift and transfer test, where average V_E was 59 L/min with the standard APR and 55 L/min with the loaded filter (Table 3b). During the self-paced load lift with APR, V_E exceeded 47 L/min for 80% of the subjects, and 47 L/min corresponds to WOB_i/V_T of about 1 to 1.5 J/L (Fig. 22). Although some of our subjects tolerated 1.5 J/L without difficulty, the results suggest that 80% of the population can tolerate the lower end of that range, or $WOB_i/V_T \leq 1$ J/L.

Even when WOB_i/V_T appeared to be acceptably low (i.e., below 1.5 J/L), V_E achieved with an APR was substantially lower than that for the same exercise load and no APR (Fig. 22). Subjects who expended about 1.5 J/L achieved V_E of 45 to 75 L/min, but with no APR they had breathed 70 to 140 L/min for the same external work.

The current APR standards call for testing with a constant flow of 85 L/min. At that peak flow, WOB_i/V_T does not exceed 0.75 J/L (Fig. 21), and V_E with an APR is similar to that without one (Fig. 8).

Expiratory Pressures and Flows

Although expiratory work could not be calculated because expiratory pressure and flow were measured by nonsynchronized systems with different sample rates, expiratory pressures (Fig. 17) were always lower — by a factor of 3 to 5 — than inspiratory pressures (Fig. 15a). The expiratory flow pathway is much simpler than the inspiratory pathway. Resistance to flow is generated by the pressure to open the one-way valve and by gas passage through the outlet. The pressure increases linearly with flow probably because the valve opens in proportion to the pressure.

Effects of Dead Space

Dead space in a mask causes an increase in average inspired CO_2. The dead space of the oronasal cup is as small as is practicable. However, when the oronasal cup leaks into the face space of the mask, inspired CO_2 may be considerably and unpredictably elevated as leaks open and close. Increased inspired CO_2 necessitates increased V_E to prevent elevation of $F_{ET}CO_2$; V_E has been reported to increase by 58% per liter of external dead space,[14] but if subjects cannot increase V_E, $F_{ET}CO_2$ will increase until it limits performance.

CONCLUSIONS

Our stated goals were to (1) identify types of activity for which an approved APR limits performance, (2) determine the extent of the limitation, (3) identify the changes in breathing patterns imposed by the APR, and (4) suggest changes in standards and mask design to improve APR usability.

Exercise Limitation Caused by APR Use — Exercise Type and Extent of Limitation

The standard APR used in these tests significantly limited heavy endurance exercise — specifically, exercise of intended duration longer than three minutes and at an intensity greater than 80% $VO_{2\ peak}$. For subjects running at 85% $VO_{2\ peak}$, endurance time with the APR was less than half of that without APR. The APR also decreased maximum physical work output. We saw an average 15% reduction in attainable peak VO_2. However, neither self-paced work (for our subjects, about 60% $VO_{2\ peak}$ when unencumbered) of 24-minute durations nor the approximately 30-second sprint of hose dragging was severely affected by flow limitation.

The exercise limitation resulted from the ventilatory reduction imposed by the APR. Depending on the exercise, the APR reduced V_E by 16% to 30%. When exercise conditions pushed VO_2 past the rate that the subject's V_E could support, the subject could not continue and sometimes remained severely distressed for five or ten breaths. Even at moderate exercise, the external restriction to flow reduced V_E and VO_2 and by inference increased anaerobic production of energy.

In a few cases, a leaking oronasal mask and the resultant large mask dead space and elevated F_ICO_2 made continued APR wear untenable.

Changes in Breathing Imposed by the APR

The reduced V_E at moderate to heavy exercise resulted primarily from a reduced f_R necessitated by the reduction in $V_{i\ peak}$ despite high $P_{i\ peak}$. Individual variability, presumably in respiratory muscle strength and endurance, allowed a range of $P_{i\ peak}$. The range of $P_{i\ peak}$ and the different fits of the masks to different subjects caused a range of $V_{i\ peak}$. However, none of the subjects was able to generate the same $V_{i\ peak}$ with and without an APR. Particularly because of turbulence in the mask, high inspiratory flows require very high inspiratory pressures and therefore involve extremely high WOB_i/V_T. APR pressure-flow characteristics, and particularly the turbulence that becomes important at high flows, blunted peak flows.

Recommended Changes in Standards and Mask Design

The sprint was unaffected only because the work was finished before effects of hypoventilation could develop. The load lift and transfer, however, was conducted at a WOB_i/V_T that was tolerated by the subjects wearing the APR. We conclude that at least 80% of subjects find inspired WOB/V_T of 1 J/L to be acceptable, and we recommend this as a high-flow target for APR design.

The high flows that need to be addressed in APR standards should be driven by measured values. For the exercise imposed on our subjects, the maximum one-minute average peak inspiratory flow we recorded was 434 L/min without an APR, and a target pressure-flow relation to allow V_i = 360 L/min with P_i = 24 cm H_2O would have satisfied the requirements of 80% of our subjects at heavy exercise. The turbulence implicates the mask's inlet pathway in generating the limiting pressure decreases. As can be seen in the difference between loaded filter and standard APR, filter resistance is important at all flows,[1] but low inlet, pathway turbulent resistance is critical for high peak flows, and designers should not neglect that component. Inlet valves and flow pathways should be protected against obstruction when high inspiratory pressures squeeze the external mask against the oronasal cup and facial structures.[1] Also, the oronasal cup must fit well to maintain low F_ICO_2.

The APR we tested had passed breathing resistance standards for a constant flow of 85 L/min. APRs designed for a flow of 85 L/min will protect a person who is at rest or walking slowly (without a pack). However, those are not the needs of war fighters or first responders. Standards and testing methods must be changed if their needs are to be met.

REFERENCES

1. J. Camperman, "Implications of Human and Simulator High Ventilation Testing to Air Purifying Respirator Standards," DTRA JSTO-CBD BA07PRO0006 (under review), Diving and Life Support Division, Naval Surface Warfare Center, Panama City, FL, Apr 2010.
2. P. W. F. Wilson, R. B. D'Agostino, D. Levy, A. M. Belanger, H. Silbershatz, and W. B. Kannel, "Prediction of Coronary Heart Disease Using Risk Factor Categories," *Circulation*, Vol. 97, No. 18 (May 1988), pp. 1837–1847.
3. American College of Sports Medicine, *ASCM's Guidelines for Exercise Testing and Prescription*, 6th ed. (Baltimore, MD: Lippincott Williams and Wilkins, 2000), p. 101.
4. PublicSafetyTesting.com, *Public Safety Testing — Apply with Public Safety Agencies Online*, <http://www.publicsafetytesting.com/infodoc.cfm?id=10>, 22 April 2005, reviewed 11January 2007.
5. L. B. Rowell, *Human Cardiovascular Control* (New York, NY: Oxford University Press, 1993), Chapter 9, pp. 326–366.
6. B. D. Johnson, K. W. Saupe, and J. A. Dempsey, "Mechanical Constraints on Exercise Hyperpnea in Endurance Athletes," *J. Appl. Physiol.*, Vol. 73, No. 3 (1992), pp. 874–886.
7. F. N. Craig, W. V. Blevins, and E. G. Cummings, "Exhausting Work Limited by External Resistance and Inhalation of Carbon Dioxide," *J. Appl. Physiol*., Vol. 29, No. 6 (1970), pp. 847–851.
8. B. Shykoff, D. Warkander, and D. Winters, "Effects of Carbon Dioxide and UBA-like Breathing Resistance on Exercise Endurance," NEDU TR 10-03 (under review) Navy Experimental Diving Unit, Panama City, FL, Apr 2010.
9. S. N. A. Hussain, R. L. Pardy, and J. Dempsey, "Mechanical Impedance as Determinant of Inspiratory Neural Drive during Exercise in Humans, "*J. Appl. Physiol.*, Vol. 59, No. 2 (1985), pp. 365–375.
10. C-S. Poon, "Effects of Inspiratory Resistance Load on Respiratory Control in Hypercapnia and Exercise," *J. Appl. Physiol*., Vol. 66, No. 5 (1989), pp. 2391–2399.
11. A.D. D'Urzo, K.R. Chapman, and A.S. Rebuck, "Effect of Inspiratory Resistive Loading on Control of Ventilation during Progressive Exercise," *J. Appl. Physiol.*, Vol. 62, No. 1 (1987), pp. 134–140.
12. V. Flook and G.R. Kelman, "Submaximal Exercise with Increased Inspiratory Resistance to Breathing," *J. Appl. Physiol.,* Vol. 35, No. 3 (1973), pp. 379–384.
13. D. E. Warkander, G.K. Nagasawa, and C.E.G. Lundgren. "Effects of Inspiratory and Expiratory Resistance in Divers' Breathing Gear," *Undersea. Hyper. Med.* Vol. 28, No. 2 (2001), pp. 63–73.
14. D. E. Warkander and C.E.G. Lundgren, "Dead Space in the Breathing Apparatus: Interaction with Ventilation," *Ergonomics*, Vol. 38, No. 9 (1995), pp. 1745–1758.