AL-TP-1992-0061

AD-A265 221

ARMSTRONG LABORATORY

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CHARACTERIZATION OF CHEMICAL DEFENSE MASK BREATHING RESISTANCE TOLERANCES

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March 1993

Final Technical Paper for Period May 1991 to January 1992

93-11581

93 5 25 025

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The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-3.

The Office of Public Affairs has reviewed this paper, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This paper has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1993

3. REPORT TYPE AND DATES COVERED
Final May 1991 to January 1992

4. TITLE AND SUBTITLE
Characterization of Chemical Defense Mask Breathing Resistance Tolerances

5. FUNDING NUMBERS
C-F33615-89-C-0603
PE-62202F
PR-2729
TA-03
WU-33

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
KRUG Life Sciences, Incorporated
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Armstrong Laboratory
Crew Systems Directorate
2504 D Drive, Suite 1
Brooks Air Force Base, TX 78235-5104

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AL-TP-1992-0061

11. SUPPLEMENTARY NOTES
Armstrong Laboratory Technical Monitor: Dr. Stefan H. Constable, (210) 536-3771

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The purpose of this study was to evaluate the effects of wearing MCU-2/P and M-17 groundcrew chemical defense masks during steady-state work. Five MCU-2/P mask configurations (MC) were tested: mask without filter (MCU-OF), mask + 1 filter (MCU-1F), mask + 2 filters (MCU-2F), mask + 1 filter + air blower A (MCU-ABA), and mask + 1 filter + air blower B (MCU-ABB). Ten subjects walked on a treadmill (3 mph - 5.0% grade) for 1 hr wearing each MC. Variables measured included inspiratory and expiratory mask cavity pressures (IMCP & EMCP), mask cavity pressure-swing (MCPS), peak inspiratory airflow rate (PIAFR), respiratory rate (RR), peak tidal volume (PTV), minute volume (MV), heart rate (HR), rating of perceived exertion (RPE), perceived inspiratory and expiratory effort (PIE & PEE), and overall breathing discomfort (OBD). Each MC was characterized by a significantly different IMCP. The MCU-ABA produced the lowest IMCP, while MCU-1F produced the highest. MCU-2F reduced inspiratory resistance by about 47%. There were no significant differences in PIAFR, RR, PTV, MV, RPE, PIE, PEE, and OBD among the various MC. The new MCU-2/P mask does not improve total breathing resistance over the standard M-17 mask. Neither mask should induce significant cardiorespiratory strain providing the physical work is of low intensity. A very effective (but logistically difficult) approach to reduce the level of inspiratory resistance imposed by the MCU-2/P mask is to provide powered ventilation as compared to the relatively simple installation of a second filter.

14. SUBJECT TERMS
Breathing resistance
Exercise
Perceived effort
Protective mask
Ventilation

15. NUMBER OF PAGES
44

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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CHARACTERIZATION OF CHEMICAL DEFENSE MASK BREATHING RESISTANCE TOLERANCES

INTRODUCTION

The new MCU-2/P Groundcrew Chemical Defense (CD) Mask is a full-face combat mask that protects the face, eyes, and respiratory tract of the wearer from field concentrations of chemical and biological agents, riot control agents, and alpha contamination. The major components of the mask assembly include: 1) a facepiece made of silicone rubber which forms an effective seal on the user's face; 2) a flexible single lens made of optically clear urethane material, bonded onto the facepiece, that provides distortion-free all-around view; 3) a soft rubber nosecup which fits over the nose and mouth of the wearer and prevents lens fogging by directing expired air through the outlet valve; 4) two voicemitters, one located in the center of the facepiece above the outlet valve assembly and the other located on the right side of the facepiece; 5) one inlet valve assembly located at the left side of the facepiece, which consists of a plastic air deflector with post mounted rubber valve disc, and a rubber valve body; 6) one outlet valve assembly located underneath the center voicemitter which consists of a metal tube and valve body, and a rubber valve disc; 7) one outlet valve cover made of rubber which fits over the end of the outlet valve body. (The cover has a pocket which holds the drinking tube coupling); 8) a drinking tube made of rubber onto a metal feed-thru pipe on the outside of the outlet valve body, and a quick disconnect coupling bonded to the other end of the tube; 9) a head harness that holds the facepiece to the wearer to provide an airtight seal; and 10) six clip-and-buckle assemblies for adjusting the head harness. This mask utilizes a C2 filter canister, a metal can that contains a filter for removing biological agents, riot-control agents, and alpha contamination from inhaled ambient air. The C2 canister has a NATO standard thread that easily screws into the inlet valve assembly.

The new MCU-2/P CD-mask provides effective individual protection against airborne chemical, biological, and nuclear contaminants. Unfortunately, its design did not solve problems common to almost every CD-mask currently available; these problems include external resistance to airflow during breathing, existence of a dead space between the mask and the face, and impairment of evaporative cooling from the face. The filters and valve assemblies of a CD-mask interfere with the free flow of air during normal breathing increasing the mask cavity pressure required to maintain a given ventilatory airflow across the mask. It is well known that external resistance to breathing (inspiratory & expiratory) is an important factor that determines an individual's physiological and psychological tolerance to wearing respiratory protective equipment. It is also recognized that this problem becomes critical when an individual, who is wearing respiratory protective equipment, is required to perform physical work. However, there is limited experimental data on the breathing resistance characteristics of the new MCU-2/P mask and its physiological impact on individuals during physical work. Therefore, human research is necessary in order to evaluate the overall stress imposed by this mask, especially during sustained exercise of moderate-to-high intensity.

In a previous study, we investigated the acute physiological responses of individuals wearing three configurations of the MCU-2/P CD-mask (1 filter, 2 filters, and 1 filter + air blower) during short-duration physical exercise (5 min) of low and moderate intensity (1). Results indicated that the best approach to decrease inspiratory resistance associated with the use of the MCU-2/P mask was to provide assisted ventilation through the C2 filter canister. Results from additional manikin testing suggested that the MCU-2/P mask in its current operational configuration (1 filter) did not show an improvement in reducing breathing resistance compared to the old M-17 mask. However, it was suggested to conduct additional research using human subjects in order to corroborate this finding.

The main objectives of this study were: 1) compare the breathing resistance characteristics of the new MCU-2/P CD-mask versus the M-17 mask, 2) investigate cardiorespiratory and psychological effects of wearing MCU-2/P (5 configurations) and M-17 CD-masks during steady-state physical exercise, and 3) evaluate the effectiveness of two commercially available portable air blowers to reduce the level of inspiratory resistance through the C2 filter canister and the inhalation valve assembly of the MCU-2/P mask.

METHODS AND MATERIALS

Five MCU-2/P mask configurations were tested (Figs. 1a-1e): 1) mask without a filter (MCU-0F), 2) mask + 1 filter (MCU-1F), 3) mask + 2 filters (MCU-2F), 4) mask + 1 filter + air blower "A" (MCU-ABA), and 5) mask + 1 filter + air blower "B" (MCU-ABB). To accommodate a second filter canister on the MCU-2/P mask (MCU-2F), the voicemitter on the right side of the facepiece was replaced with an inlet valve assembly. Two different types of air blowers ("Pusher Blower" (ABA) and "Power Plus Blower" (ABB) manufactured by Racal Health & Safety, Inc.) were used to provide assisted ventilation to the subjects. The ABA was attached to the inlet side of the C2 filter canister, while the ABB was installed between the inlet valve assembly of the faceplece and the C2 filter canister. The ABA was a continuous-flow unit that supplied an average airflow rate (during inspiration) of 2.3 cfm (65 l/min) of ambient air through the filter. The ABB was a pressure-demand unit which produced a variable airflow rate. At idle speed, this air blower supplied an average airflow rate of 1.1 cfm (31 l/min) through the filter. However, it was impossible to quantify its airflow rate during inspiration. Rechargeable Nickel-Cadmium battery packs were used to operate both air blowers. A standard M-17 CD-mask (Fig. 1f) was also included in this study in order to assess any improvements in the breathing resistance characteristics of the new MCU-2/P mask in its current operational configuration (with a single C2 filter canister).

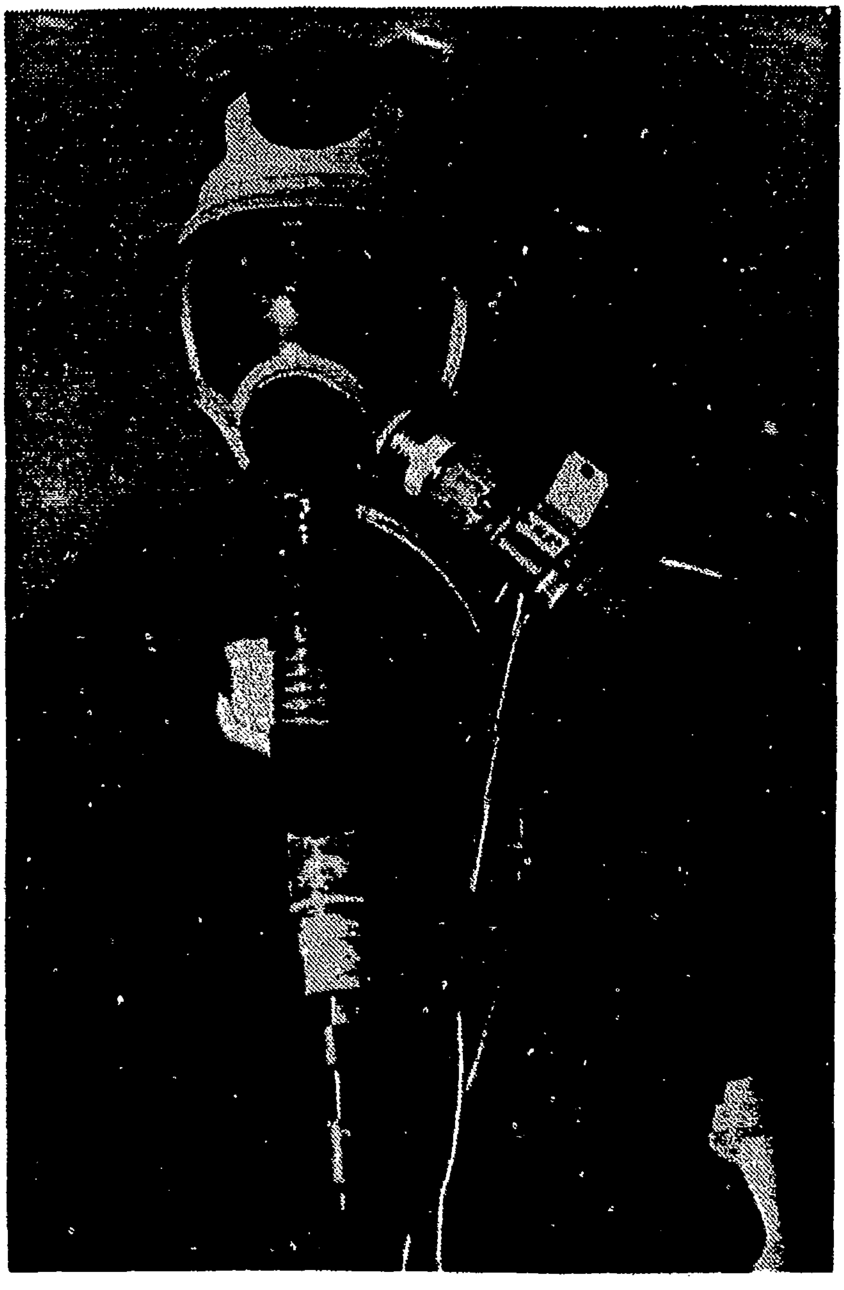

Figure 1a. MCU-2/P without filter (MCU-0F).

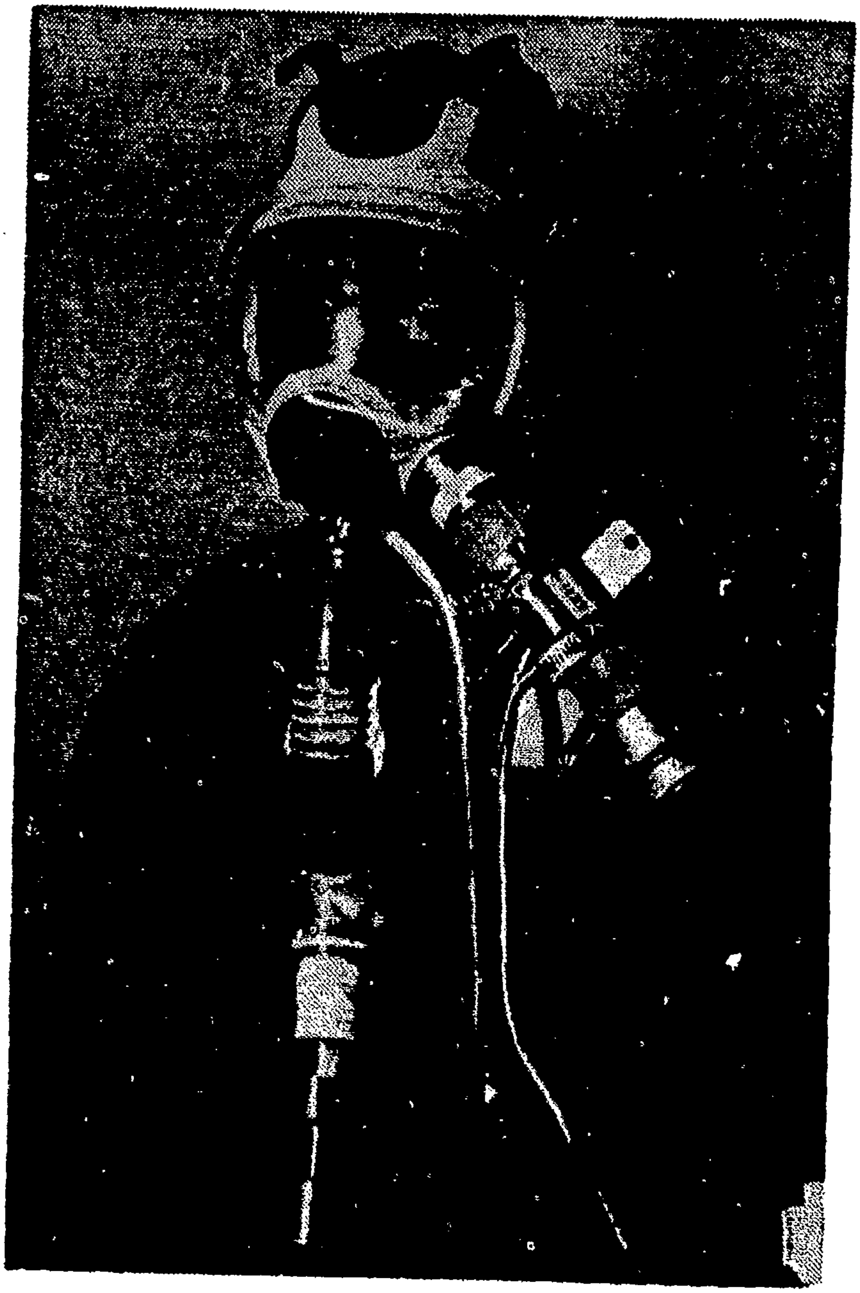

Figure 1b. MCU-2/P with 1 filter (MCU-1F).

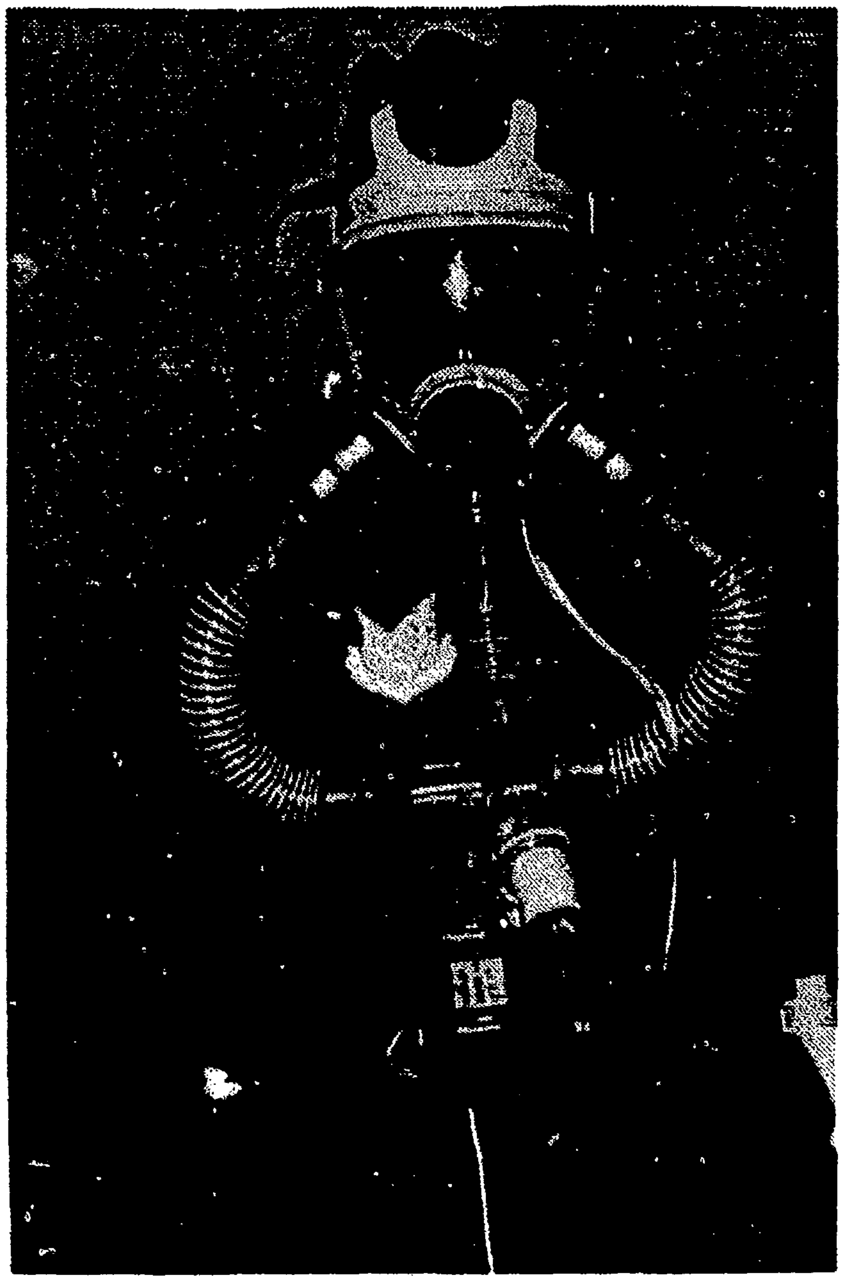

Figure 1c. MCU-2/P with 2 filters (MCU-2F).

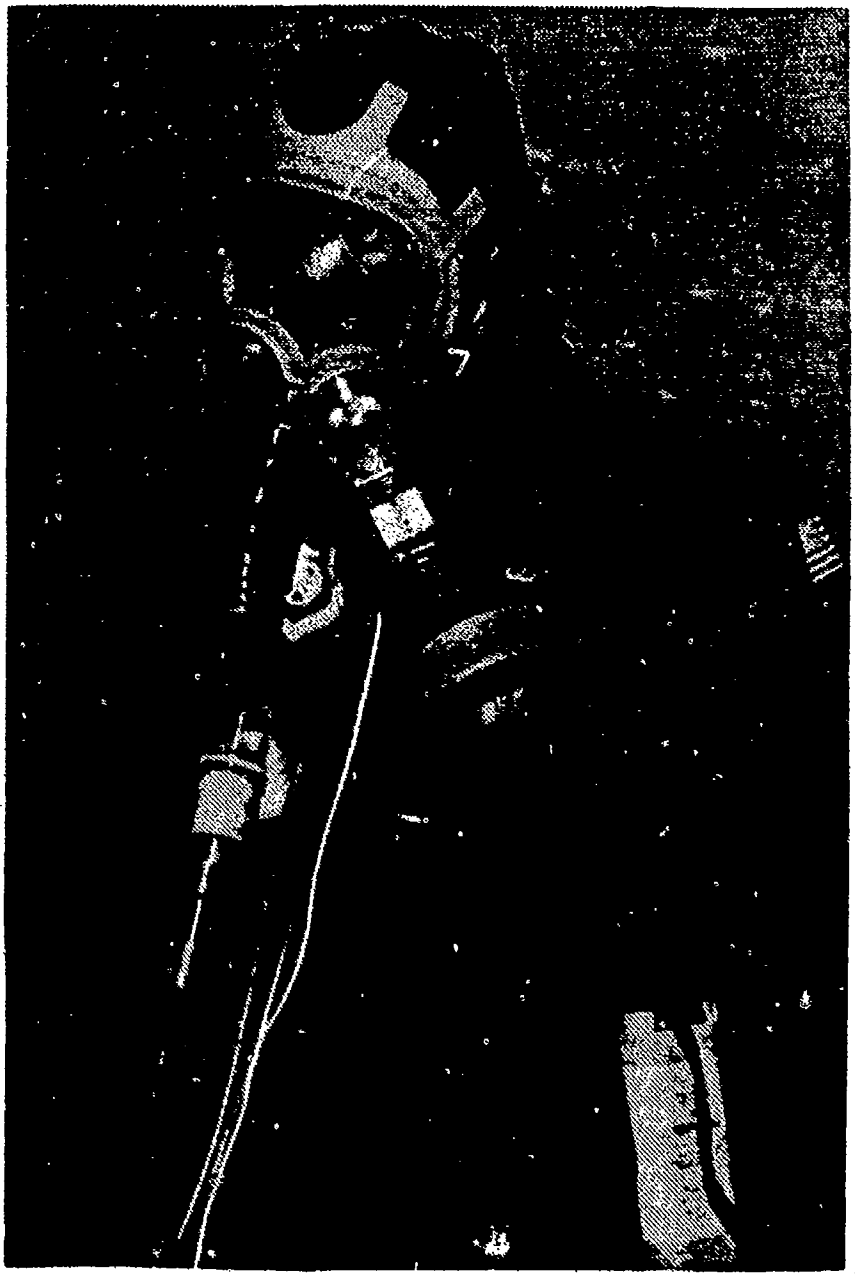

Figure 1d. MCU-2/P with 1 filter and Air Blower A (MCU-ABA).

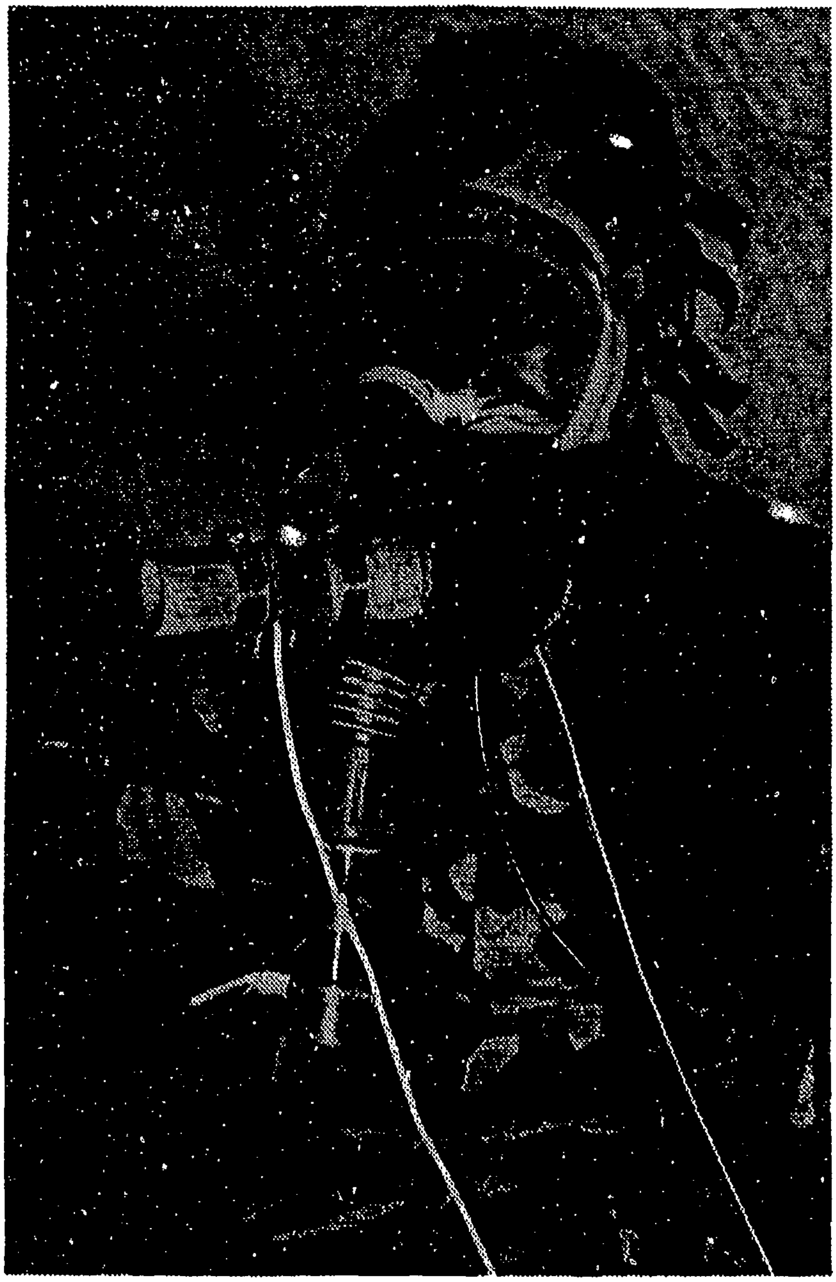

Figure 1e. MCU-2/P with 1 filter and Air Blower B (MCU-ABB).

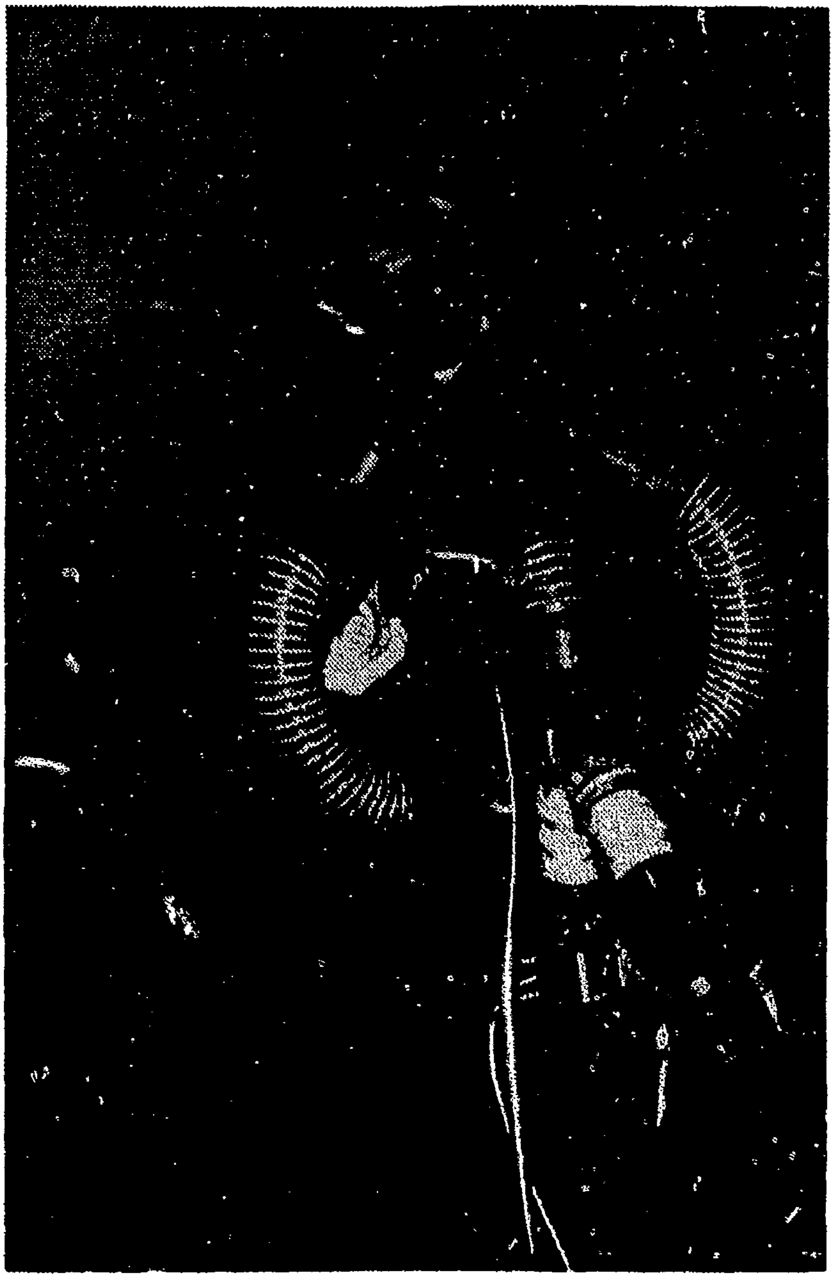

Figure 1f. M-17 mask.

Ten healthy male subjects were informed of the purposes and possible risks of this study, and signed informed consent statements in accordance with AFR 169-3. Each subject underwent a complete medical examination, pulmonary function testing, echocardiographic evaluation, and peak aerobic capacity testing (Vo_{2max}). The physical characteristics of the subjects were (mean ± SD): age 28.5 ± 5.8 years; weight 83.8 ± 9.6 kg; height 178 ± 6 cm; Vo_{2max} 48.1 ± 5.6 ml/kg^{-1}; $Vo_{2submax}$ 17.5 ± 1.8 ml/kg^{-1}; V_{Emax} 136 ± 16.4 l/min^{-1} STPD; and $V_{Esubmax}$ 37 ± 7.6 l/min^{-1} STPD. $Vo_{2submax}$ and $V_{Esubmax}$ were determined with the subjects walking on a treadmill at the same workload intensity selected for the experiments (Table 1). Subjects wore shorts, tee-shirt, socks, and tennis shoes. The experiments were carried out in a comfortable environment (26°C dry bulb temperature (Tdb), 15°C wet bulb temperature (T_{wb}), and 26°C black globe temperature (T_{bg})) inside a thermal chamber.

Table 1 shows the treadmill settings used in the experiments and the corresponding workload intensity (total metabolic cost) measured among the subjects. Table 1 also shows the mean relative workload calculated from metabolic rate as a percentage of measured Vo_{2max}. The physical task consisted of walking on a treadmill at the predetermined settings for 1 hour. Each of the 6 mask configurations was evaluated among each of the 10 subjects in a semirandomized (counterbalanced) order. Subjects were tested once every other week in order to avoid carryover (training) effects.

Table 1. Treadmill Settings and the Corresponding Workload Intensity (Total Metabolic Cost) Among the Subjects.

TREADMILL speed/grade (mph / %)	EXTERNAL WORKLOAD (Watts)	RELATIVE LOAD (% of Vo_2)
3.0 / 5.0	511 ± 83	37 ± 4

The variables measured during each experiment included: Inspiratory Mask Cavity Pressure (IMCP), Expiratory Mask Cavity Pressure (EMCP), Mask Cavity Pressure-Swing (MCPS), Peak Inspiratory Airflow Rate (PIAFR), Peak Tidal Volume (PTV), Minute Volume (MV), Respiratory Rate (RR), Heart Rate (HR), Rating of Perceived Exertion (RPE), Perceived Inspiratory Effort (PIE), Perceived Expiratory Effort (PEE), and Overall Breathing Discomfort (OBD). Mask cavity pressures (IMCP & EMCP) were used as indicators of breathing resistance (inspiratory and expiratory).

Group means were calculated for each variable and then analyzed among the different mask configurations and across time using a three-way analysis of variance. When significant F values were found, a Duncan's Multiple Range Test was used to test for significant differences at the p <0.05 level. Results of the statistical analysis are presented on Tables 2-9 as group means ± standard deviation (SD).

IMCP and EMCP were measured using a Validyne Pressure Transducer (Model DP15-50) and a Validyne Sine Wave Carrier Demodulator (Model CD15). PIAFR was measured using a Fleisch Pneumotachograph connected to a Validyne Pressure Transducer (Model MP45-1) and a Validyne Sine Wave Carrier Demodulator (Model CD12). PTV and MV were measured using a SensorMedics Ventilation Measurement Module (Model VMM-1). RR was obtained indirectly from the processing of the VMM-1 signal. A telemetry system (Transkinetics) was used to monitor HR and rhythm. All of these variables were continuously monitored and automatically recorded using a Lab View Data Acquisition System and a Macintosh FX Computer. RPE levels were compared using Borg's standard scale (3). Numerical scales were used to determine the level of both PIE and PEE. These scales ranged from 1 to 7, which represented a spectrum of breathing sensations ranging from "Not Noticeable Effort" to "Intolerable Effort" (Appendix). Another numerical scale was used to evaluate OBD. This scale ranged from 1 to 7, to indicate sensations ranging from "No Discomfort" to "Intolerable Discomfort" (Appendix). RPE, PIE, PEE and OBD were manually recorded at 5-min intervals during each test.

Table 2. Statistical Analysis of Mask Main Effect on Inspiratory Mask Cavity Pressure (Inspiratory Resistance) Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Means ± SD. (++ Significantly Different at P<.05), (NS Not Significant).

	MCU-1F - 3.23 ± .43	MCU-2F - 1.73 ± .32	MCU-ABA + .31 ± .30	MCU-ABB - 2.28 ± .31	M-17 - 2.80 ± .36
MCU-0F - 1.45 ± .37	++	++	++	++	++
MCU-1F - 3.23 ± .43	----	++	++	++	++
MCU-2F - 1.73 ± .32	----	----	++	++	++
MCU-ABA + .31 ± .30	----	----	----	++	++
MCU-ABB - 2.28 ± .31	----	----	----	----	++

Table 3. Statistical Analysis of Mask Main Effect on Expiratory Mask Cavity Pressure (Expiratory Resistance) Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Means ± SD. (++ Significantly Different at P<.05), (NS Not Significant).

	MCU-1F .85 ± .19	MCU-2F .94 ± .13	MCU-ABA 1.15 ± .16	MCU-ABB .87 ± .31	M-17 1.05 ± .16
MCU-0F .85 ± .19	NS	NS	++	NS	++
MCU-1F .74 ± .28	—	++	++	NS	++
MCU-2F .94 ± .13	—	—	++	NS	NS
MCU-ABA 1.15 ± .16	—	—	—	++	NS
MCU-ABB .87 ± .31	—	—	—	—	++

Table 4. Statistical Analysis of Mask Main Effect on Mask Cavity Pressure-Swing Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Group Means ± SD (++ Significantly Different at P<.05), (NS Not Significant).

	MCU-1F 3.97 ± .55	MCU-2F 2.66 ± .37	MCU-ABA 1.47 ± .34	MCU-ABB 3.15 ± .41	M-17 3.86 ± .41
MCU-0F 2.30 ± .40	++	++	++	++	++
MCU-1F 3.97 ± .55	—	++	++	++	NS
MCU-2F 2.66 ± .37	—	—	++	++	++
MCU-ABA 1.47 ± .34	—	—	—	++	++
MCU-ABB 3.15 ± .41	—	—	—	—	++

Table 5. Statistical Analysis of Mask Main Effect on Peak Inspiratory Airflow Rate Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Group Means ± SD (++ Significantly Different at P<.05), (NS Not Significant).

	MCU-1F 92.03 ± 10.79	MCU-2F 96.85 ± 21.10	MCU-ABA 86.25 ± 11.45	MCU-ABB 91.83 ± 13.42	M-17 88.72 ± 14.34
MCU-0F 96.93 ± 14.96	NS	NS	NS	NS	NS
MCU-1F 92.03 ± 10.79	—	NS	NS	NS	NS
MCU-2F 96.85 ± 21.10	—	—	NS	NS	NS
MCU-ABA 86.25 ± 11.45	—	—	—	NS	NS
MCU-ABB 91.83 ± 13.42	—	—	—	—	NS

Table 6. Statistical Analysis of Mask Main Effect on Respiratory Rates Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Group Means ± SD (++ Significantly Different at P<.05), (NS Not Significant).

	MCU-1F 25.67 ± 6.22	MCU-2F 24.32 ± 4.98	MCU-ABA 23.64 ± 6.23	MCU-ABB 24.14 ± 4.92	M-17 25.53 ± 4.47
MCU-0F 25.85 ± 5.34	NS	NS	NS	NS	NS
MCU-1F 25.67 ± 6.22	—	NS	NS	NS	NS
MCU-2F 24.32 ± 4.98	—	—	NS	NS	NS
MCU-ABA 23.64 ± 6.23	—	—	—	NS	NS
MCU-ABB 24.14 ± 4.92	—	—	—	—	NS

Table 7. Statistical Analysis of Mask Main Effect on Peak Tidal Volume Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Group Means ± SD. (++ Significantly Different at P<.05), (NS Not Significant).

	MCU-1F 1.53 ± .25	MCU-2F 1.54 ± .32	MCU-ABB 1.60 ± .26	M-17 1.54 ± .28
MCU-0F 1.58 ± .25	NS	NS	NS	NS
MCU-1F 1.53 ± .27	—	NS	NS	NS
MCU-2F 1.54 ± .32	—	—	NS	NS
MCU-ABB 1.60 ± .26	—	—	—	NS

Table 8. Statistical Analysis of Mask Main Effect on Minute Volume Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Means ± SD. (++ Significantly Different at P<.05), (NS Not Significant)

	MCU-1F 36.46 ± 6.96	MCU-2F 36.42 ± 5.91	MCU-ABB 36.56 ± 4.78	M-17 38.50 ± 5.65
MCU-0F 39.33 ± 5.25	NS	NS	NS	NS
MCU-1F 36.46 ± 6.96	—	NS	NS	NS
MCU-2F 36.42 ± 5.91	—	—	NS	NS
MCU-ABB 36.56 ± 4.78	—	—	—	NS

Table 9. Statistical Analysis of Mask Main Effect on Heart Rates Among Human Subjects Wearing MCU-2/P and M-17 Chemical Defense Masks. Results are Presented as Means ± SD. (++ Significantly Different at P<.05), (NS Not Significant).

	MCU-1F 119.4 ± 13.0	MCU-2F 114.2 ± 13.4	MCU-ABA 113.5 ± 13.8	MCU-ABB 114.6 ± 15.7	M-17 118.1 ± 13.4
MCU-0F 116.3 ± 14.5	NS	NS	NS	NS	NS
MCU-1F 119.4 ± 13.0	—	NS	++	NS	NS
MCU-2F 114.2 ± 13.4	—	—	NS	NS	NS
MCU-ABA 113.5 ± 13.8	—	—	—	NS	NS
MCU-ABB 114.6 ± 15.7	—	—	—	—	NS

RESULTS

Figure 2 shows the IMCPs recorded during steady-state physical exercise by subjects wearing the MCU-2/P (5 different configurations) and M-17 masks. With the exception of the MCU-ABA and the MCU-2F, all of the other mask configurations showed a time-effect (response over time) characterized by a progressive increase in IMCP. However, this time-effect was minimal and did not have any physiological significance. On the other hand, each mask configuration was characterized by a significantly different IMCP (Table 2). With the exception of the MCU-ABA, all of the other mask configurations showed negative IMCPs (pressure-drop) during inhalation. The highest level of inspiratory resistance recorded in these experiments corresponded to the MCU-1F mask (-3.22 inH_2O). The old M-17 mask produced a lower inspiratory resistance (-2.80 inH_2O) than the MCU-1F. The MCU-2F showed an overall decrease in inspiratory resistance of about 47% (-1.72 inH_2O) compared to the MCU-1F. As expected, the MCU-ABA mask produced the lowest level of inspiratory resistance. During inspiration the ABA supplied an airflow rate of about 65 l/min, which exceeded the subjects' average ventilatory requirements of 37 ± 7.6 l/min. Under these conditions, the ABA maintained a positive-pressure (+.31 inH_2O) airflow during inhalation. The MCU-ABB, on the other hand, was comparatively less efficient than either the MCU-ABA or the MCU-2F in reducing the level of inspiratory resistance (-2.28 inH_2O).

Figure 3 shows the EMCPs recorded in subjects during steady-state physical exercise wearing the MCU-2/P (5 configurations) and M-17 masks. Overall, the levels of expiratory resistance produced by all of these masks were low (ranged from 0.7 to 1.2 inH_2O). There were no significant changes in expiratory resistance over time (time effect). We observed several significant differences on expiratory resistance between mask configurations (Table 3). However, the physiological significance of any of these statistical differences is negligible and does not justify a detailed description. The MCU-ABA mask produced the highest level of expiratory resistance suggesting that the ABA was able to maintain some airflow through the mask inhalation-valve during the exhalation phase. Under usual conditions, this valve remains closed during the expiratory phase of the breathing cycle.

Figure 4 shows the Mask Cavity Pressure-Swing (MCPS) data calculated by adding the IMCP and the EMCP that corresponded to each mask configuration (MCU-2/P & M-17). The MCPS represents a single value of total breathing resistance (inspiratory + expiratory) that characterized each mask. All of the mask configurations showed a progressive increase in MCPS over time (time effect). MCPSs showed a response-pattern similar to that previously described for IMCPs, with the one exception that the MCPSs for the MCU-1F and M-17 masks were statistically the same (Table 4).

Figure 5 shows the PIAFRs recorded during steady-state physical exercise wearing the MCU-2/P (5 configurations) and M-17 masks. With the exception of the MCU-ABA, all of the other mask configurations showed a significant progressive increase in PIAFR over time (time effect). Table 5 shows that there were no significant differences in PIAFR between mask configurations (mask effect).

Figure 6 shows the RRs recorded during steady-state physical exercise wearing the MCU-2/P (5 configurations) and M-17 masks. With the exception of MCU-ABA, all of the other mask configurations showed a significant progressive increase in RR over time. However, this time effect was minimal and had no physiological significance. Table 6 shows that there were no significant differences in RR between mask configurations (mask effect).

Figure 7 shows the PTVs recorded during steady-state physical exercise wearing the MCU-2/P (4 configurations) and M-17 masks. MCU-ABA was not included in this analysis because the PTV measurements did not represent the individuals' ventilatory volumes, but rather the total volume of air supplied by ABA during the inspiratory phase of the breathing cycle. With the exception of the MCU-ABA, all of the mask configurations showed a significant decrease in PTV over time (time effect). There were no significant differences in the PTVs between mask configurations (Table 7).

Figure 8 shows the MVs recorded during steady-state physical exercise wearing the MCU-2/P (4 configurations) and M-17 masks. There were no significant differences on MVs over time (time effect) or between mask configurations (Table 8).

Figure 9 shows the HRs recorded during steady-state physical exercise wearing the MCU-2/P (5 configurations) and M-17 masks. Each of the mask configurations produced a similar progressive increase in HR over time (time effect). With respect to mask effect, the only significant difference in HR was observed in comparing the MCU-1F with the MCU-ABA (Table 9). This comparison shows that the highest and the lowest heart rates corresponded to those mask configurations that caused the highest and the lowest levels of inspiratory resistance respectively.

Figure 10 shows the RPE scores recorded during steady-state physical exercise of subjects wearing 5 configurations of the MCU-2/P mask. Individual perceptions of physical effort were all the same regardless of the mask configuration utilized. The overall perception of physical effort among the subjects corresponded to a very light workload.

Figure 11 shows the relationship between IMCPs and PIE ratings during physical exercise in subjects wearing 5 configurations of the MCU-2/P mask. We expected to observe a response pattern in which PIE ratings closely followed the different levels on inspiratory resistance (IMCP). However, this figure shows that there was no relationship between these two variables. Overall, the PIE ratings indicated that the subjects were aware of the additional ventilation effort required during inspiration. However, the low magnitude of this inspiratory effort did not cause breathing difficulties.

Figure 12 shows the relationship between EMCPs and PEE ratings during physical exercise in subjects wearing 5 configurations of the MCU-2/P mask. There were no significant differences in PEE scores among the various mask configurations. Overall, the PEE ratings indicated that the subjects were aware of the additional ventilation effort required during expiration, but such an effort was easily tolerable.

Figure 13 shows the relationship between MCPS and OBD ratings during physical exercise in subjects wearing 5 configurations of the MCU-2/P mask. OBD ratings represent individual perceptions of total breathing effort (inspiratory + expiratory) resulting from the use of the various mask configurations. We expected to observe a response pattern in which OBD ratings closely followed the response trends on MCPS. However, there were no significant differences in OBD scores corresponding to the various mask configurations. The OBD ratings indicated that the subjects wearing the various mask configurations experienced slight breathing discomfort.

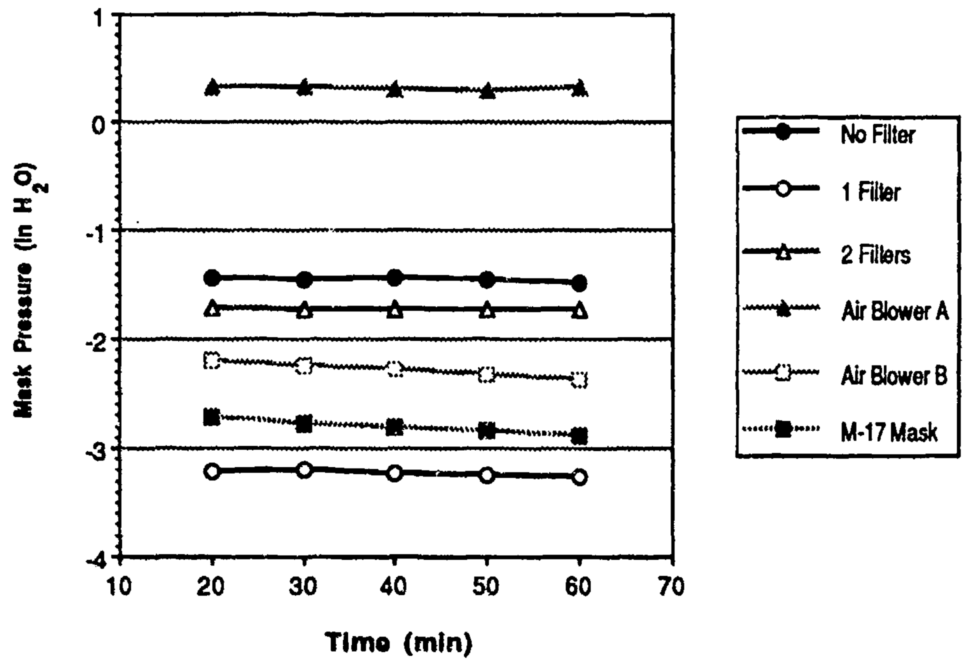

Figure 2. Inspiratory mask cavity pressures (IMCP) during steady-state exercise wearing MCU-2/P (5 configurations) and M-17 chemical defense masks.

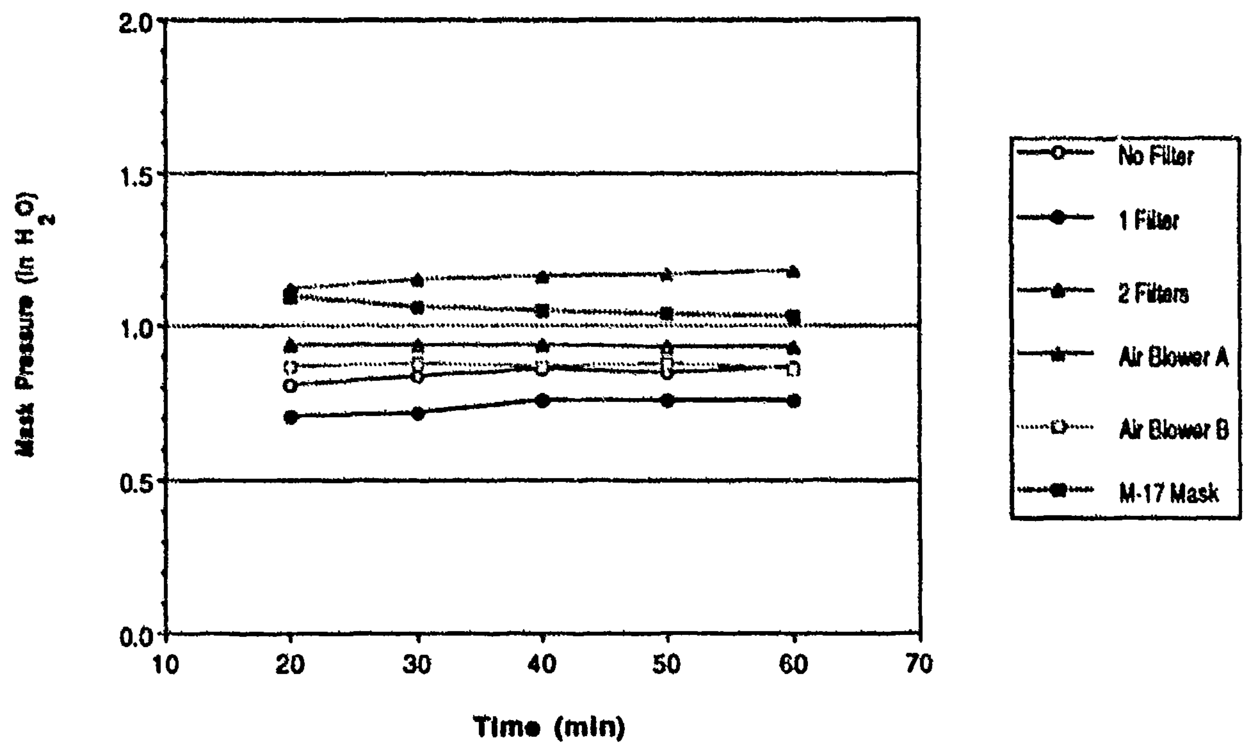

Figure 3. Expiratory mask cavity pressures (EMCP) during steady-state exercise wearing MCU-2/P (5 configurations) and M-17 chemical defense masks.

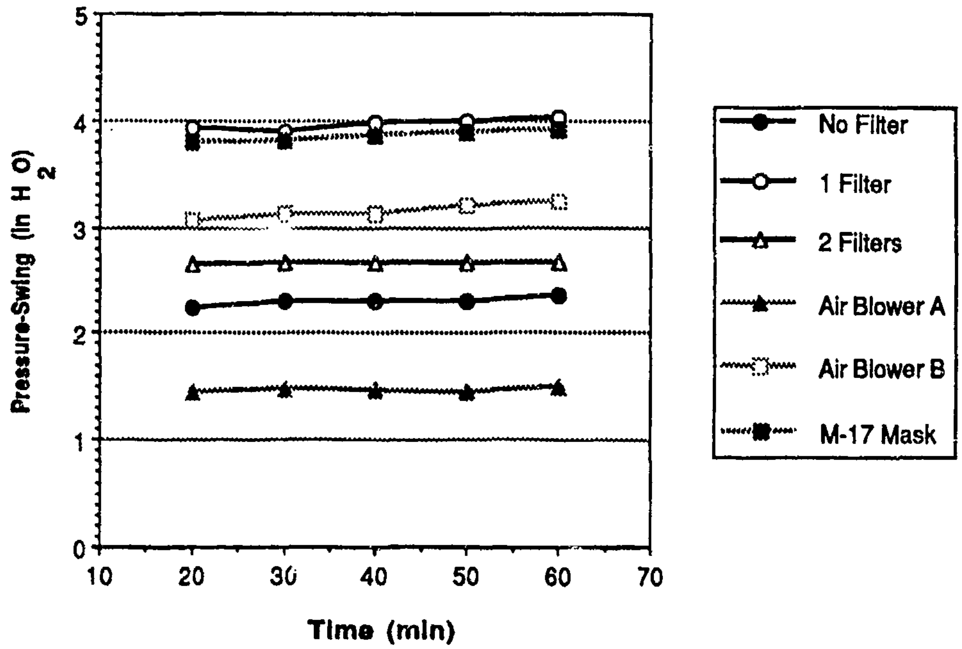

Figure 4. Mask cavity pressure-swing (MCPS) during steady-state exercise wearing MCU-2/P (5 configurations) and M-17 chemical defense masks.

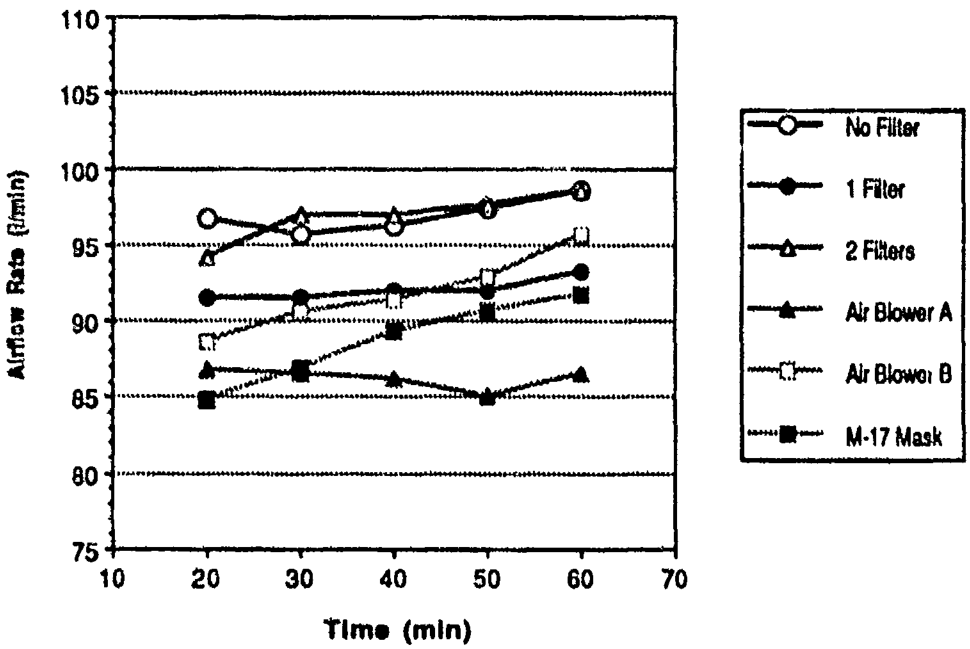

Figure 5. Peak inspiratory airflow rates (PIAFR) during steady-state exercise wearing MCU-2/P (5 configurations) and M-17 chemical defense masks.

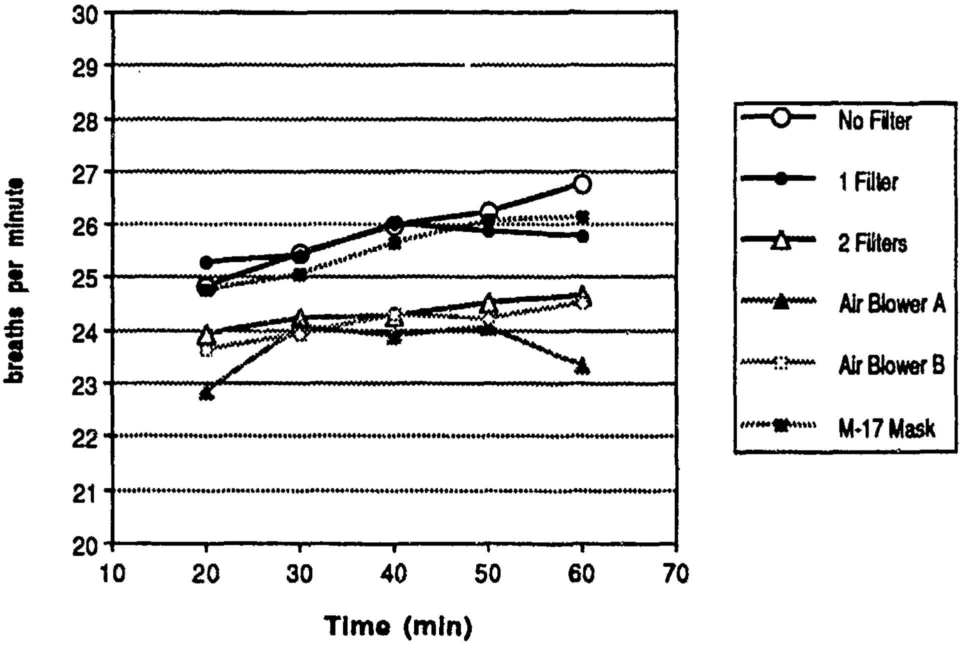

Figure 6. Respiratory rates (RR) during steady-state physical exercise wearing MCU-2/P (5 configurations) and M-17 chemical defense masks.

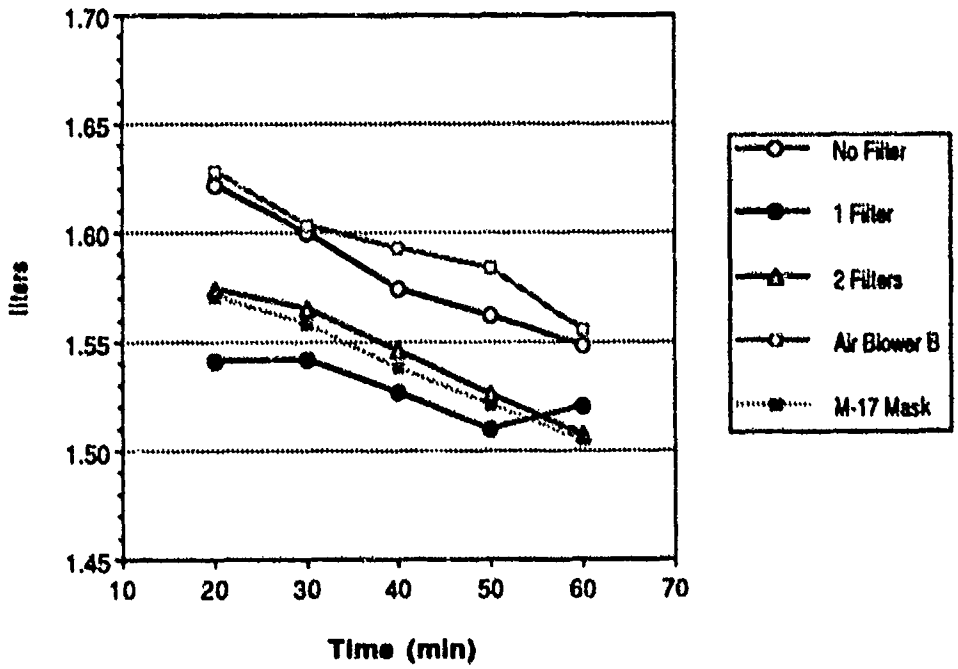

Figure 7. Peak tidal volumes (PTV) during steady-state physical exercise wearing MCU-2/P (4 configurations) and M-17 chemical defense masks.

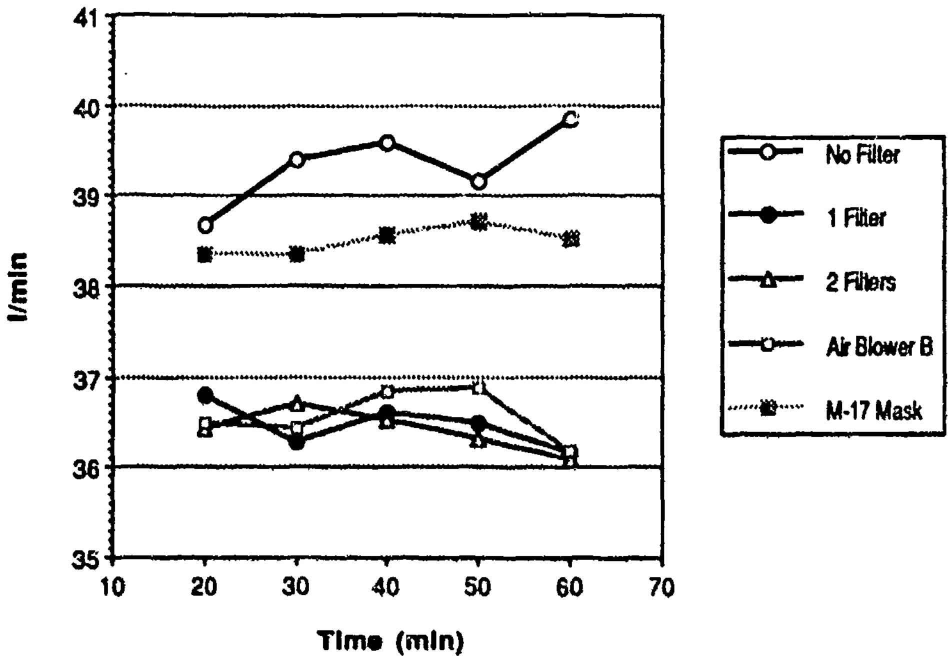

Figure 8. Minute volumes (MV) during steady-state physical exercise wearing MCU-2/P (4 configurations) and M-17 chemical defense masks.

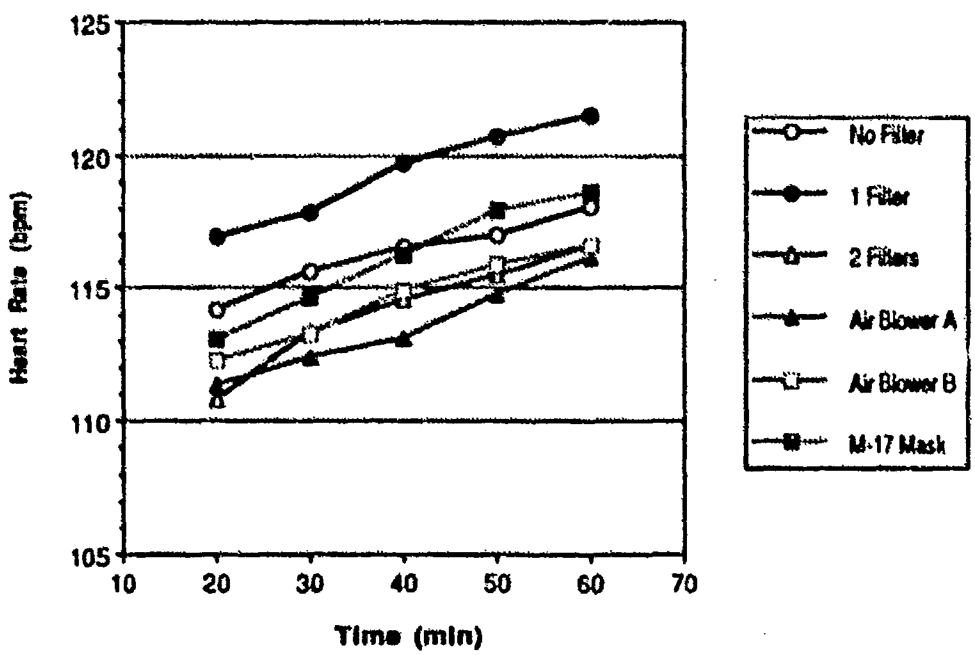

Figure 9. Heart rates (HR) during steady-state physical exercise wearing the MCU-2/P (5 configurations) and M-17 chemical defense masks.

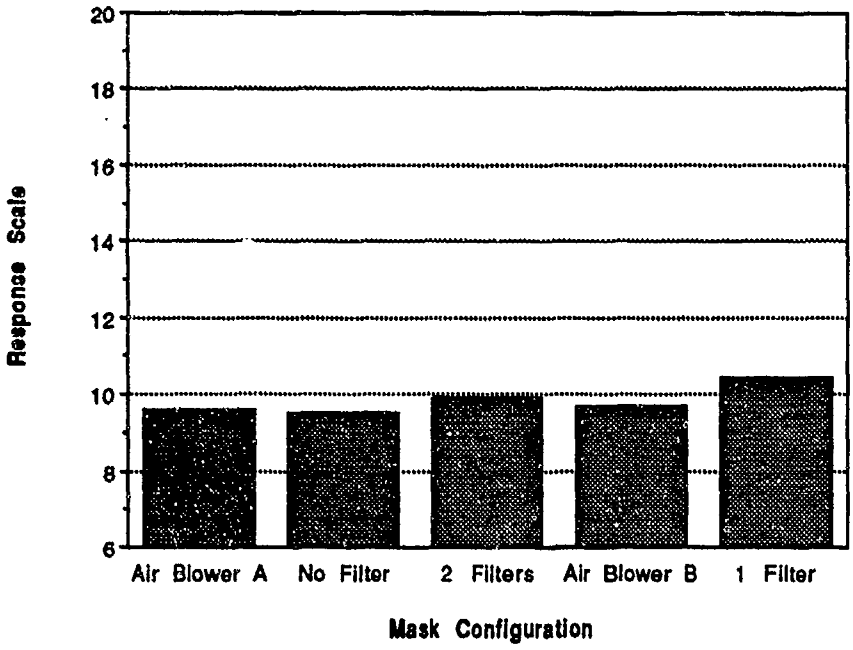

Figure 10. Ratings of perceived exertion (RPE) during steady-state exercise wearing 5 configurations of the MCU-2/P chemical defense mask.

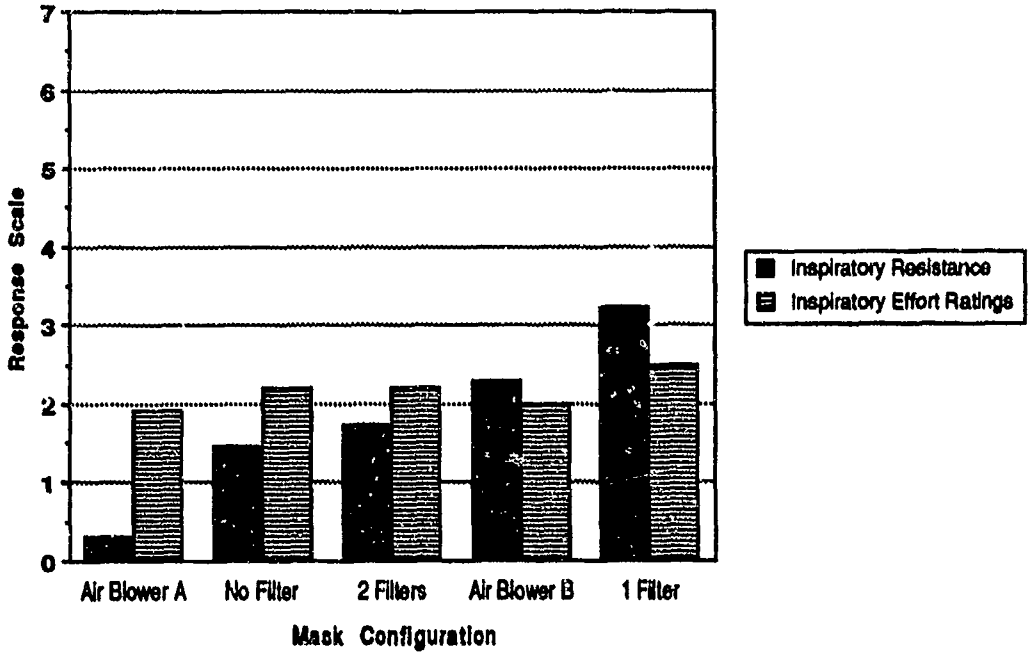

Figure 11. Relationship between inspiratory mask cavity pressure (IMCP) and perceived inspiratory effort (PIE) during exercise while wearing 5 configurations of the MCU-2/P chemical defense mask.

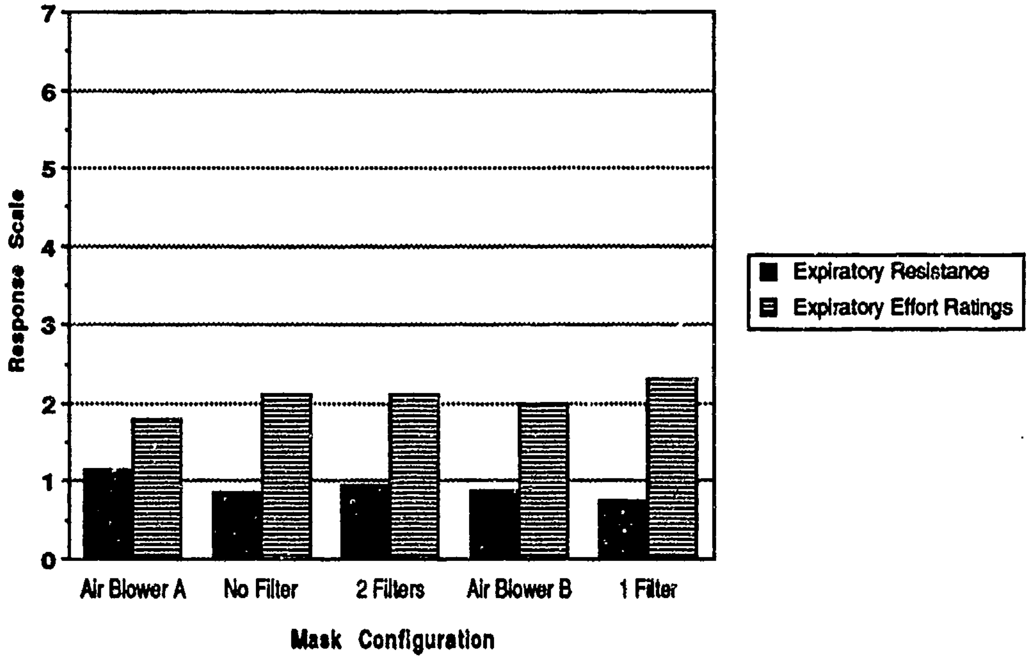

Figure 12. Relationship between expiratory mask cavity pressure (EMCP) and perceived expiratory effort (PEE) during exercise while wearing 5 configurations of the MCU-2/P chemical defense mask.

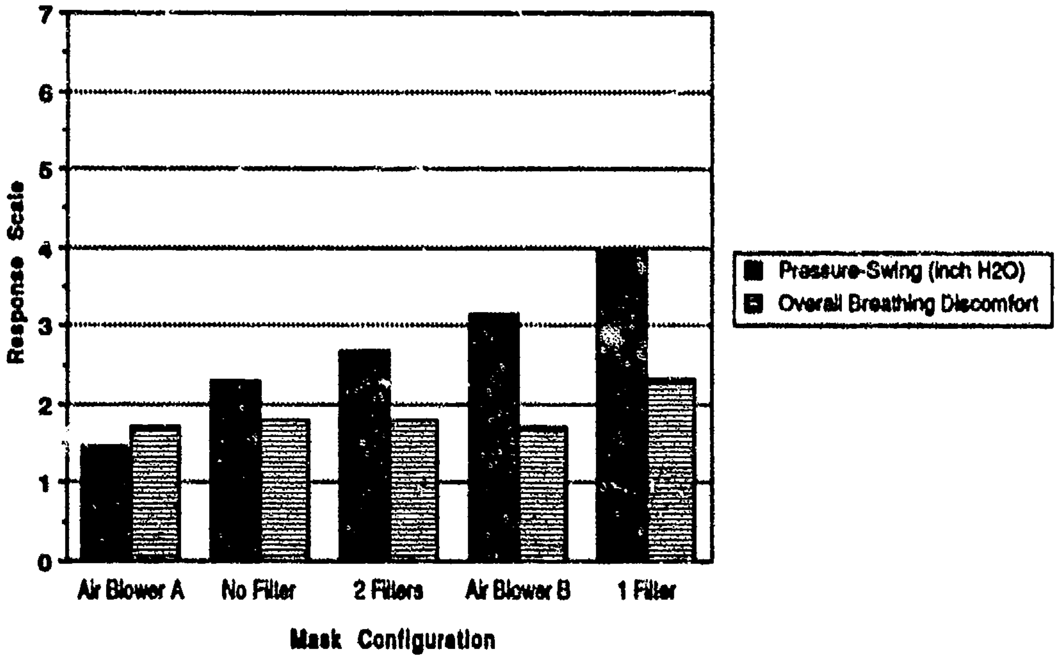

Figure 13. Relationship between mask cavity pressure-swing (MCPS) and overall breathing discomfort (OBD) during exercise wearing 5 configurations of the MCU-2/P chemical defense mask.

DISCUSSION

Results showed that the new MCU-2/P mask in its 1-filter configuration produced a slightly higher level of inspiratory resistance compared to the old M-17 mask. Nevertheless, this difference was so small that it does not have any practical significance. Furthermore, comparison of MCPS data showed that there were no significant differences between these two masks. These results support our previous suggestion that the new MCU-2/P mask in its current operational configuration (with 1 filter) does not provide an improvement in overall breathing resistance over the old M-17 mask. It is reasonable to expect that any decrements in exercise performance and endurance resulting from the use of the MCU-2/P mask will be similar to those decrements that have been previously reported with the use of the M-17 mask (7,13,24,26).

The use of a "Pusher Blower" (ABA) attached to the C2 filter canister proved an effective method in reducing the level of inspiratory resistance. The evaporative cooling effect of the air blown to the face resulted in perceptions of facial thermal comfort, especially among those subjects who were sweating profusely during the exercise task. The operational advantages and disadvantages of using this type of air blower in conjunction with the MCU-2/P mask were discussed in detail in the final report of our previous study (1). The "Power Plus" (ABB) blower, on the other hand, proved less effective to reduce the level of inspiratory resistance. While the ABA was able to prevent a drop in mask cavity pressure during inspiration, the ABB could only reduce the level of inspiratory resistance by about 29%. Furthermore, using two filters attached to the mask was more effective in reducing inspiratory resistance than was the ABB. Based on these results we cannot justify nor recommend the use of the ABB.

The use of two filters attached to the MCU-2/P mask made it possible to reduce the overall level of inspiratory resistance by about 47% compared to the MCU-1F. The installation of a second C2 filter canister to the MCU-2/P mask represents a logistically feasible, simple, fast, and economical way of reducing inspiratory resistance.

As expected, the expiratory valve assemblies on both the MCU-2/P and the M-17 masks produced a low level of expiratory resistance. This is not a surprising development taking into account that individuals are known to have lower tolerance to expiratory resistance than to inspiratory resistance (6,17,21). Consequently, in the design of any respiratory protective mask there is a critical requirement to minimize exhalation resistance.

Results indicated that although each mask configuration was characterized by a significantly different IMCP, the PIAFR values were all the same regardless of the mask configuration. This result is surprising because we expected to observe a direct relationship between IMCP and PIAFR, which should have resulted in different PIAFR values for each mask configuration. It is possible that such a direct relationship indeed existed, but was obscured as a result of the individual variability on PIAFR responses. Another possibility is that the equipment used for the measurement of peak flow rates could have malfunctioned. However, this occurrence is unlikely because that equipment was calibrated prior to each experiment.

There are many reports in the literature indicating a decrease in RR as a result of exposure to increased inspiratory resistance (10,12,14,25). Our results showed no relationship between inspiratory resistance and RRs, which suggests that RRs were determined by the intensity of the physical work and were not significantly affected by differences in inspiratory resistance.

Decrements in PTVs and MVs have been reported as a result of exposure to increased inspiratory resistance (4,8,11,12,14,21,22). However, in our experiments, no differences were observed either in PTVs or in MVs during exposure to the various levels of inspiratory resistance. One possible explanation is that individual ventilatory volumes were determined mainly by the metabolic cost of physical workload, and any response patterns associated with the different levels of inspiratory resistance were probably obscured by the exercise-related changes. Under these conditions, the subjects were able to maintain similar ventilatory requirements regardless of the differences in inspiratory resistance observed with the various mask configurations.

In our previous study (1) no relationship was found between HR and IMCP. The findings from this study are very similar, with one exception. Subjects wearing the mask configuration with the highest level of inspiratory resistance (MCU-1F) showed an HR response which was about 6 beats per minute higher than the response recorded when they were wearing the mask with the lowest respiratory resistance (MCU-ABA). Therefore, it seems there is an inverse relationship between the level of inspiratory resistance and individual HR responses. However, reports in the literature are conflicting, indicating either increments (9,12,15,23), decrements (14,20,26), or no change (5,16,18,19) in HR as a result of individual exposure to different levels of inspiratory resistance.

Overall, the results on PTVs, MVs, RRs, and HRs suggest that the use of either the MCU-2/P mask or the old M-17 mask should not be expected to produce significant cardiorespiratory strain as long as the user is limited to perform physical exercise of low intensity, and as long as other stresses are avoided (heat stress, fatigue, dehydration, etc.). These results also suggest that the experimental conditions were not too stressful (low workload = 37% of the subjects $\dot{V}O_{2max}$); consequently, the subjects were able to maintain relatively stable cardiorespiratory responses regardless of the differences in inspiratory resistance.

According to Bentley et al. (2), 90% of a population breathing through masks with low resistance expiratory valves should experience no breathing discomfort, if the MCPS in a given mask does not exceed 6.69 inH_2O, and if the inspiratory resistance does not exceed 5.5 inH_2O. In our study, subjects wearing the MCU-1F mask experienced slight breathing discomfort with an MCPS of about 4.0 inH_2O and an IMCP of about 3.2 inH_2O. As indicated in our previous report, this finding is not surprising because the accurate assessment of individual subjective perceptions such as breathing effort and discomfort has always been difficult.

CONCLUSIONS

From the point of view of total breathing resistance (inspiratory & expiratory), the new MCU-2/P CD-mask in its current 1-filter operational configuration does not offer any practical improvement over the old M-17 mask. Therefore, it is reasonable to expect that any decrements in physical performance resulting from the use of the MCU-2/P mask will be similar to those decrements that have been reported with the use of the M-17 mask.

A very effective method to reduce the level of inspiratory resistance imposed by the MCU-2/P mask is to provide powered ventilation through the C2 filter canister. However, the selection of an air blower to fulfill this objective must be carefully made. It was shown that the ABA (continuous-flow type) was very effective in reducing inspiratory resistance; however, the ABB (pressure-demand type) demonstrated only a marginal improvement.

The installation of a second filter canister to the MCU-2/P mask also proved an effective alternative to reduce inspiratory resistance. Even though this method was about 50% less effective compared to the use of ABA, it is logistically simpler and more economical to implement.

It is evident that the use of either the new MCU-2/P or the old M-17 CD-masks did not produce significant cardiorespiratory strain among individuals performing steady-state physical work of low intensity.

Additional research is necessary in order to evaluate the physiological and psychological effects of wearing these various mask configurations under more stressful conditions. We are currently investigating the responses of individuals wearing MCU-2/P and M17 masks during physical workloads of various intensities (ranging from low to high). These experiments also include the evaluation of two other candidate air blowers in conjunction with the MCU-2/P mask. Based on the results from these continuing experiments, it will be possible to elaborate more accurate recommendations with respect to the operational limitations of the MCU-2/P mask especially regarding effective methods to counteract breathing stress.

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APPENDIX
NUMERICAL SCALES

Perceived Inspiratory Effort Scale

Indicate the sensation that better describes your INSPIRATORY EFFORT at this moment:

1) NOT NOTICEABLE
2) NOTICEABLE BUT NOT DIFFICULT
3) SLIGHTLY DIFFICULT
4) MODERATELY DIFFICULT
5) VERY DIFFICULT
6) EXTREMELY DIFFICULT
7) INTOLERABLE

Perceived Expiratory Effort Scale

Indicate the sensation that better describes your EXPIRATORY EFFORT at this moment:

1) NOT NOTICEABLE

2) NOTICEABLE BUT NOT DIFFICULT

3) SLIGHTLY DIFFICULT

4) MODERATELY DIFFICULT

5) VERY DIFFICULT

6) EXTREMELY DIFFICULT

7) INTOLERABLE

Overall Breathing Discomfort Scale

Indicate the statement that describes your perception of OVERALL BREATHING DISCOMFORT at this moment:

1) NO DISCOMFORT
2) SLIGHT DISCOMFORT
3) MODERATE DISCOMFORT
4) MODERATE - HIGH DISCOMFORT
5) HIGH DISCOMFORT
6) EXTREMELY HIGH DISCOMFORT
7) INTOLERABLE DISCOMFORT