

Influence of Respirator Design on Subjective Comfort

David M. Caretti

U.S. Army Edgewood Chemical Biological Center

Aberdeen Proving Ground, MD 21010-5424

Email: David.Caretti@us.army.mil

ABSTRACT

Subjective estimates of mask comfort were measured under simulated work conditions to identify design criteria that influence user comfort and to assess how mask comfort impacts work performance. Comfort data, including subjective measures of perceived exertion, thermal sensation, and breathing apparatus comfort, were obtained from 12 subjects during and after one hour of respirator wear and work performance. An M40A1 respirator and five modified versions of the M40A1 were worn on separate occasions. Test results indicated the following: 1) reducing inspiratory resistance had little impact on mask comfort during light to moderate intensity work; 2) a 15% reduction in M40A1 mask weight caused no discernable improvements in wearer comfort; 3) a skullcap type headharness neither improved nor degraded subjective comfort; 4) a rubber headharness caused substantial discomfort to most test volunteers; 5) padding under the buckles of the M40A1 forehead facepiece straps did not alter subjective comfort rankings compared to the standard M40A1; 6) the nose cup of the respirator was identified by subjects as the main design change needed for the majority of the respirator configurations worn in this study; and 7) subjects felt that mask discomfort only slightly impacted their working abilities. These findings bring to light shortcomings of current full facepiece respirators as far as user comfort is concerned and can serve as a design aid for alleviating discomfort of future systems.

Keywords: Comfort, respirators, work performance

INTRODUCTION

Objective measures of the respirator wear factors of vision, communications, respiration, and protection are likely to determine the effectiveness of any new respirator system. However, objective analysis of any respirator does not take into account subjective impressions that result from wearing the device. Indeed, subjective impressions of a respirator, especially those of the mask's end users, may determine whether the device will even be accepted and worn. Since reluctance to wearing respirators may be connected directly to issues of comfort, subjective comfort assessment of the characteristics of a mask appears to be a critical factor in determining mask acceptance (Meyer *et al.*, 1997).

Poor knowledge of mask comfort parameters may explain why comfort continues to be an issue with today's respirators. Evaluations of human performance with respirators have primarily addressed issues of physiological strain (Caretti and Whitley, 1998; Craig *et al.*, 1970; Dählback and Balldin, 1984; Demedts and Anthonisen, 1973; Deno *et al.*, 1981; Johnson *et al.*, 1999; Raven, *et al.*, 1979; Stemler and Craig, 1977; Wilson *et al.*, 1989). The psychological effects and psychomotor alterations of respirators on the wearer have been studied to a lesser extent (Caretti, 1997; Caretti *et al.*, 1995; Johnson *et al.*, 1997; Zimmerman *et al.*, 1991). However, the results of many of these investigations have indicated that a major problem with the effective use of respirators is user discomfort or subjective strain. Even so, few studies have focused on subjective evaluations of respirator comfort. Some investigators have reported that at rest subjective measures of respirator comfort are linearly related to lip temperature such that a rise in lip temperature increases wearer discomfort (DuBois *et al.*, 1990; Nielsen *et al.*, 1987). However,

recent evidence suggests that lip temperature has no effect on respirator comfort during exercise (Coyne and Johnson, 1999).

If mask designers had evidence that one or more components of a design negatively influence wearer comfort and acceptance of the design, such components could, if practical, be redesigned to neutralize such effects. In this way, defining the subjective parameters of mask comfort would aid in the development of more comfortable and more acceptable devices. Therefore, the purpose of this study was to evaluate subjective estimates of comfort of a negative pressure respirator and modified respirator components under simulated work conditions.

METHODS

Subjects

Twelve members of the U.S. Army (11 males and 1 female) aged 18 to 36 years were recruited to participate in this study. Volunteer subjects were healthy and free of coronary risk factors, as determined by completion of a medical history questionnaire. Subject characteristics were as follows (mean $\pm$ standard deviation (SD)): age, 24.0 ± 4.8 years; weight, 73.4 ± 14.5 kg; height, 174.1 ± 11.1 cm; and trait anxiety, 34.6 ± 9.9 , indicating that test subjects were relatively 'low-anxious' individuals (Spielberger *et al.*, 1983). Test participant facial characteristics included Menton-Sellion lengths ranging between 109 mm and 137 mm and face widths (Bizygomatic breadth) between 126 mm and 156 mm. All subjects reported prior experience with military respirators that ranged from six months to 13 years. A written statement of voluntary consent was obtained from each volunteer before testing began.

Mask Wear Conditions

Mask wear tests were completed over a one-hour period of continuous wear. The six experimental mask wear conditions selected for this study (Table I) included the following: the U.S. Army M40A1 full-facepiece, negative pressure respirator (M40); a low breathing resistance version of the M40A1 (LR M40); a light weight M40A1 (LW M40); an M40A1 with a "skullcap" headharness design (Skull M40; Figure 1); an M40A1 with a stiff rubber headharness (Rubber M40); and an M40A1 with foam padding placed under the buckles of the mask's forehead straps (Figure 2).

Table I. Experimental Mask Wear Conditions

Mask Wear Condition	Condition Designator	Specific Difference vs. M40
Standard M40A1	M40	N/A
Low resistance M40A1	LR M40	Inspiratory resistance reduced from $3.4 \text{ cmH}_2\text{O} \cdot \text{s} \cdot \text{L}^{-1}$ to $1.9 \text{ cmH}_2\text{O} \cdot \text{s} \cdot \text{L}^{-1}$
Light weight M40A1	LW M40	Filter element weight reduced $\sim 30\%$; total mask weight lowered $\sim 15\%$
Skullcap M40A1	Skull M40	Distributed the mask weight over a larger area of the head
Rubber harness M40A1	Rubber M40	Different harness material; stiff rubber with notched size-adjustment straps
Padded harness M40A1	Padded M40	Provided a layer of thin padding between the facepiece strap buckles of the forehead straps and the skin



Figure 1. Skullcap headharness design used for the Skull M40 condition.



Figure 2. Placement of padding beneath the buckles of the M40 forehead straps for the Padded M40 condition.

All mask wear conditions were randomly administered and subjects were unaware of the condition that they were to wear until a mask was donned. Test respirators were sized and fitted by trained U.S. Army civilian personnel for each subject before testing began. Briefly, sizing procedures included checking the positioning of the edge of the facepiece on a subject's forehead, cheeks, and chin, ensuring that an individual's hairline did not fall beneath the peripheral seal, checking the positioning of the respirator's nosecup on the bridge of the nose, and the location of a subject's eyes in relation to the mask's eye lenses. Test volunteers wore their own battle dress uniforms, minus the long sleeve blouse over the T-shirt, for all test sessions. Subjects were instructed to get adequate rest the night before each trial, to eat a light breakfast or lunch, and to drink plenty of fluids excluding caffeine and alcohol before reporting for their scheduled test sessions.

Simulated Workplace Tasks

The tasks selected for this investigation represented light to moderate intensity physical workloads, which simulated conditions frequently found in both military and industrial occupational activities. Subjects walked on a treadmill at an intensity of approximately 75% of age-predicted maximal heart rate. Treadmill speeds and grades were adjusted for each individual to reach this level of intensity. However, treadmill speeds remained at a walking pace at all times. The large assembly task involved construction and dismantling of a metal storage rack (approximately 0.9 m wide by 2.1 m high by 0.6 m deep) that had five shelves. This task required subjects to follow assembly instructions, to lift and position support brackets and shelves, and use hand tools (e.g., screwdrivers and wrenches). The small assembly task involved piecing together 100-piece jigsaw puzzles. Subjects completed the large assembly task in pairs, but the small assembly task was done individually. For the computer keyboard entry and display-monitoring task, subjects completed one trial of the Vision Aerobics® task and entered either numerical or text data into a file. The Vision Aerobics® task is a visual tracking exercise that displays the letters A or L, one at a time, in random order and location on the computer monitor (Johnson *et al.*, 1997). Subjects fixed their attention on the computer monitor and responded to seeing a letter by pressing the keyboard key that matched the letter that they perceived to be displayed. As with mask conditions, task conditions were randomly administered to subject pairs.

Data Collection Procedures

Data collection occurred over four consecutive days for each subject. Subjects completed two mask wear conditions on each test day, one in the morning and one in the afternoon, separated by at least one hour. Subjects reported to the lab one day prior to commencement of testing to complete volunteer consent forms, to receive instructions concerning the subjective scales and post-test questionnaire, and to practice specific tasks selected for this study.

Prior to the first test period, subjects were briefed on how to answer the questions contained in a subjective comfort assessment questionnaire. The principal investigator verified the understanding of the wording of each question after a full explanation was given. Subjects also received instructions on the techniques that they were to employ to complete the small and large assembly tasks and the computer-based tasks selected for this study. Subjects were given as much time as needed to practice the methods required for completing each task.

Upon arrival to the lab, subjects were required to drink 300 ml of water to safeguard against becoming inadequately hydrated during testing. Water was not available to subjects during periods of mask wear. However, volunteers were encouraged to drink after completion of each trial.

All respirators were donned with the help of test administrators prior to commencement of a test session. The following objective and subjective parameters were monitored during each mask wear session: room climatic conditions, heart rate, rating of perceived exertion (RPE), breathing apparatus comfort (BAC), and thermal sensation. A portable RSS-214 WibGeT WBGT monitor (Imaging & Sensing Technology, Horseheads, NY) was used to record wet bulb globe temperatures (WBGT) in the three separate rooms used in the laboratory for the different work tasks. The treadmill walk and the keyboard entry and display monitoring task were administered in the same room, but at separate times so that subjects would not be distracted by others performing the opposite task. Heart rate was monitored using a Polar Vantage XL® heart rate monitor consisting of transmitter and wristwatch monitor (Polar CIC, Inc., Port Washington, NY). Subjective RPE, BAC, and thermal sensation scores were obtained using specific subjective scales following initial donning of the test mask and at 10-minute intervals up to the end of each session (Abadie and Carroll, 1993; Borg, 1982; Nielsen *et al.*, 1987). Subjects rated comfort of the following mask components using the BAC scale (Figure 3): facepiece, nosecup, headharness, filter resistance, and overall comfort of the complete mask system.

Breathing Apparatus Comfort (BAC) Scale

- 10 Very, very comfortable
- 8 Very comfortable
- 6 Fairly comfortable
- 4 Fairly uncomfortable
- 2 Very uncomfortable
- 0 Very, very uncomfortable

Figure 3. The breathing apparatus comfort (BAC) scale.

The State-Trait Anxiety Inventory (Spielberger *et al.*, 1983) was administered to subjects as follows: The trait anxiety inventory, a 20-item scale that evaluates how respondents *generally* feel, was administered to each subject only at the beginning of their initial test iteration. The state anxiety inventory, a 20-item scale that assesses how people feel "*right now*," at this moment," was completed

before and after each mask wear test. In addition to the state anxiety inventory, subjects also completed a mood state questionnaire before and after each period of mask wear (Thorne *et al.*, 1985). An overall mood disturbance score was obtained by weighting the individual factor scores. Both the State-Trait Anxiety Inventory and the mood scale profile were computer administered tasks.

Once a mask wear session was completed, an estimate of the acceptable duration of wear without significant discomfort was obtained by asking each subject the question "How much longer could you keep this mask on before it became too difficult to wear?" Subjects were also asked to answer the question "If you could change one design feature of the mask to help you perform better, what would that one feature be?" Additional subjective feedback of mask comfort and its impact on work performance was obtained through administration of an automated questionnaire. Questionnaire items were presented one at a time on a computer monitor to prevent subjects from reviewing previous responses before answering the question at hand. Finally, subjects were given an opportunity to provide general comments concerning their wear experience for each of the mask trials.

Statistical Analyses

Analysis of variance was used to test for statistical significance of objective and subjective data within and between mask wear conditions. Scheffe's *post-hoc* analysis was computed to determine significant differences between group means if a significant *F* statistic was initially obtained. Relationships between subjective responses and mask wear conditions were also assessed using Pearson's method of least squares for simple and multiple regression analyses. Statistical computations were performed using SPSS 7.5 for Windows. Statistical significance was accepted at the $p < 0.05$ level.

RESULTS

Environmental conditions (i.e., WBGT) differed statistically between the laboratory rooms used for administration of the large assembly task (20.3 ± 0.6 °C) and the treadmill walk and keyboard entry and display tasks (19.3 ± 0.6 °C) independent of mask wear condition. However, the difference in WBGT values was not practically significant. Room WBGT values averaged 19.9 ± 0.8 °C (approximately 68°F) for all mask sessions.

No significant interactions of mask condition and work task were observed for heart rate, RPE, facepiece comfort, nosecup comfort, headharness comfort, breathing comfort, overall comfort, and thermal sensation. Independent of mask condition, average heart rates, RPE, and thermal sensation scores were higher during treadmill walking compared to the remaining work tasks. Likewise, heart rate and RPE were greater for the large assembly task when compared to both the small assembly and keyboard entry tasks. However, subjective facepiece comfort, nosecup comfort, headharness comfort, breathing comfort, and overall mask comfort scores did not differ between the different work tasks.

Subject pre-test and post-test state anxiety scores did not differ within or between mask conditions. Likewise, analysis of the mood questionnaire scores found no differences in Anger, Happiness, Fear, Depression, Activity, Fatigue, or overall mood disturbance scores before and after test sessions within or between the various conditions.

Average headharness comfort score for the Rubber M40 was significantly lower than all other mask conditions independent of work task (Table II). The average headharness comfort ranking for the Rubber M40 indicated that subjects were "Fairly uncomfortable" with this particular mask headharness design. On average, the lowest overall mask comfort scores were observed for the Rubber M40 condition. In general, average subjective facepiece comfort, nosecup comfort, headharness comfort, breathing comfort, and overall comfort scores were between a "Fairly comfortable" and "Fairly uncomfortable" ranking on the BAC scale, suggesting that subjects were not overly uncomfortable or comfortable with any of the mask wear conditions of the study.

Table II. Heart Rate and Subjective Responses (mean $\pm$ SD) Independent of Work Tasks (Comfort Scores Represent BAC Scale Values)

Mask Condition	Heart Rate (min ⁻¹)	RPE	Thermal Sensation	Breathing Comfort	Facepiece Comfort	Headharness Comfort	Nosecup Comfort	Overall Comfort
M40	101.3 $\pm$ 25.3	9.7 $\pm$ 2.8	4.5 $\pm$ 1.3	5.6 $\pm$ 1.6	5.8 $\pm$ 1.5 ^B	6.1 $\pm$ 1.5 ^B	5.3 $\pm$ 1.4 ^A	5.7 $\pm$ 1.3 ^B
LR M40	103.0 $\pm$ 24.9	10.3 $\pm$ 2.8	4.4 $\pm$ 1.4	5.8 $\pm$ 1.5	5.8 $\pm$ 1.4 ^B	6.0 $\pm$ 1.4 ^B	4.9 $\pm$ 1.9	5.7 $\pm$ 1.5 ^B
LW M40	103.8 $\pm$ 26.4	10.4 $\pm$ 2.6	4.4 $\pm$ 1.3	5.6 $\pm$ 1.7	5.6 $\pm$ 1.5	6.3 $\pm$ 1.4 ^{B,C}	4.8 $\pm$ 1.8	5.6 $\pm$ 1.5 ^B
Skull M40	104.5 $\pm$ 25.5	10.2 $\pm$ 2.9	4.6 $\pm$ 1.4	5.1 $\pm$ 1.8	5.4 $\pm$ 1.6	5.3 $\pm$ 1.8 ^B	5.0 $\pm$ 1.8	5.3 $\pm$ 1.6
Rubber M40	105.0 $\pm$ 24.2	10.1 $\pm$ 2.8	4.6 $\pm$ 1.4	5.4 $\pm$ 1.7	5.0 $\pm$ 1.4	4.3 $\pm$ 2.2	4.6 $\pm$ 1.8	4.8 $\pm$ 1.5
Padded M40	101.9 $\pm$ 25.9	9.8 $\pm$ 2.6	4.5 $\pm$ 1.1	5.7 $\pm$ 1.4	5.5 $\pm$ 1.0	5.9 $\pm$ 1.1 ^B	4.3 $\pm$ 1.7	5.4 $\pm$ 1.2
All Conditions	103.2 $\pm$ 25.3	10.1 $\pm$ 2.7	4.5 $\pm$ 1.3	5.5 $\pm$ 1.6	5.5 $\pm$ 1.4	5.7 $\pm$ 1.7	4.9 $\pm$ 1.8	5.4 $\pm$ 1.5

^A Significant difference vs. the Padded M40

^B Significant difference vs. the Rubber M40

^C Significant difference vs. the Skull M40

Regression analyses performed to quantify the interactions of average facepiece, noseclip, headharness, and breathing comfort with overall comfort scores produced significant correlations dependent upon mask condition. Overall mask comfort scores correlated significantly with breathing, facepiece, headharness, and noseclip comfort for each mask condition with the exception of the Padded M40 condition (Table III). The facepiece comfort variable explained the highest percentage of the variability (R^2) in overall comfort for the M40 (79%), LR M40 (92%), and LW M40 (88%) conditions. Noseclip comfort accounted for approximately 63% of the variability of overall comfort for the Rubber M40 condition and 51% for the Padded M40 condition. Breathing comfort explained almost 94% of the overall comfort scores for the Skull M40 condition. Independent of condition, overall mask comfort correlated significantly with breathing, facepiece, headharness, and noseclip comfort. Both facepiece and noseclip comfort demonstrated the strongest linear relationships with overall mask comfort.

Since multiple significant correlations were observed for many of the test conditions (Table III), multiple regressions using both backward and stepwise variable selection methods were performed for each condition independently and as a whole to identify which subset or subsets of comfort would be most effective for estimating overall comfort. The first criterion used for selecting effective predictors of overall comfort was variables with a t statistic well below -2 or above $+2$. If this first criterion was met, collinearity of selected variables was assessed and components with a condition index greater than 15 that contributed substantially to the variance of two or more variables of the model were eliminated (SPSS, Inc., 1997). Table IV lists the estimated models for each test condition as well as for all mask conditions together. Several inferences concerning overall mask comfort can be drawn as a result of these analyses. First, comparisons between the models of overall comfort for the M40, LR M40, and LW M40 conditions suggest that the impact of breathing comfort on overall mask comfort can be minimized by either reducing inspiratory breathing resistance by approximately 50% or decreasing filter element weight approximately 30% (or total mask weight by 15%). Secondly, differences in M40 headharness designs caused considerable differences in determining predictors of overall comfort. The skullcap headharness design did not change the predictors of overall comfort from those of the M40 with its standard headharness. However, wearing the M40 with the padding beneath the mask's forehead straps changed the model variables from breathing comfort and facepiece comfort to only noseclip comfort. This change suggests that adding the padding somehow shifted user attention to the comfort of the mask's noseclip and away from facepiece and breathing comfort factors. Headharness comfort was an effective predictor of overall comfort only for the Rubber M40 condition. Independent of mask condition,

facepiece comfort was the only predictor that met the criteria used for selecting effective predictors of overall comfort.

Table III. Correlations (multiple R and coefficient of determination (R^2)) of Average Facepiece, Nosecup, Headharness, and Breathing Comfort with Overall Mask Comfort Scores

Condition	Breathing Comfort		Facepiece Comfort		Headharness Comfort		Nosecup Comfort	
	R	R^2	R	R^2	R	R^2	R	R^2
M40	0.795 ^B	0.632	0.889 ^B	0.790	0.818 ^B	0.669	0.772 ^B	0.596
LR M40	0.832 ^B	0.692	0.961 ^B	0.924	0.629 ^A	0.396	0.750 ^B	0.563
LW M40	0.935 ^B	0.874	0.937 ^B	0.878	0.927 ^B	0.859	0.705 ^B	0.497
Skull M40	0.971 ^B	0.943	0.849 ^B	0.721	0.594 ^A	0.353	0.925 ^B	0.856
Rubber M40	0.741 ^B	0.549	0.760 ^B	0.580	0.700 ^A	0.490	0.791 ^B	0.626
Padded M40	0.648 ^A	0.420	0.258	0.067	0.187	0.035	0.712 ^B	0.507
All Conditions	0.829 ^B	0.687	0.839 ^B	0.704	0.658 ^B	0.433	0.759 ^B	0.576

^A Correlation significant at the 0.05 level (2-tailed)

^B Correlation significant at the 0.01 level (2-tailed)

Table IV. Estimated Models for Prediction of Overall Mask Comfort for Each Condition and for All Masks Together (Comfort Scores Are Based on the BAC Scale)

Condition	Model for Overall Comfort Score (y)
M40	$y = 0.577(\text{Facepiece comfort}) + 0.311(\text{Breathing comfort}) + 0.584$
LR M40	$y = 1.064(\text{Facepiece comfort}) - 0.426$
LW M40	$y = 0.921(\text{Facepiece comfort}) + 0.330$
Skull M40	$y = 0.281(\text{Facepiece comfort}) + 0.634(\text{Breathing comfort}) + 0.477$
Rubber M40	$y = 0.352(\text{Nosecup comfort}) + 0.306(\text{Breathing comfort}) + 0.304(\text{Headharness comfort}) + 0.269$
Padded M40	$y = 0.486(\text{Nosecup comfort}) + 3.285$
All Conditions	$y = 0.863(\text{Facepiece comfort}) + 0.632$

The amount of additional time that was acceptable for wearing the mask without significant discomfort was similar for all mask conditions. Independent of condition, the acceptable additional wear period ranged from not any longer to 10 hours. The overall average was 3.2 ± 2.3 hours. The additional acceptable duration of wear was significantly related to nosecup comfort ($R = 0.259$; $p < 0.05$), but the linear relationship was not strong ($R^2 = 0.07$).

The most frequent answers provided to the question "If you could change one design feature of the mask to help you perform better, what would that one feature be?" are presented in Table V. These

results show that nosecup designs were not highly regarded for the majority of the masks used in this study.

Table V. Main Design Changes Recommended by Test Volunteers

Condition	Recommended design change	Response Frequency (%)
M40	Breathing resistance	25
LR M40	Nosecup	46.2
LW M40	Nosecup	50
Skull M40	Nosecup	38.5
Rubber M40	Headharness	50
Padded M40	Nosecup	41.7
All Conditions	Nosecup	36.8

The post-test subjective computer questionnaire asked subjects to rate the degree to which comfort constraints associated with the mask caused their attention to be diverted away from performing the work tasks of each test session. Distractions due to nosecup discomfort were considered to be no more than slightly distracting for the majority of subjects for all conditions other than the LR M40 condition. For the LR M40, 46% of respondents rated nosecup comfort to be somewhat highly distracting and 23% answered that it was highly distracting. Frequency responses to the answers given for the level of distraction due to headharness comfort showed 58% of subjects were somewhat highly to highly distracted by the comfort of the headharness for the Rubber M40 condition. This finding indicates that the rubber headharness significantly impacted task performance. Distractions due to facepiece comfort were considered to be no more than slightly distracting for the majority ($\geq 75\%$) of subjects for all mask conditions. Finally, subjects primarily found the level of breathing comfort for each condition to be only minimally distracting during the completion of the various work tasks of this study. In spite of the various distractions from work performance reported for the factors of nosecup, headharness, and facepiece comfort, a global estimation of the impact of each mask on overall work performance showed that subjects generally felt that mask wear only slightly impacted their working abilities.

DISCUSSION

The results of this investigation demonstrate that subjective estimates of comfort for negative pressure respirators will fluctuate with only minor manipulations of a respirator's design components under conditions of light to moderate physical work loads. The differences observed in the various estimates of comfort between the standard M40 (the baseline mask chosen for the study) and the other respirator configurations as well as the practical consequences of these results will be discussed successively. Also, the implications of the estimates of comfort on worker performance will be addressed.

Average BAC scores for breathing comfort were similar for both the M40 and LR M40. This finding suggests that, contrary to popular belief, breathing discomfort is not negated by simply reducing mask filter element resistance. Facepiece comfort was a common predictor of overall comfort for both the M40 and LR M40 conditions and accounted for the greatest percentage of variability in overall comfort scores for both conditions. However, reducing the level of breathing resistance appeared to reduce the impact that breathing comfort had on predicting overall mask comfort for two reasons: 1. The model for the LR M40 condition did not include breathing comfort as a predictive variable; and 2. The number one recommended design change for the LR M40 condition was improvement to the nosecup, whereas subjects mainly recommended improving breathing resistance of the M40 mask. Even so, average BAC scores for overall comfort were identical between conditions. Therefore, these findings suggest that reducing inspiratory breathing resistance had a marginal effect on subjective ratings of breathing comfort

and overall mask comfort during 60 minutes of light to moderate intensity work. Similar results specific to breathing comfort and moderate work rates have been reported elsewhere for both laboratory and field studies that have lasted from 15 minutes to 60 minutes in duration (Meyer *et al.*, 1997). However, under high intensity, short duration work loads, decreased levels of inspiratory resistance appear to alleviate subjective ratings of breathing discomfort (Carette and Whitley, 1998; Johnson *et al.*, 1999).

For the LW M40 condition, a NIOSH approved riot-control type filter canister (approval number TC-14G-177) was used in place of the C2 filter canister that is common to the M40. This canister weighed 100 g less than the C2 canister but imposed roughly the same amount of inspiratory resistance on the subjects. With a lighter weight respirator system, differences in facepiece comfort, neck comfort, and movement of the mask on the face were anticipated compared to the standard M40. However, no differences in facepiece BAC scores were observed between the two conditions. This finding indicates that a 15% reduction in weight of the M40 respirator system causes no discernable improvements in comfort.

The Skull M40 condition, which utilized a headharness that covered more of the head (Figure 1), was one of the three headharness design manipulations used in this study. In addition to the larger surface area that the skullcap occupies on the head, the cap is made of a permeable material that may minimize heat retention. Despite these differences, headharness BAC scores did not differ between the Skull M40 and M40 conditions and no differences in overall comfort scores between the two conditions were observed. In addition, the prediction models for overall comfort had the same predictive variables for the two conditions. However, the primary recommended design change for the Skull M40 condition was improvement of the nose cup. These findings suggest that utilization of some type of a skullcap headharness design will not improve nor degrade subjective levels of mask comfort.

The second headharness design tested in this study was a six-strap suspension harness made out of rubber. These headharnesses were obtained from an in-house stock of respirator parts and fitted to M40 respirators to create the Rubber M40 condition. With this modification, the following results were observed: 1. Headharness BAC scores were significantly lower for the Rubber M40 condition than for all other masks, and the lowest overall comfort scores were found for this mask configuration; 2. The model for overall mask comfort included the predictive variable of headharness comfort; and 3. The primary design change recommended by test volunteers was a change in the design of the headharness. In addition, when asked to rate the overall comfort of each mask condition taking into account all the constraints of each system in the post-test questionnaire, the Rubber harness condition was the only mask that received an "Unbearable" rating. From these points, it can be concluded that a rubber harness should not be considered as a feasible headharness design for any respirator systems.

The final headharness configuration that was evaluated involved the placement of a thin layer of rubber padding under the metal forehead anchors of the M40 facepiece where two of the headharness straps connect to the mask facepiece (Figure 2). This modification was attempted to see if such a simple alteration in the M40 would eliminate cursory complaints about discomfort of the forehead straps due to the metal anchors or buckles, which could be digging into the forehead. When compared to the standard M40, no differences in headharness or overall BAC scores were found. These results indicate that the addition of padding under the buckles of the M40 forehead facepiece straps did little to alter subjective comfort compared to the standard mask configuration. Unfortunately, this conclusion may only be partially correct for one main reason: The potential for the development of forehead buckle discomfort would be significantly greater when a helmet is worn in conjunction with the respirator, as is the case for military mask users. Therefore, an accurate impact of adding padding beneath the metal forehead buckles on mask comfort remains in question until the M40 and Padded M40 conditions can be repeated with the use of a helmet.

In addition to the evaluations of respirator comfort associated with the different mask conditions, the post-test subjective questionnaire provided some insights into how comfort impacted work performance. In general, impacts on work performance due to respirator comfort were related to the specific design modifications and their effects on comfort. Distractions due to headharness comfort were predominantly high for the Rubber harness, which received the most negative comfort ratings of all the headharness manipulations used in this study.

In spite of the various distractions from work performance reported for the factors of nosecup and headharness comfort, a global estimation of the impact of each mask on overall work performance showed that subjects generally felt that mask wear only slightly impacted their working abilities. Also, the majority of respondents rated overall comfort as acceptable for all test conditions. Given that subjects generally accepted the level of comfort afforded by the different respirator configurations, the expectations for an acceptable period of mask wear were much longer than the predicted 3.2 ± 2.3 hours reported independent of mask condition. These findings suggest that maintaining an acceptable level of user comfort during respirator wear will be difficult if the mask must be worn continuously for more than approximately four hours (i.e., one hour of testing plus 3.2 hours).

It could be argued that predictions of additional acceptable wear time are not representative of results that would be obtained for tests that actually required subjects to rate comfort during extended periods of mask wear. There is very little research to indicate what can be expected from respirator wear lasting more than a few hours. One reason for this is the practical logistical aspect of conducting long-term tests. Another reason is that the acute effects of more intense activities while wearing a mask have been given greater emphasis and are thought to be of greater concern for determining the impacts of mask wear on performance. Of the limited research that has involved respirator wear for extended periods of time, subjective measures of wearer comfort have been few. Cummings *et al.* (1976) assessed wearability of both a silicone mask and a rubber mask under simulated combat conditions for 32 hours and wearability of the M17 respirator during 72 hours of simulated combat (Cummings *et al.*, 1961). The longest continuous mask wear period was for the first 24 hours of the 72-hour test, but this study also involved wear of chemical protective clothing. The results of the 32-hour wear trial, which entailed continuous mask wear, except at mealtimes, showed that discomfort of the mask was due to pressure generally over the mastoid process and due to lens fogging. Breathing discomfort was not an important factor of discomfort in the test. As in the current investigation, one post-test questionnaire item used by Cummings *et al.* (1976) asked subjects to indicate if they would be able to wear the mask for an additional 1-hour, 3-hour, or 8-hour period, for an additional day, or indefinitely. Unfortunately, the results of this questionnaire item were not reported. However, in response to a similar question about wear of the protective ensemble, the greater percentage of participants in the 72-hour wear trial said the system could be worn for an additional three days (Cummings *et al.*, 1961)! This finding could be a reflection of the fact that the simulated combat conditions of the test employed various deterrents to prevent mask removal including an odoriferous chemical agent, psychological deterrents, direct observations by test personnel, and social deterrents. After being subjected to these conditions for 72 hours, it seems highly likely that the three-day response was a direct reflection of the rigorous simulated chemical combat conditions. In fact, Cummings *et al.* (1961) found that an adaptive process occurred during the first day of protective ensemble wear that reduced complaints of discomfort and increased subjective tolerance of the ensemble under these conditions.

Therefore, in the current study, the relatively short amount of additional time subjects felt that the mask could be worn before it became too uncomfortable to wear may be a reflection of the relatively short test period of continuous mask wear. Secondly, the current results could mean that the continuous wear period was too short to permit adequate adaptation to mask wear. Finally, the additional three hour wear period may simply reflect the mask wear experiences of the study's military test participants encountered during their own chemical/biological operational exercises and maneuvers. Nevertheless, the point for mask designers is that current respirator designs still have a significant impact on comfort. This holds true for both military and commercial respirators. As reported by Cummings *et al.* (1961), individuals are likely to wear a mask indefinitely if their lives are in danger regardless of personal comfort. Even so, future mask systems must address comfort issues of existing designs to minimize potential problems with the effective use of respirators due to wearer discomfort.

CONCLUSIONS

The purpose of this study was to evaluate subjective estimates of comfort of negative pressure respirators and respirator components under simulated work conditions to identify design criteria that negatively influence user comfort. In addition, this investigation attempted to obtain some insight into how mask comfort impacted work performance. Although much of the data generated by this test brings to light shortcomings of the various mask configurations used in the study, the information is meant to serve as a guide to the mask design community to make future respirators more comfortable and acceptable to the end users. The findings of this investigation are summarized as follows:

1. Reducing inspiratory breathing resistance had little impact on subjective ratings of breathing comfort and overall mask comfort during 60 minutes of light to moderate intensity work.
2. A 15% reduction in weight of the M40 respirator system resulted in no discernable improvements in comfort.
3. Comfort results suggest that a skullcap type headharness design will neither improve nor degrade subjective levels of comfort.
4. A rubber headharness should not be considered as a feasible headharness design for any future respirator systems.
5. The addition of padding under the buckles of the M40 forehead facepiece straps will not alter subjective comfort compared to the standard mask configuration.
6. The respirator nosecup design was not highly regarded for the majority of the mask conditions of this study.
7. In general, impacts on work performance due to respirator comfort were related to the specific design modifications and their effects on comfort. Nevertheless, a global estimation of the impact of each mask condition on overall work performance showed that mask wear only slightly impacted working abilities.
8. Even though subjects generally accepted the level of comfort afforded by the different respirator configurations, the shortest average additional acceptable wear time and the longest average additional accepted duration of wear only differed by 1.3 hours.

REFERENCES

- Abadie, B.R., and J. Carroll: Effect of Facemask vs. Mouthpiece Use on Physiological Responses to Exercise. *Res. Quart. Exer. Sport.* 64S: A23 (1993).
- Borg, G.: Psychophysical Bases of Perceived Exertion. *Med. Sci. Sports Exerc.* 14: 377-381 (1982).
- Caretti, D.M., and J.A. Whitley: Exercise Performance during Inspiratory Resistance Breathing under Exhaustive Constant Load Work. *Ergonomics.* 41: 501-511 (1998).
- Caretti, D.M.: Cognitive Performance during Long-term Respirator Wear while at Rest. *Am. Ind. Hyg. Assoc. J.* 58: 105-109 (1997).

Caretti, D.M., L.A. Bay-Hansen and W.D. Kuhlmann: Cognitive Performance during Respirator Wear in the Absence of Other Stressors. *Am. Ind. Hyg. Assoc. J.* 56: 776-781 (1995).

Coyne, K.M., and A. T. Johnson. Effect of face temperature on respirator comfort, thermal sensation, and performance time during exercise. Northeast Agricultural / Biological Engineering Conference, Lancaster, PA, 1-3 August 1999.

Craig, F.N., W.V. Blevins and E.G. Cummings: Exhausting Work Limited by External Resistance and Inhalation of Carbon Dioxide. *J. Appl. Physiol.* 29: 847-851 (1970).

Cummings, E.G., S.E. Jackson, C.R. Bulette and R.P. Merkey: *Thirty-two Hour Outdoor Wearing Trial of Silicone XM29 and Rubber XM31 Prototype Masks under Simulated Combat Conditions*, EB-TR-76042, Edgewood Arsenal, Aberdeen Proving Ground, MD, July 1976.

Cummings, E.G., J. Marrero, E. Bird, and E. Davy: *Seventy-two Hour Outdoor Wearing Trial of Individual CBR Protective Clothing with M17Mask and E33 Hood under Simulated Combat Conditions*, CRDLR 3097, U.S. Army Chemical Research and Development Laboratories, Army Chemical Center, MD, September 1961.

Dählback, G.O., and U.I. Balldin: Physiological Effects of Pressure Demand Masks during Heavy Exercise. *Am. Ind. Hyg. Assoc. J.* 45: 177-181 (1984).

Demedts, M., and N.R. Anthonisen: Effects of Increased External Airway Resistance during Steady-state Exercise. *J. Appl. Physiol.* 35: 361-366 (1973).

Deno, N.S., E. Kamon and D. Kiser: Physiological Responses to Resistance Breathing during Short and Prolonged Exercise. *Am. Ind. Hyg. Assoc. J.* 42: 616-623 (1981).

DuBois, A.B., Z.F. Harb and S.H. Fox: Thermal Discomfort of Respiratory Protective Devices. *Am. Ind. Hyg. Assoc. J.* 51: 550-554 (1990).

Johnson, A.T., W.H. Scott, C.G. Lausted, M.B. Benjamin, K.M. Coyne, M.S. Sahota and M.M. Johnson: Effect of Respirator Inspiratory Resistance Level on Constant Load Treadmill Work Performance. *Am. Ind. Hyg. Assoc. J.* 60: 474-479 (1999).

Johnson, A.T., C.R. Dooly, D.M. Caretti, M. Green, W. Scott, K. Coyne, M. Sahota and B. Benjamin: Individual Work Performance during a Ten-hour Period of Respirator Wear. *Am. Ind. Hyg. Assoc. J.* 58: 345-353 (1997).

Meyer, J.P., M. Hery, J. Herrault, G. Hubert, D. Francois, G. Hecht and M. Villa: Field Study of Subjective Assessment of Negative Pressure Half-masks. Influence of the Work Conditions on Comfort and Efficiency. *Appl. Ergonomics*. 28: 331-338 (1997).

Nielsen, R., A.R. Gwosdow, L.G. Berglund and A.B. DuBois: The Effect of Temperature and Humidity Levels in a Protective Mask on User Acceptability during Exercise. *Am. Ind. Hyg. Assoc. J.* 48: 639-645 (1987).

Raven, P.B., A.T. Dodson and T.O. Davis: The Physiological Consequences of Wearing Industrial Respirators: A review. *Am. Ind. Hyg. Assoc. J.* 40: 517-534 (1979).

SPSS, Inc.: "Simple and Multiple Linear Regression," Chapter 12, In *SPSS Base 7.5 Applications Guide*, SPSS Inc., Chicago, IL (1997).

Spielberger, C.D., R.L. Gorsuch and R.E. Lushene: *The State-Trait Anxiety Inventory*, Consulting Psychologist Press, Palo Alto, CA, 1983.

Stemler, F.W., and F.N. Craig: Effects of Respiratory Equipment on Endurance in Hard Work. *J. Appl. Physiol.* 42: 28-32 (1977).

Thorne, D.R., S.G. Genser, H.C. Sing and F.W. Hegge: The Walter Reed Performance Assessment Battery. *Neurobehav. Toxicol. Teratology.* 7: 415-418 (1985).

Wilson, J.R., P.B. Raven, S.A. Zinkgraf, W.P. Morgan and A.W. Jackson: Alterations in Physiological and Perceptual Variables during Exhaustive Endurance Work while Wearing a Pressure-demand Respirator. *Am. Ind. Hyg. Assoc. J.* 50: 139-146 (1989).

Zimmerman, N.J., C. Eberts, G. Salvendy and G. McCabe: Effects of Respirators on Performance of Physical, Psychomotor and Cognitive Tasks. *Ergonomics.* 34: 321-334 (1991).