

Effects of PAPR Helmet Weight on Voluntary Performance Time at 80-85% of Maximal Aerobic Capacity

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ABSTRACT

Powered Air Purifying Respirators (PAPRs) sometimes locate weights of blower, batteries, and filter on the head. When recommending that more powerful equipment be used, the result is usually more mass carried on the head. To date, none have determined the performance time penalty caused by extra mass even though there are many reports to determine the metabolic effects of added weight on the head. This study was performed to evaluate possible work performance time using several helmet weights at 80-85% $\dot{V}O_{2\max}$. Nine subjects were tested with four weighted helmets of 0.54, 1.03, 1.85, and 3.36 kg. This study showed that performance time in minutes was linearly related to helmet mass:

$$t_{\text{perf}} = 20.25 - 2.552 \cdot \text{kg}$$

Each additional kilogram of mass resulted in 2.5 minutes less time. The comfort of the helmet also decreased as mass increased.

Keywords: respirator mask, ergonomics, work capacity, load

INTRODUCTION

Protective helmets are usually light weight (about 300g) and strong enough to provide head protection against dropped objects. When combined with protection against other health and safety risks (for example, respiration, vision, and hearing), the weight carried on the head can become burdensome. There are commercially-available powered air-purifying respirators (PAPRs) that locate the filter, blower, and battery in the helmet, thus placing the weight of these components on the head. Despite the fact that light loads placed on the head, high on the back, or otherwise distributed around the center of mass of the body, are carried relatively efficiently (Martin, 1985; Soule and Goldman, 1969), the extra weight does require additional energy expenditure. If an attempt is made to improve helmet PAPR respiratory protection, the additional hardware weight is likely to have some effect on work performance while wearing the device. The intent of this study was to determine how much penalty was to be paid for the recommendation of improved respiratory protection when the filters, blowers, and batteries are located in the helmet.

High work rates of about 80-85 percent of maximal aerobic capacity have been found to be the most sensitive range to test the respiratory burden of respirator masks (Johnson, 1991). Because the basic concept related to this study is a trade-off between the potential beneficial effects of increased blower flow rate and the burden of additional weight needed to power the blower, this study was conducted at the same high work rate that is used for respiratory testing of respirator masks.

METHODS

Nine volunteers agreed to take part in this investigation. Of these, six were males and three were females. Their ages ranged from 20 to 42, with average of 24.8 years and 7.8 years standard deviation. Their heights averaged $168 \text{ cm} \pm 12 \text{ cm}$ (std. dev.) with a 138-178 cm range. Their masses averaged $71.3 \text{ kg} \pm 13.6 \text{ kg}$, with range of 52.3 to 93.2. Their maximum oxygen uptakes averaged $3.01 \text{ L/min} \pm 1.02$, with range of 1.91-4.87 L/min. They can be described as young, healthy, and reasonably fit. They also had little or no previous experience with occupational helmet wear.

Participants were asked to report to the laboratory on five separate occasions to perform one maximal aerobic capacity test and four weighted-helmet sessions at 80-85% of maximal aerobic capacity. The test protocol was approved by the University of Maryland Institutional Review Board.

Maximal Oxygen Consumption

A Quinton (Bothell, WA) motorized treadmill was used to determine subject maximal aerobic capacity. The participant was allowed to warm-up at approximately 60% of his or her age-predicted maximal heart rate response. A brief stretching period was permitted immediately following the completion of the warm-up phase. Next, the participant was asked to wear a Hans Rudolph (Kansas City, MO) mask configured with a one-way breathing valve. This configuration permitted the collection of expiratory air, which was directed to a mixing chamber using a flexible airflow tube. A Fleisch pneumotach (Phipps and Bird; Richmond, VA) was used to measure expired airflow and a mass spectrometer (Perkin-Elmer 1100; St. Louis, MO) analyzed expiratory gas concentrations. A computer was used to determine oxygen consumption based on flow and gas concentration values.

Prior to the start of the experiment, a maximal oxygen consumption test ($\dot{V}O_{2\text{max}}$ test) was performed on each subject using a Quinton (Bothell, WA) motorized treadmill and a modified Bruce incremental treadmill exercise protocol. Subjects were asked to warm-up and stretch for approximately 5-10 minutes prior to the start of the test, and were then equipped with a Hans Rudolph (Kansas city, MO) one-way breathing valve configured with a rubber adaptable mouthpiece. This apparatus was interfaced with a standard Fleisch (Phillips and Bird, Richmond, VA) pneumotach and Perkin Elmer (Pomona, CA) model 1100 mass spectrometer to monitor continuous expired airflow.

The initial work rate was established at a speed and grade designed to elicit 60% of the participant's age-predicted maximal heart rate. The work rate was adjusted by increasing the treadmill grade (1-2%) and speed (0.09 to 0.13 m/sec) every third minute until the participant experienced volitional fatigue, failed to display a rise in oxygen consumption rate of $150 \text{ mL O}_2/\text{min}$ or more in accordance with the increase in work rate, or exhibited cardiovascular responses that contraindicated further assessment.

Helmet-Weight Sessions

Participants were asked to report to the lab on four separate occasions to exercise at 80-85% of maximal capacity while wearing a typical construction helmet (Model V-GARD; MSA, Pittsburgh, PA) modified with lead weights for helmet plus weight totals of 0.54, 1.03, 1.85, or 3.36 kg (Figure 1). The weights were located inside the helmets to minimize the possibility that the subjects could immediately recognize the treatment levels and adjust their efforts accordingly. All participants were asked to warm-up for approximately 5 minutes on the treadmill at 60% of his or her age-predicted maximal heart rate before they were given a weighted helmet. The order of the weights was randomized, and subjects could not tell the sizes of the weights from visual cues external to the helmets to minimize the possibility that the subjects could immediately recognize the treatment levels and adjust their efforts accordingly. A strap around the chin was used to help keep the helmets in place on their heads. Next, the participant was asked to begin walking on the motorized treadmill programmed at a work rate corresponding to the warm-up exercise intensity. The treadmill was adjusted to the appropriate exercise intensity (80-85% maximal oxygen consumption) during a 90 second ramping phase. Treadmill speed and grade to elicit 80-85% $\dot{V}O_{2\text{max}}$ were determined during the $\dot{V}O_{2\text{max}}$ test. Thereafter, treadmill speed and grade remained the same for each subject through the different treatments. Participants were asked to exercise at this

intensity until they experienced volitional fatigue or were no longer able to tolerate the helmet. Heart rate was continuously tracked during the session using a Hewlett Packard (Siemens, Andover, MA) Patient Monitoring System. Participants were asked to provide numerical subjective feedback on physical exertion and helmet comfort (appendix) every two minutes while performing the exercise task. The Borg Rating of Perceived Exertion Scale (6-20) was also periodically administered.

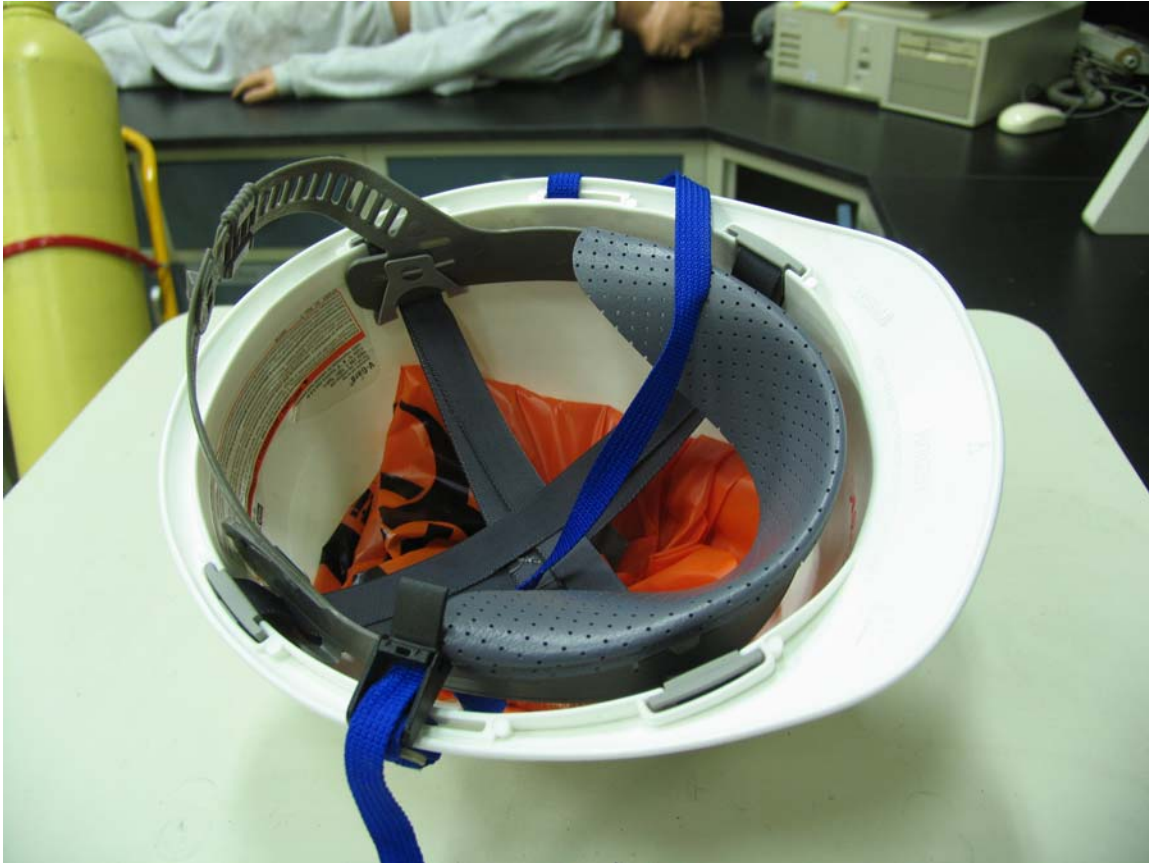


Figure 1. Photograph showing the inside of one of the helmets used in this study. Additional weight was affixed on the inside of the helmet where subjects could not immediately see which weight was being tested. The lead weight was enclosed in plastic and held in place with a bolt through the helmet.

Performance time data were analyzed with standard analysis of variance (ANOVA) procedures. The level of statistical significance was set at $p=0.05$ (probability of a Type I error is one out of 20). Pairs of means were tested with the Student's t-test. Linear regression was used to obtain the quantitative information that was the objective of this study.

Although it is not expected that helmet-placed hardware would ever be as heavy as the weights used in this study, a wide range of weights was used in order to give the best chance to separate weight effects from experimental variability. The applicable range of any conclusions drawn from these data would be wide enough to accommodate any realistic helmet weights commercially used.

RESULTS

In Figure 2 can be seen the decrease in performance times for the four weighted helmets. A linear least square regression line to describe the data was:

$$\text{time} = 20.25 - 2.552 * \text{kg} \quad (1)$$

Thus, each additional kilogram mass on the head could be expected to result in 2.5 min performance penalty at this rate of work.

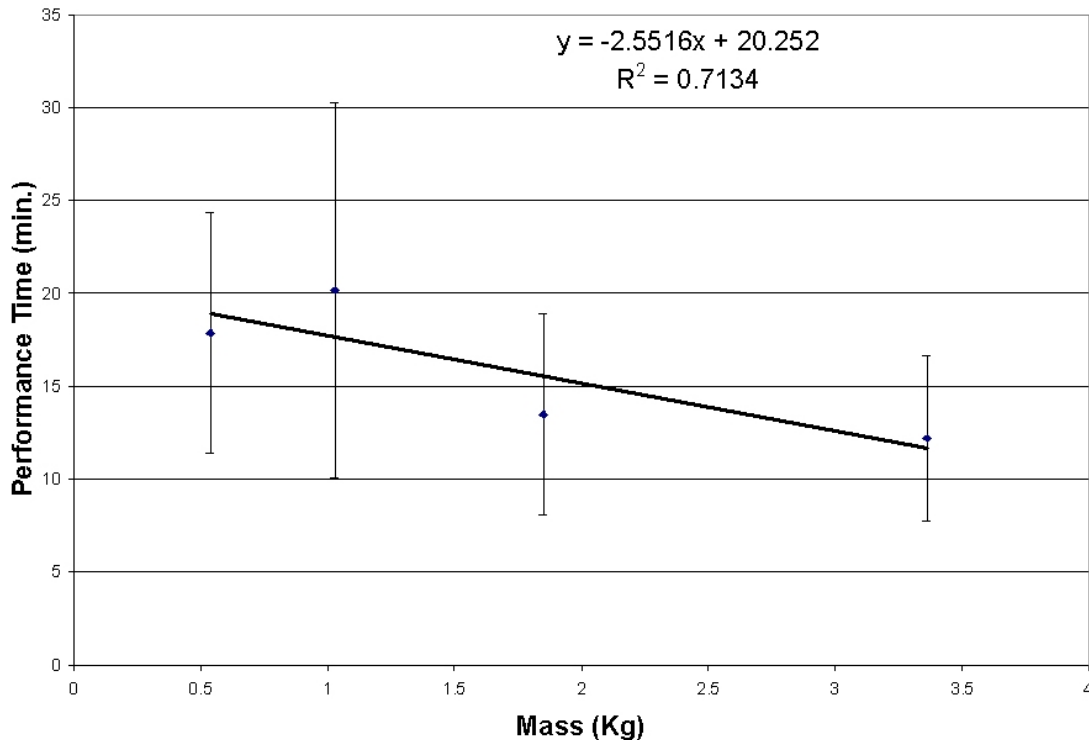


Figure 2. Average performance times for four different helmet weights.

An Analysis of Variance indicated that the different weighted helmet treatments affected performance times at a probability level of $p = 0.07$. This result did not meet the established level for statistical significance, but did show a tendency for different helmet weights to affect performance time. When performance times for pairs of means were tested with one-tailed t-tests, the only two that failed to achieve statistical significance of $p = 0.05$ were performance times with the two lightest weights, and the two heaviest weights. The other four paired comparisons were statistically significant.

A summary of test results appears in Table I. Helmet comfort degraded monotonically during the test for each helmet condition. Helmet comfort scale values taken four minutes into the test, when all subjects were still participating, show that helmet comfort degraded from an average of 6.1 (fairly comfortable) for the lightest helmet to 1.2 (very uncomfortable) for the heaviest. Helmet comfort values taken when subjects voluntarily terminated their tests ranged from 4.4 (neutral) for the lightest helmet to 1.4 (very uncomfortable) for the heaviest. An ANOVA relating helmet comfort at four minutes to helmet weight indicated that the effects were statistically highly significant ($p = 0.000007$). Paired t-tests indicated that all paired comparisons were statistically significant ($p \leq 0.05$). Termination helmet comfort values were also statistically significant ($p = 0.05$) but the only statistically significant paired comparisons were those involving the lightest helmet with each of the others.

Table I. Summary of Test Results

Helmet Weight (kg)	0.54	1.03	1.85	3.36
Performance Time	17.9	20.2	13.5	12.2
(min)	±6.5	±10.1	±5.4	±4.5
RPE (4 min)	14.3	14.1	15.3	15.2
	±1.3	±1.3	±1.5	±1.6
RPE (termination)	19.2	19.1	18.9	18.2
	±0.67	±0.78	±1.2	±1.3
Helmet Comfort	6.1	4.9	3.6	1.2
(4 min)	±1.8	±1.5	±2.1	±1.3
Helmet Comfort	4.4	3.0	1.7	1.4
(termination)	±3.0	±2.4	±1.6	±2.6

Values given are means ± std dev. All values were obtained from nine subjects.

One observation that could have some importance is that the helmets, especially the heaviest, often slipped to one side of the head or the other during testing. Thus, the chin strap was necessary to assure that the helmets stayed on the heads. Helmet slippage however, may have contributed to lower comfort values.

Ratings of Perceived Exertion (RPE) at four minutes were nearly indistinguishable for all helmet conditions. The same was true for termination values. Normally, if there was an RPE difference to be seen, it would have been seen before termination. Equal values at termination indicate equal effort by subjects, and values are usually close to maximum (18-20). These values indicate that helmets had little effect on the effort invested by the subjects.

DISCUSSION

Data from this simple test has provided the information needed to make recommendations to improve protection of wearers of multifunction PAPRs. For instance, one commercially-available multifunction PAPR is the Centurion MAX (Martindale Protection, Norfolk, UK) worn voluntarily by some U.S. coal miners. This PAPR includes a helmet, eye-protection visor, hearing protection, and respiratory protection against dust. A blower, battery, and filter are located in the helmet. This entire apparatus weights 1.7 kg. Our data would indicate that the penalty for working intensely while wearing the Centurion MAX is about 4 min. If additional respiratory protection were to be added, increasing the size and weight of the blower, battery, and filter, then an additional performance penalty of about 2.5 min. could be expected for each one kilogram increment in mass. Given that people would be expected to be able to work at 80-85% $\dot{V}O_2$ max for 15-25 minutes, this additional time penalty can be significant.

This study was conducted at an exercise rate (90-85% $\dot{V}O_2$ max) that is normally used in our laboratory for respiratory stress (Johnson, 1991; Johnson et al., 2005A). Work at this intensity cannot be sustained for a very long time, and thus is not representative of average work activities. Work rates can, however, peak this high during periods of high exertion, and these are often critical to work performance or even survival. Immediately coming to mind are fire fighting and military operations. There are times, as well, that miners or construction workers must work very hard. It is during these periods of intense activity that weight of equipment located on the helmet can be important.

Although the rate of work used in this study was high, it is at this high rate of work that additional respiratory protection would be most needed. Previous studies have shown that peak inspiratory flow rates at 80-85% $\dot{V}O_2$ max can be expected to be up to 440 L/min (Johnson et al., 2005A). The Centurion

MAX has been found to deliver about 110 L/min (Mackey et al., 2005), producing a shortfall of about 330 L/min. The result is that unfiltered air is supplied to the wearer from outside the visor.

It is always instructive to compare one's test results against others in the literature. Carrying weights, including on the head, has been the subject of many previous studies. These, however, have been concerned mostly with metabolic effects and not with performance times. Human load carrying is important for certain underdeveloped regions of the world (Heglund et al., 1995; Maloiy et al., 1986; Charteris et al., 1989; Datta et al., 1975; Malville et al., 2001) and the military (Stevenson et al., 2004; Reid et al., 2004; Knapik et al., 2004; Stauffer et al., 1987). As long as the weight is carried such that force it represents falls within the center of mass of the body, most investigators have found no additional metabolic penalty of the load other than the actual cost of the load (Maloiy et al., 1986; Soule and Goldman, 1969); that is, a load representing 20% of body weight increased the rate of energy consumption by 20%. Carrying loads outside the body center of mass was accompanied by increased cost (Abe, et al., 2004).

Under certain circumstances, however, an increase in load carried was not accompanied by increased oxygen consumption. Certain African women who carry loads routinely on their heads have apparently developed biomechanical adjustments that allow them to carry up to 20% of their body weights without additional energy cost (Heglund et al., 1995; Maloiy et al., 1986; Charteris et al., 1989). For loads greater than 20% of body mass, the first 20% can be subtracted from the load cost. There also appears to be an interaction between load carried and walking speed (Abe et al, 2004; Griffin et al., 2003).

Although results in Figure 2 might suggest a nonlinear relationship between helmet weight and mean performance times, a simple linear relationship was used because of several reasons. First, the large variances of the results, and, second, the small number of conditions make it hard to justify more complex mathematical treatment. Increases in oxygen consumption accompanying greater carried weights would, perhaps, be reason to fit the data with a hyperbolic relationship, but, again, such an expression would be highly speculative.

If the regression line in Figure 2 is extrapolated back to zero mass carried, then unencumbered performance time would have been about 20.3 min. The heaviest helmet reduced performance time to 12.2 min, a 60% decrease. Because the previous references related to energy expenditure and not the maximum time that the load could be carried, there is no real comparison that can be made.

To investigate this issue quantitatively, we can use the Kamon formula that relates time to exhaustion to relative oxygen consumption (Johnson, 1991):

$$t_{\text{exh}} = 120 \left(\frac{\dot{V}O_{2\text{max}}}{\dot{V}O_2} \right) - 117 \quad (2)$$

where t_{exh} is in minutes.

Average $\dot{V}O_{2\text{max}}$ for our subjects was 3.01 L/min, and unencumbered subjects would perform (t_{exh}) for 20.3 min (extrapolated). Thus, the estimated average oxygen consumption ($\dot{V}O_2$) for the unencumbered condition calculates to be 2.63 L/min. This turns out to be $2.63/3.01 = 87\% \dot{V}O_{2\text{max}}$, which is nearly equal to the target work rate of 80-85% $\dot{V}O_{2\text{max}}$.

Obviously, subjects in this study did not react as those African women. The heaviest weighted helmet was 3.36 kg, or 5% of average body mass. Adding 5% to the estimate of the unencumbered oxygen consumption gives $(2.63)(1.05) = 2.76$ L/min for the heaviest helmet. Plugging this back into the Kamon formula gives a performance time (t_{exh}) of 13.8 min. The actual average performance time for this condition was 12.2 min. There is an apparent $(13.8 - 12.2)/13.8 = 11\%$ performance time penalty for carrying the heaviest weight on the head compared to the predicted value. The oxygen consumption value that gives a performance time of 12.2 min is 2.80 L/min, or a $(2.80 - 2.63)/2.80 = 6\%$ increase in oxygen consumption for a 5% increase in mass carried. Results of these calculations are encouraging because the values are reasonable.

CONCLUSION

Voluntary performance time decreased as the mass held on the head increased. Each additional kilogram mass decreased average performance time by about 2.5 min.

Acknowledgements

This work was funded in part by the National Institute for Occupational Safety and Health (NIOSH Contract 200-2002-00531).

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Appendix

Helmet Comfort Scale (Johnson et al., 2005B)

10	very, very comfortable
8	very comfortable
6	fairly comfortable
4	fairly uncomfortable
2	very uncomfortable
0	very, very uncomfortable