

Using Self-Contained Self-Rescuers at High Work Rates

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ABSTRACT

The CSE SR-100 Self-Contained Self-Rescuer (SCSR) is intended to supply oxygen to wearers in hazardous atmospheres during emergency situations. Used properly, the wearer should only move slowly and cautiously in order for the SCSR to deliver oxygen for at least 60 minutes. It is possible, however, that during a dire emergency some wearers may try to stretch the capabilities of the SCSR beyond its limits. To investigate the consequences of doing so, one subject walked on a treadmill at five different work rates corresponding to 65, 70, 75, 80, and 85% of maximal oxygen consumption. Attainable run times with the SCSR were much shorter than they would have been without the SCSR, being 45.7, 40.5, 28.4, 10.4, and 6.5 minutes for the five work rates. The amounts of oxygen delivered to the subject were 88, 84, 63, 25, and 16 L. Additional generated oxygen was lost to the atmosphere. It was concluded that using the SCSR outside of its recommended range incurs severe penalties.

Keywords: emergencies, hazardous atmospheres, oxygen consumption

INTRODUCTION

Self-Contained Self-Rescuers (SCSRs) are devices meant for emergency use in mine disasters when atmospheric oxygen levels reach dangerously low levels or a mine fills up with toxic gases. SCSR's supply chemically-produced oxygen at a rate determined by the quantity of exhaled moisture and carbon dioxide. They may be worn on the belt or may be strategically placed in mines for ad lib use.

Use of SCSR's requires that wearers walk at a controlled pace in order that their oxygen demands not outpace the rate of oxygen supply. Training for correct donning and use is necessary if successful operation is to be expected.

The CSE (Monroeville, PA) SR-100 SCSR is intended to be used at a low-to-moderate work rate, where respiratory minute volume is roughly linearly related to oxygen consumption. The SR-100 contains potassium superoxide that releases oxygen when it comes in contact with exhaled moisture. As long as minute volume is not too great, oxygen is generated at a rate only slightly greater than necessary for exercise metabolic needs. At high work rates, respiration is stimulated and hyperventilation ensues. This has the effect of releasing more oxygen than can be consumed, and excess oxygen is spent into the atmosphere.

It was thus expected that using the SR-100 at oxygen consumption rates higher than recommended would result in much shorter durations of oxygen generation. This test was performed in order to test the device and the wearer to determine what can be expected when the SCSR is used at rates exceeding those recommended.

METHODS

One participant was asked to report to the laboratory on 5 separate occasions to exercise on a motorized treadmill at randomly assigned work rates corresponding to 65, 70, 75, 80, and 85% of maximal oxygen consumption while wearing a CSE self-contained self-rescuer. The subject was a 23-year-old female experienced in exercise testing with a height of 168 cm, mass of 66 kg, and maximum oxygen uptake of 3.0 L/min (BTPS). She was instructed in the proper use of the CSE SR-100 (CSE). 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 maximal aerobic capacity. The participant was allowed to warm up for approximately 5 minutes at a work rate corresponding to approximately 60% of her age-predicted maximal heart rate response. A brief stretching period was permitted immediately following the completion of the warm-up period. Next, the participant was fitted with a Hans Rudolph mask configured with a one-way breathing valve. This apparatus permitted the collection of expiratory air, which was directed to a mixing chamber using flexible airflow tubing. The mixing chamber was adapted with a Fleisch #3 (Phipps and Bird; Richmond, VA) pneumotach to assess airflow, and a capillary tube interfaced to a mass spectrometer for the assessment of expiratory gas concentrations. A computer was used to calculate oxygen consumption based on the flow and gas concentration values.

Maximal aerobic capacity was determined by gradually adjusting the work rate every third minute until the participant reached volitional fatigue or failed to display a rise in oxygen consumption rate corresponding to the increase in work rate. The initial work rate was set at 60% of the participant's age-predicted heart rate and was adjusted every third minute by increasing the speed (0.09-0.13 m/sec) and or grade (1-2%).

The maximum oxygen uptake test was used to identify treadmill speeds and grades to be used for later treatment work rates. These were determined at submaximal stages of the test. Heart rates and respiratory minute volumes were also determined at this time.

Test Procedure

The participant performed a brief warm-up and stretching period prior to donning the SCSR. The warm-up phase was conducted on the treadmill with the speed set at 1.6 m/sec and lasted for approximately 5 minutes. Next, the participant was fitted with the SCSR. Previously, participants have reported sensing heat generated by the unit that produced considerable discomfort to the area where the equipment contacted the body (Johnson et al., 2006). Our findings suggest that the temperature of the unit's outer shell exceeded 50 C. To attenuate this heat stress, a small towel was attached to the unit to insulate the participant.

The participant was instructed to activate the CSE unit by exhaling into the SCSR and by pulling the unit's ripcord attachment. A nose clip was positioned on the subject's nose and the participant was asked to inhale and exhale through the unit. The participant was allowed to develop a comfortable breathing pattern for approximately 60-90 seconds before the work rate was gradually increased to the target. The initial treadmill work rate was set at 1.3 m/sec (about 50% $\dot{V}O_2$ max) and was gradually adjusted over 5 minutes to the pre-determined exercise intensity (65, 70, 75, 80, or 85% $\dot{V}O_2$ max). The start of the performance time began when the target intensity was reached. The participant was asked to exercise at this exercise intensity until she reached volitional fatigue.

Heart rate was measured using surface skin electrodes and a Hewlett Packard (Siemens; Andover, MA) Patient Monitoring System. The participant was asked to provide subjective feedback on perceived exertion and breathing apparatus comfort. Exertion measurements (RPE) were assessed using the Borg Rating Scale (6-20). Breathing comfort (BACS) was determined using a scale with numerical values ranging from 0-10 with the number "10" representing very comfortable and "0" indicating

very uncomfortable. The participant was asked to provide reasons for requesting to terminate the session, and these were recorded.

RESULTS

Results appear in Table I. Experimental data consisted of testing conditions, performance times, and subjective responses. For most tests, the subject reported that lack of volume from the SCSR was the cause of exercise termination. Performance times decreased linearly as oxygen consumption increased (Figure 1). None of these times reached the 60 minutes that the SCSR is supposed to supply oxygen, so all work rates were higher than recommended for use with the SCSR. A work rate of 65% $\dot{V}O_2$ max would be considered to be moderate and a work rate of 85% $\dot{V}O_2$ max would be considered heavy. Performance times for these two work rates ranged from about 46 minutes to about 6 minutes. Termination values of the Rating of Perceived Exertion (RPE) and Breathing Apparatus Comfort Scale (BACS) are nearly the same across all work rates, indicating approximately the same degree of effort and subjective feeling for all conditions. The same two scale readings at 6 minutes distinguish among treatments.

Table I. Test Results

Experimental Data									
Relative Oxygen Consumption	Treadmill Speed	Grade	Oxygen Consumption	Performance Time	Minute Volume	RPE		BACS	
						6 min	term	6 min	Term
65%	1.8	3.0	1.92	45.7	50	13	20	5	2
70%	1.8	3.5	2.07	40.5	56	12	19	5	0
75%	1.9	4.0	2.22	28.4	62	15	20	3	0
80%	1.8	5.0	2.37	10.4	68	15	19	2	0
85%	2.0	4.0	2.52	6.5	75	19	20	1	1

Calculated data appear in the Table II. Unencumbered performance time was calculated from the Kamon formula (Johnson, 1991):

$$t_{\text{perf}} = 120 \left(\frac{\dot{V}O_2 \text{ max}}{\dot{V}O_2} \right) - 117 \quad (1)$$

where t_{perf} is the performance time in minutes. The time penalty is the difference between the measured performance time and performance time calculated from equation (1), assuming that the subject would have walked for the calculated time if not for the SCSR. The absolute time penalty paid for wearing the SCSR was very roughly the same for all rates of work; the relative time penalty accelerated as the rate of work intensified. Distance walked was calculated as the measured performance time multiplied by the treadmill speed. Oxygen used was calculated as the rate of oxygen consumption multiplied by the measured performance time. The more intense the rate of work, the smaller was the amount of oxygen that the SCSR supplied to the subject. The remainder, or the difference between the capacity of the

SCSR to generate oxygen and the oxygen used by the subject, was presumably blown off into the atmosphere or remained in the apparatus if the subject stopped before it was empty.

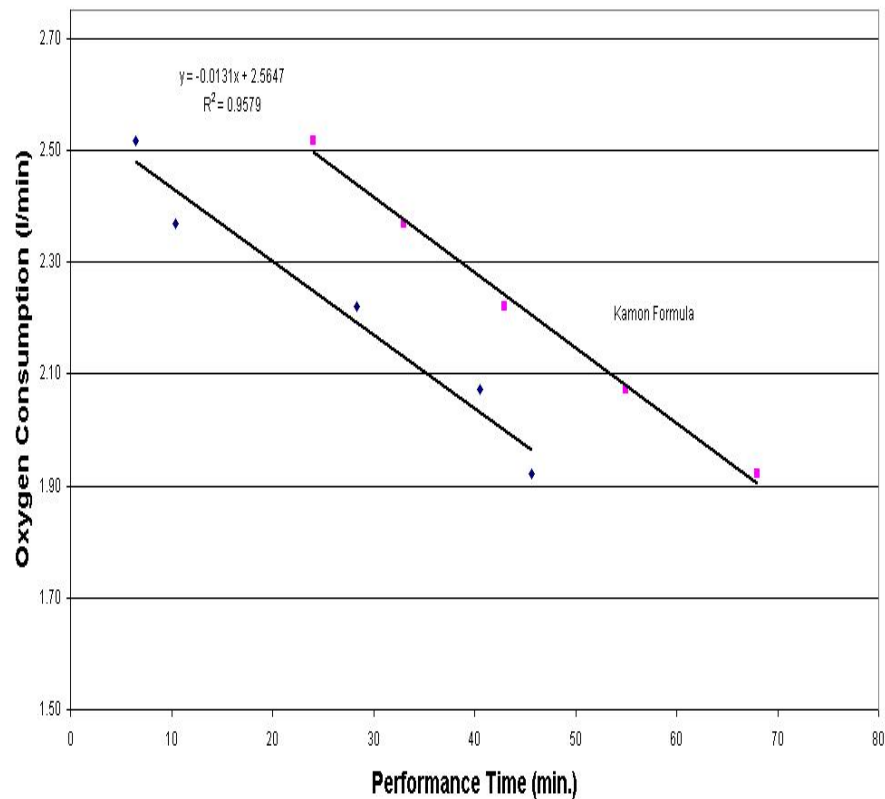


Figure 1. Performance times for each rate of work. The line on the left is the performance time while wearing the SCSR. The line on the right is performance time calculated from the Kamon formula for an unencumbered condition. Despite the fact that the Kamon formula plots as a hyperbola over a wide range of oxygen consumption values, it plots nearly linearly over this range.

Table II. Calculated Data

Performance Time (min)	Time (min)	Penalty (%)	Distance Walked (km)	Oxygen Used (L)
68	24	35	4.8	88
55	15	27	4.3	84
43	15	35	3.2	63
33	23	70	1.1	25
24	18	75	1.0	16

The subject reported that the SCSR felt very uncomfortable. The air was very warm; breathing was difficult, and rapid shallow breaths were required; the nose clip repeatedly slipped from its proper position; the mouthpiece was uncomfortable and caused saliva accumulation; and the weight of the unit on the chest felt constrictive. The subject declared the use of the SCSR to be an unpleasant experience.

DISCUSSION

Although the SCSRs in these tests were used at rates far exceeding those recommended, it is not unimaginable that wearers stressed by emergency situations could lack the self-control to pace themselves as they should. Especially when panicked, some people may attempt to distance themselves from danger as quickly as possible. Results from this experiment demonstrate how erroneous that course of action would be. The penalty for rushing is a device that is much more uncomfortable (as indicated by the BACS scores), an effort that is more difficult (as indicated by the RPE scores), a much lower amount of accessible oxygen, and a consequently much shorter performance time. If this wearer could have reached her target location in about 6 minutes or less, meaning that the distance to be traveled was one km or less, then she could have reached safety within the limitations of the device and her own need for oxygen by walking or running at a very high rate. If the distance to be traveled was only a little farther than that, but the atmosphere was still deadly, then she would have been found later not too far from her goal. The penalty for misjudgment is very severe. This points out the fact that it is much better to use the SCSR as intended because at a moderate walking pace she could have traveled 4.8 km in 46 minutes. At a slightly slower pace, the distance that could have been covered would have been farther and the time longer (Johnson et al., 2006).

The subject who performed in this experiment had a maximum oxygen consumption of 3.0 L/min, which is very close to the expected average value for the adult population. She was thus likely to exhibit typical responses to the SCSR.

The Kamon formula for calculating aerobic exercise performance times has generally been found to give reasonably good estimates. These times are relevant here because, under normal circumstances, this subject would have expected to be able to walk for the calculated times at the given work rates. Without a familiarity with the SCSR, she would not have known how to judge her endurance with the device. Her basis for judgment would have been her past experience, and that would have been in error by an average of 48%, or 75% at the highest exercise rate tested here. If you think you can walk for 24 minutes, and you can only walk for 6 minutes, then that could be quite a surprise. Training is a must!

Calculations of the amounts of oxygen supplied to the subject by the device assume that the subject was in the same metabolic state at termination for each level of work. Normally, this would not be the case over the full work rate range tested here. The maximum oxygen deficit (Johnson, 1991) would certainly have been reached for the 85% $\dot{V}O_2$ max condition, but it is questionable whether the maximum oxygen deficit would have been reached for the 65% $\dot{V}O_2$ max condition without the SCSR. This means that, without the SCSR, the anaerobic state of the subject would have been more extreme for the more intense work rate.

With the SCSR, however, exercise termination might have been due to limited oxygen supply, almost as if $\dot{V}O_2$ max for the subject decreased toward the end of each bout of exercise. Oxygen deficit would have accumulated during the final minutes of testing no matter what the intensity. Thus, it is possible that the subject had reached her maximum oxygen deficit for all test sessions. Whether or not maximum oxygen deficit assumed the same value for all these sessions is not known, but at least the subject can be assumed to be in a similar physiological state at termination of each test session.

The CSE SR-100 SCSR generates oxygen by a chemical reaction involving moisture in the exhaled breath. At low to moderate exercise rates, exhaled minute volume is proportional to the rate of work, so the greater need for oxygen is matched by the greater capacity of the device to generate oxygen. At work rates above the anaerobic threshold, minute volume increases disproportionately with work rate, and so the greater the work rate, the higher is the excess amount of oxygen generated. Extra

oxygen that cannot be used by the wearer, and cannot be stored in the SCSR, must be lost to the atmosphere during exhalation. That is why the SCSR needs to be used at very low rates of work, where oxygen use can be matched by oxygen generation.

If the subject stopped exercising before the SCSR was empty, then some of the oxygen-generating capacity would have remained in the apparatus. Slowing or stopping, and allowing breathing to slow, then would have made it possible for the SCSR to continue supplying oxygen. Based on the subject's comments at exercise termination, it is unlikely that a large oxygen capacity remained in the device, at least for the four less severe work rates.

This subject used the same type SCSR for a self-paced test (Johnson et al., 2006), and for that test she adjusted her walking speed to a great extent. She was not allowed to adjust her speed for this test. If she had been able to do so, we could have definitely been able to determine if some oxygen generation capacity remained in the device. As it is, no such definite answer can be given.

Human subjects sense high breathing pressures, high temperatures, and a vague feeling of insufficiency due to high CO₂ levels. The SR-100 exhibits both high breathing pressures and high CO₂ levels, especially at high work rates. Stopping a test for high pressures or high CO₂ levels, however, does not necessarily imply an expended chemical bed. The subject stopped the testing because of high stressor levels, not necessarily because the apparatus was expended. High stressor levels could have prevented the subject from utilizing the full capacity of this SCSR.

Although this experiment was conducted outside the recommended limits of the SCSR, it did yield useful information. It was confirmed that the SCSR must be used as intended. It was also shown how much penalty can be expected if the SCSR is used outside its range. Given that there is some inefficiency to all training programs, some potential wearers may be tempted to don the SCSR during an emergency and bolt for the nearest exit. Given the results shown here, the nearest exit may not be near enough.

CONCLUSIONS

The SCSR should not be used at very high rates of work. When it is, the penalty can be very severe.

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