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ORIGINAL RESEARCH ARTICLE

Incremental exercise test performance with and without a respiratory gas collection system

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Abstract

Objective. Despite their widespread use in exercise testing, few data are available on the effect of wearing respiratory gas collection (RGC) systems on exercise test performance. Industrial-type mask wear is thought to impair exercise performance through increased respiratory dead space, flow resistance and/or discomfort when compared with RGC facemasks, but whether performance decrements exist for RGC facemask wear versus non-wear is unclear. The objective of this study was to evaluate the difference in incremental exercise test performance with and without a RGC system.

Design. Twenty moderately active males (age 21.0 ± 1.9 years; VO_{2peak} 55.9 ± 3.0 $ml\cdot kg^{-1}\cdot min^{-1}$) performed two progressive treadmill tests to volitional exhaustion. In random order subjects ran with (MASK) or without (NO-MASK) a RGC facemask and flow sensor connected to a gas analyzer. Descriptive data (mean ± SD) were determined for all parameters. The Wilcoxon signed rank test for paired differences was used to assess mean differences between MASK and NO-MASK conditions.

Results. Exercise time to exhaustion, peak treadmill speed, peak blood lactate concentration, peak heart rate and rating of perceived exertion (RPE) were not different ($p>0.05$) between MASK and NO-MASK conditions.

Conclusions. Incremental exercise test performance is not adversely affected by RGC and analysis equipment, at least in short duration progressive treadmill exercise. Respiratory gas analysis during exercise testing for diagnostic, performance assessment or training prescription purposes would appear to be unaffected by RGC systems.

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Introduction

Exercise testing with respiratory gas collection (RGC) and analysis during indirect calorimetry has long been a routine procedure in exercise physiology laboratories, enabling the simultaneous measurement of respiratory, cardiovascular and metabolic variables.[24] In a clinical setting, risk assessment or diagnosis in patients with known or suspected cardiopulmonary disease is aided by data obtained from respiratory gas analysis during exercise.[29] In sport science laboratories, performance assessment of athletes like runners, cyclists and rowers is frequently performed using respiratory gas analysis to monitor training status, evaluate programme efficacy or formulate individual training recommendations.[24] However, practical application of measures such as maximal oxygen uptake (VO_{2max}) and mechanical efficiency rely not only on accurate gas analysis during exercise, but also on the premise that RGC does not influence exercise test performance.

A range of RGC and analysis systems are available to measure airflow, gas concentrations, and other respiratory variables in the laboratory or field.[24] Yet a compulsory element of all systems remains the need for a facemask or mouthpiece to physically sample expired air. Traditionally this involved a mouthpiece and nose clip, but the oro-nasal facemask has become an increasingly common method of gas collection. A frequently encountered query in practice relates to the effect which the wearing of RGC equipment has on exercise test performance. Common criticisms include poor comfort and fit, difficulty breathing and increased anxiety.[2,5,10,28] Following exercise testing, many individuals complain of an inability to produce true all-out effort performances while wearing the apparatus needed to assess performance from a respiratory or metabolic perspective (Clark: unpublished observations). Factors implicated in limiting exercise while wearing RGC and analysis systems include the increased dead space and flow resistance they impose.[6,14,20] It is also difficult to dismiss the possibility of a psychological effect on exercise performance as a result of wearing such apparatus.[5] This raises the concern that exercise testing with RGC systems may not produce truly representative exercise data, potentially affecting the accuracy and value of subsequent performance analysis, training prescription or diagnosis.[5,10]

The effect of wearing standard RGC equipment, as used in exercise testing, has been the subject of studies before, but these have been limited to comparing one or more gas collection methods rather than comparing mask wear with non-wear.[2,3,13,15,28] The aim of this study was therefore to compare incremental exercise test performance, physiological response and perceived exertion of subjects with and without a RGC facemask and flow sensor system.

Methods

Subjects

Twenty male physical education students with no history of respiratory or cardiovascular disease volunteered for the study. Table I lists subject physical characteristics. All were healthy, moderately active young men engaging in physical activity involving running, cycling and/or resistance training 3 - 4 days per week. Subjects were briefed on the study purpose and procedures before giving written informed consent. The experimental protocol was approved by the Research Ethics Committee of the University of Pretoria.

Procedures

Each subject reported to the laboratory on three occasions, each separated by 4 - 7 days. Testing sessions were conducted at the same time of day on each occasion. Subjects were instructed to arrive well rested, well hydrated, approximately 3 hours post-prandial, and to avoid caffeinated food and beverages on the day of testing. Participants were also required to maintain their normal dietary and physical activity patterns during the study, and to avoid exercise on the day prior to, as well as on the day of exercise testing. The first session involved anthropometrical measurement and familiarisation with the RGC equipment and test procedures. The latter included verbal explanation of the procedures, attachment of the facemask and flow sensor, and a 15-minute treadmill run at 10 $km \cdot h^{-1}$.

TABLE I. Subject physical characteristics (*N*=20)

Characteristic	Mean	SD	Range
Age (years)	21.0	1.9	18.0-25.0
Body mass (kg)	73.8	3.6	61.6-78.8
Stature (cm)	177.8	4.9	170.1-187.3
%BF	14.4	3.1	9.9-22.1
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	55.9	3.0	51.9-62.0

%BF = estimated percentage body fat (Durnin & Womersley, 1974); VO_{2peak} = peak oxygen uptake.

Anthropometry

Body mass (Tanita BF-350 electronic scale, Tanita Co., Tokyo, Japan), stature (Seca 214 stadiometer, Seca Co., Hanover, USA) and skinfold thickness (Harpenden caliper, British Indicators, West Sussex, England) were measured at the first testing session. The Durnin and Womersley[12] method was used to predict body density and percentage body fat (%BF) was estimated using the Siri formula described by Lohman.[22]

Incremental exercise tests

Subjects performed a continuous progressive treadmill test (STM-55, Quinton Instrument Co., Bothell, WA, USA) to volitional exhaustion on each of the two remaining visits to the laboratory. Following 5 minutes of light stretching subjects ran for 5 minutes at 10 $km \cdot h^{-1}$ to warm up. Thereafter, treadmill speed was increased by 1 $km \cdot h^{-1}$ each minute and treadmill grade by 0.5% every 2 minutes. Subjects were instructed to provide a maximal effort and verbal encouragement was provided throughout the test. One test involved gas analysis using a RGC facemask and flow sensor (MASK condition) connected to an automated gas analyser while the other test was performed without any gas collection or analysis equipment (NO-MASK). Exercise was conducted in an air-conditioned room (~21°C, 50% relative humidity) and both temperature and barometric pressure (~665 mmHg) recorded at the start of each test. The order of the tests was randomised to eliminate any learning effect on test performance over the two trials. Laboratory technicians were blinded to the study hypothesis as well as to the subjects' prior performances during the second tests.

During MASK testing, a form-fitting silicone rubber Hans Rudolph 7400 series Vmask^{TM} facemask (Hans Rudolph, Inc., Shawnee, KS, USA) was attached to the subject's face using standard mesh headgear. All subjects in this study were appropriately sized for using the small-size facemask with a mask-sizing caliper from the same manufacturer. A 22-mm internal diameter plastic straight swivel port was attached to the mask for a mask plus adaptor dead space volume reported by the manufacturer to be approximately 89 ml. The mask assembly was fitted to the subject and completely sealed, allowing air movement only through the port at the front of the mask. A custom-made silicon adaptor was used to attach the port to a Silverman-type Blendenspiroeptor flow sensor (Ganshorn Medizi, Niederlauer, Germany) with a dead space of 55 ml and flow resistance of <1.0 cm $H_2O \cdot l^{-1} \cdot s^{-1}$ according to the manufacturer. This resulted in a combined dead space for the mask plus flow sensor system of approximately 150 ml.

Pulmonary gas exchange and ventilation were analysed with an automated ergo-spirometer (Schiller CS-200, Ganshorn Medizi, Niederlauer). During MASK tests, oxygen uptake (VO_2), carbon dioxide production (VCO_2), minute ventilation (V_E), respiratory rate (f_R) and tidal volume (V_T) were monitored continuously and recorded every 10 seconds. Peak oxygen uptake (VO_{2peak}) and peak ventilation (V_{Epeak}) were recorded as the highest VO_2 and V_E respectively, averaged over 30 seconds during the test. During both MASK and NO-MASK tests, heart rate (HR) was monitored continuously using

TABLE II. Difference in incremental exercise test performance with (MASK) and without (NO-MASK) a respiratory gas collection system

	Time (s)		Speed (km.h^{-1})		HR_{peak} (beats.min^{-1})		$[La^-]_{peak}$ (mmol.l^{-1})		RPE	
Subject	MASK	NO-MASK	MASK	NO-MASK	MASK	NO-MASK	MASK	NO-MASK	MASK	NO-MASK
1	617	614	15.0	15.0	207	210	9.4	9.0	16	17
2	728	726	17.0	17.0	201	198	14.3	12.2	17	17
3	677	672	16.0	16.0	190	188	12.3	13.4	18	18
4	709	672	16.0	16.0	189	186	14.3	11.0	19	19
5	699	719	16.0	16.0	188	188	15.8	15.7	18	19
6	883	842	19.0	19.0	190	185	13.3	9.1	18	18
7	734	746	17.0	17.0	196	192	12.0	11.0	17	17
8	615	654	15.0	15.0	190	194	12.9	13.0	17	18
9	682	676	16.0	16.0	190	188	12.7	11.0	18	17
10	613	596	15.0	14.0	212	209	9.6	8.1	18	19
11	675	666	16.0	16.0	203	206	10.2	12.4	18	18
12	634	616	15.0	15.0	201	198	9.6	9.2	17	18
13	677	681	16.0	16.0	205	207	10.9	13.0	19	18
14	670	673	16.0	16.0	203	200	11.7	8.7	17	16
15	672	689	16.0	16.0	207	205	11.6	11.3	17	17
16	691	720	16.0	16.0	183	184	8.3	11.3	18	18
17	684	696	16.0	16.0	205	202	12.3	12.2	18	17
18	624	645	15.0	15.0	191	203	7.7	7.1	16	16
19	652	631	15.0	15.0	201	198	11.0	10.4	18	14
20	606	606	15.0	15.0	188	189	9.7	9.1	16	15
Mean	677.1	677.0	15.9	15.9	197	197	11.5	10.9	17.5	17.3
SD	61.6	57.0	1.0	1.0	8	9	2.1	2.1	0.9	1.3
p value*	0.984		1.000		0.221		0.100		0.593	

Time = treadmill exercise time to exhaustion; speed = peak treadmill speed; HR_{peak} = peak heart rate; $[La^-]_{peak}$ = peak blood lactate concentration; RPE = rating of perceived exertion.
* Wilcoxon signed rank test for paired differences (MASK v. NO-MASK).

an electrocardiograph. Peak HR (HR_{peak}) was recorded as the highest exercise HR averaged over 10 seconds. Exercise time was recorded as the time in seconds from the start of the treadmill until test termination by the subject. Peak treadmill speed was defined as the speed of the highest completed 1-minute exercise stage. During all familiarisation and test procedures the subjects had no access to any feedback or information regarding their performance or the elapsed time.

Blood lactate and perceived exertion

Capillary blood was obtained from an earlobe using standard procedures described by Maw *et al*.[25] Blood lactate concentration was measured using a Lactate Pro (Arkray Inc. Shiga, Japan) portable analyser. This was done at 2, 4, and 6 minutes following test termination. Peak blood lactate concentration ($[La^-]_{peak}$) was measured as the highest measured post-exercise blood lactate concentration. Immediately following termination of the treadmill test, subjects were asked to rate their overall level of exertion using Borg's rating of perceived exertion (RPE) 15-point category scale.[8]

Data analysis

Descriptive data (mean ± standard deviation (SD)) were determined for all parameters. The Wilcoxon signed rank test for paired differences (BMDP Statistical Software, Inc., Los Angeles, CA, USA) was used to assess mean differences between MASK and NO-MASK conditions as well as to assess whether there were significant differences between the first and second tests regardless of condition. Statistical significance was set at the 0.05 level.

Results

Table II displays the differences in exercise time, peak treadmill speed, HRpeak, $[La^-]_{peak}$, and RPE for each of the 20 subjects between the two test conditions. There were no significant differences between MASK and NO-MASK conditions for any of these variables. Comparisons between the first and second tests also revealed no significant differences (first v. second) in exercise time (677.7±64.0 v. 676.4±54.2 s; p=0.856), peak treadmill speed (15.9±1.0 v. 15.9±1.0 km·h^{-1}; p=1.000), HR_{peak} (197±8 v. 197±8 beats·min^{-1}; p=0.723), $[La^-]_{peak}$ (11.5±2.2 v. 10.9±2.0 mmol·l^{-1}; p=0.131) and RPE (17.5±1.0 v. 17.4±1.2; p=0.782). This suggests that there was no significant learning effect between the first and second incremental test.

Discussion

The major finding of this study was that there were no significant differences between MASK and NO-MASK conditions in incremental exercise test performance. This is different to the finding of Burkett and Porr,[10] who reported significantly shorter (~4%) exercise times with a RGC system in both male and female subjects. They concluded that wearing oxygen uptake measuring equipment clearly reduced treadmill running time and suggested that use of such equipment during exercise testing may produce inaccurate results.[10] The results of the present study show no impairment in exercise test performance in MASK compared with NO-MASK conditions, and suggest that concerns over failure to achieve 'true' exercise performances as a result of RGC system wear are unfounded. For example, mean exercise time differed by less than 0.1% between MASK and NO-MASK tests in the present study.

The effects of wearing full respirator masks,[11] gas masks,[17] military-type biological respirators,[19,20] and self-contained breathing apparatus[23] during exercise have been reported. However, these studies all compared exercise using these industrial-type masks with standard RGC systems. Results from these studies include reduced submaximal [17] and maximal V_E [11,17,19,20], f_R [11,17,20] and VO_{2max} ,[11,17] but increased submaximal HR[17] and VO_2[23] while wearing industrial-type masks. In contrast, Johnson *et al*.[20] found reduced submaximal

VO_2 while wearing a respirator mask and along with higher blood lactate concentrations prompted their suggestion of greater anaerobic metabolism during mask wear. However, ventilatory and lactate thresholds are reportedly not different between respirator and gas collection mask conditions.[11,20] Interestingly, Jetté *et al.*[19] found no difference in VO_{2max}, RER, time to exhaustion, perceived exertion, f_R and V_T during progressive treadmill exercise with and without a military-type respirator. However, as Johnson *et al.*[20] state, in practice it seems workers wearing masks like those described above cannot work as long or as hard as they can without masks.

It has been demonstrated that ventilation and the work of breathing during maximal exercise is non-fatiguing and sustainable.[1] However, mask-induced respiratory changes remain central in the explanations for impaired exercise performance during mask wear in the studies discussed above. First, an obvious difference between mask wear and non-wear is respiratory dead space. It has been shown, in horses[7,14,18] and humans,[26] that increased dead space during exercise results in increased V_T but not necessarily reduced f_R,[3] resulting in variable effects on alveolar ventilation. This altered breathing pattern is thought to be a consequence of increased P_aCO_2 secondary to end-tidal re-breathing, mediated via a chemoreceptor reflex[26] or as a result of sensory stimulation of the face, mouth and nose.[3] Secondly, inhalation and exhalation resistance to airflow are augmented by some mask types,[11,17] and subject secretions and condensation during exercise may add to the resistance of the mask and flow sensor system. Increased flow resistance stimulates a reduced f_R and increased V_T,[7] potentially increasing respiratory muscle work and the oxygen cost of breathing. Together, these factors might be hypothesised to alter breathing patterns, increase respiratory muscle perfusion, impair alveolar ventilation, and hamper CO_2 elimination and O_2 uptake, ultimately contributing to impaired exercise test performance.

Other less commonly recognised mechanisms have also been proposed to explain physical performance impairment during mask wear. Altered breathing patterns may disrupt the coupling of f_R to body movement, so-called 'entrained breathing' which is characteristic of some activities, preventing V_E from reaching a mechanical optimum, and limiting alveolar ventilation.[18] Also, the additional mass and dimensions of a mask and flow sensor system may alter body movement and exercise economy.[23] Finally, a psychological limitation to exercise may occur secondary to perceived discomfort, pain or anxiety, leading to the inability to produce a true maximal effort during exercise testing.[5] Many of these factors may be interrelated. For example, increased respiratory muscle work has been shown to add to the perception of dyspnoea, likely contributing to the overall perception of exertion and discomfort during exercise.[16]

Fundamental differences between the industrial-type masks discussed above and RGC facemasks used in laboratory exercise testing may explain the results of the present study. Protective masks typically have a dead space of 150 - 500 ml and flow resistance of 8.0 - 10.0 cm $H_2O \cdot l^{-1} \cdot s^{-1}$ compared with 70 - 150 ml dead space and 0.6 - 1.7 cm $H_2O \cdot l^{-1} \cdot s^{-1}$ resistance in a variety of RGC systems.[3,11,17,19,20] Furthermore, the positioning of large diameter outlets directly opposite and close to the mouth in gas collection masks may minimise the effective dead space and flow resistance markedly in comparison to the construction of industrial-type masks. Manufacturers have modified RGC systems over the years, yielding systems with smaller dead space, alternative mask sizes, additional sealers, lighter units, improved comfort and fit, and high-velocity low-resistance valves promoting laminar air flow. It is possible that modern RGC systems are far better tolerated than those used previously.

Pulmonary ventilation is generally not considered a limiting factor to maximal exercise performance in healthy, untrained, young subjects during dynamic exercise.[4] Nevertheless, it is possible that at high ventilations turbulent air flow through a modern RGC facemask may rise and subsequently raise flow resistance sufficiently to limit air flow and V_E, as is thought to occur in horses.[18] In humans, Bradley and Younes[9] reported that the effective dead space of five commonly used respiratory valves was V_T-dependent, approaching the measured dead space only at tidal volumes in excess of 2.0 l. Therefore, during high-intensity exercise, RGC mask wear may well alter breathing strategies in a similar manner to the industrial-type masks discussed previously. Since, by its nature, no respiratory measures (V_T, f_R, V_E, VO_2) are available for the NO-MASK exercise condition in the present study, and with no measures of blood gases, acid-base status or respiratory muscle work, the effect of wearing RGC systems on these physiological parameters remains unknown. One might speculate though that since exercise test performance was not different between MASK and NO-MASK conditions in the present study, the magnitude, and more importantly, the significance, of RGC system-induced changes in any respiratory parameter seem minimal.

Jetté *et al.*[19] reported reduced exercise blood lactate concentrations during mask-induced increases in flow resistance despite similar performance time and VO_{2max} measures. They proposed reduced lactate efflux or production due to altered extracellular or intracellular pH as possible reasons.[19] The present study found no differences in $[La^-]_{peak}$ between MASK and NO-MASK exercise. This supports the notion that a RGC system does not significantly alter lactate production or removal during incremental exercise.

The possible psychological effect of wearing any device on the head and face remains a difficult factor to eliminate. In order to monitor expired gas samples some form of gas collection unit close to the face is unavoidable. Burkett and Porr[10] used the traditional method of nasal constriction and a mouthpiece connected to a respiratory valve in their study, a procedure frequently described by subjects as interfering with swallowing, altering breathing patterns and increasing discomfort during exercise (Clark: unpublished observations). Several studies indicate no difference in exercise time, gas concentration, V_E, f_R, respiratory exchange ratio (RER) or HR between mouthpiece and facemask exercise in patients with heart failure,[5] pulmonary disease[28] and in well-trained subjects.[13,15] But a RGC facemask, as used in the present study, may be more comfortable than a mouthpiece during exercise,[15] particularly maximal exercise, possibly accounting for the difference in results from that of Burkett and Porr.[10] Whatever the discomfort or anxiety associated with mask wear, no effect was observed on exercise time, peak treadmill speed or RPE in the present study, suggesting that a psychological effect is either negligible or subject-specific.

A potential limitation of this study is that while RGC systems are generally worn for the full duration of clinical or athletic exercise tests, these are mostly progressive in nature and of short duration. Dyspnoea, or indeed any mechanism leading to fatigue supposedly due to mask wear, would only need to be tolerated for the final portion of the progressive test,[19] potentially delaying exercise termination in the present study. Longer exercise times and/or sustained high-intensity exercise with gas collection systems may produce different results.[17]

From this study it would appear that those factors which determine incremental exercise test performance without mask wear also do so during RGC mask wear. In other words, 'fitter' subjects perform better in incremental exercise tests whether they wear RGC equipment or not. This implies that any RGC system-induced changes are either too small to have any significant effect on test performance or that the mechanisms leading to test termination are independent of such changes. The results are particularly relevant because indirect calorimetry measures are frequently used to gauge or modify athletic performance or add diagnostic value for patients with known or suspected cardiopulmonary disease. In light of the results of the present study, practitioners should rest assured that RGC does not appear to impair exercise test performance, and probably does not significantly alter physiological response, thereby allowing the accurate assessment of physical performance comparable with mask-free exercise testing. One may speculate that if the work of breathing is indeed altered by RGC systems in some way, conditions in which ventilatory work is already high or cardiac reserve low may well produce impaired exercise test performance during mask wear. In elite endurance athletes who may approach their mechanical limitation to ventilation during maximal exercise[21] or exhibit arterial hypoxaemia,[27] increased dead space, work of breathing or altered breathing patterns associated with mask wear may affect exercise performance. Patients already limited by respiratory or cardiovascular function may also be less resistant to physiological perturbations brought about by wearing RGC systems, if indeed these occur. Further research involving these subject populations is required to more fully understand the effects of RGC systems.

Conclusions

The results of the present study do not support the notion of reduced exercise test performance while wearing a RGC system. These results are different to the findings of several studies investigating the effects of various industrial-type masks on exercise performance, and more specifically, contradictory to commonly held views of coaches, athletes and patients regarding exercise testing with gas collection apparatus. Further research incorporating measures of ventilation, blood gases, acid-base status and respiratory muscle work is needed to better describe the physiological effect of wearing RGC systems during exercise. Future studies should consider using more sustained, intense exercise protocols and subjects more widely believed to be at risk of developing respiratory limitations during exercise.

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