A modified SCBA facepiece for accurate metabolic data collection from firefighters

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To better assess the energy expenditure and exertion of firefighters during simulated firefighting activities, a commercial firefighter self-contained breathing apparatus (SCBA) facepiece was modified to interface with a portable metabolic monitoring device (Cosmed K4b2) while still functioning as a positive pressure SCBA air supply. To validate the device, standard National Fire Protection Association 1981 SCBA function tests were conducted and 14 subjects performed variable-workload assessments using all combinations of two test devices (Cosmed K4b2 and metabolic cart) and two masks (modified SCBA facepiece and stock manufacturer-supplied breath collection). Metabolic data collected with the Cosmed K4b2 via the modified facepiece were found to be accurate when compared to a ParvoMedics Truemax 2400 metabolic cart (average per cent difference: 4.6%). This modified facepiece design is suitable for use in metabolic studies requiring the utilisation of an SCBA system. Furthermore, the well-established overestimation of oxygen consumption from the Cosmed K4b2 system was replicated.

Practitioner Summary: The nature of a firefighters’ self-contained breathing apparatus (SCBA) prevents collection of respiratory metabolic data while the firefighter consumes air from the SCBA. This study introduces and validates a modified SCBA facepiece design integrating metabolic data collection tools with firefighting SCBA allowing for data collection across various firefighting activities.

Keywords: oxygen uptake; gas analysis; firefighting; self-contained breathing apparatus; respiration

1. Introduction

Firefighting demands high levels of exertion to complete necessary tasks on the fireground. However, overexertion on the fireground is the leading cause of injury for firefighters. Exhaustion or fatigue resulted in 2150 annual injuries to firefighters between 2005 and 2009, of which 25% were moderate or severe (Karter 2012). The high occurrence and high severity of overexertion injuries on the fireground demand further insight into the physiological strain and metabolic costs associated with firefighting.

1.1 Quantifying the physiological strain of firefighting

Numerous studies have examined the physiological strain and metabolic costs associated with firefighting. It is common and practical to collect heart rate data during either simulated drills (Duncan, Gardner, and Barnard 1979; Louhevaara et al. 1994) or live-fire operations (Sothmann et al. 1992; Del Sal et al. 2009) as this measurement does not require expensive or sensitive laboratory-grade equipment. While the chronotropic index has been used to estimate metabolic cost for firefighters working in laboratory activities (Smith et al. 2012) and during firefighting operations (Sothmann et al. 1992), this approach has important limitations when the firefighter is not in steady state.

Quantifying the amount and the intensity of work performed during firefighting activities is better accomplished by the indirect measurement of energy expenditure. The measurement of oxygen uptake calculated from volumetric breath analysis is currently the most common and well-validated laboratory technique employed to quantify energy expenditure during activities (Carter and Jeukendrup 2002). These devices generally direct exhaled breath from the subject’s nose and/or mouth via a mask or headgear through gas and flow analysers. Previous firefighter studies using this technique have generally collected metabolic data from subjects wearing manufacturer-provided metabolic-measurement masks while performing simulated firefighting activities carrying a self-contained breathing apparatus (SCBA) pack without the SCBA facepiece (Sothmann et al. 1990; Holmer, Kuklane, and Gao 2006; Dreger and Petersen 2007; Elsner and Kolkhorst 2008; Smith et al. 2012), with weighted vests to simulate gear and SCBA (Harvey et al. 2008; Huang et al. 2009), or without any...
gear or SCBA (Holmer and Gavhed 2007). However, none of these approaches allow for the collection of data during simulated firefighting while breathing from an open-circuit SCBA that delivers air into a mask that maintains positive pressure (i.e. being ‘on-air’). To accurately quantify the metabolic costs of firefighting, it is important to collect data during simulated firefighting activities while firefighters are on-air. Doing so provides air to the firefighter at controlled temperature and humidity conditions and consumes air contained in the high-pressure cylinder worn on the back. Consumption of the air lessens the weight on the back, which has been shown to significantly impact oxygen consumption (VO$_2$) and heart rate (Hooper, Crawford, and Thomas 2001; Park et al. 2010). Previous research has integrated SCBA with metabolic carts (Smith et al. 1995; Eves, Petersen, and Jones 2002; Dreger, Jones, and Petersen 2006) and even portable data collection systems (Williams-Bell et al. 2010); however, no known published journal articles have integrated and validated a portable metabolic measuring device with SCBA while allowing the firefighter to remain on-air.

The metabolic cart is a well-accepted tool for the collection of metabolic data. In the standard metabolic cart, atmospheric air is inhaled through a mouthpiece and all exhaled air is sent out the mouthpiece into a large base station via a set-length of hose. The base station consists of a flow meter (turbine), exhaled gas content analysers and a computer. Computerised algorithms calculate rate of VO$_2$, rate of carbon dioxide production (VCO$_2$) and other metabolic parameters based on volume, differences in the content of inspired (assumed gas fractions) and expired air and other parameters. The large size and immobility of such systems limit their use to specific laboratory settings that restrict range of motion and the types of activities that can be conducted, such as protocols based on a treadmill or stationary cycle ergometer.

Portable devices have recently been developed to increase possibilities of metabolic data collection in a greater variety of tasks. One common portable device used for breath-by-breath analysis of metabolic data (K4b$^2$, Cosmed S.r.l., Rome, Italy) was integrated with a commercial SCBA facepiece for use in room temperature-simulated firefighting activities (Williams-Bell 2007; Williams-Bell et al. 2010). However, the facepiece does not appear to have been validated with human testing, and no peer-reviewed reports were found regarding the mechanical construction and validation of this design.

1.2 Benchmarking the Cosmed K4b$^2$

The Cosmed K4b$^2$ system (as well as other portable devices) has previously been validated against the standards in the metabolic data collection industry and is generally accepted as a portable alternative to the metabolic cart (McLaughlin et al. 2001). Previous studies have tested the Cosmed K4b$^2$ against Douglas bags (McLaughlin et al. 2001) and against a laboratory metabolic cart (Duffield et al. 2004). Both found slightly higher VO$_2$ values with the Cosmed K4b$^2$ compared with the gold-standard methods (i.e. Douglas Bags and metabolic cart). A further study found small but significant differences between the Cosmed K4b$^2$ and a metabolic cart for oxygen and carbon dioxide fractions ($F_eO_2$ and $F_eCO_2$), as well as minute ventilation ($V_E$), during treadmill running (Pinnington et al. 2001).

Portable metabolic devices have also been modified in previous research for use in activities that are not amenable to breathing through the manufacturer-supplied silicone mask. For example, Keskinen, Rodrı´ guez, and Keskinen (2003) modified a swimming snorkel device, initially developed by Toussaint et al. (1987), to collect expired air while swimming for analysis by the Cosmed K4b$^2$. Significantly higher values for $V_E$, VO$_2$ and VCO$_2$ were found with the standard mask, though the authors conclude that with corrective regression models the Cosmed K4b$^2$ can be considered a valid device for metabolic analysis when the snorkel mask is used (Keskinen, Rodrı´ guez, and Keskinen 2003).

1.3 Towards adapting the Cosmed K4b$^2$ for firefighting applications

A typical firefighting SCBA facepiece allows inhalation of air from a compressed air tank through a regulator containing a one-way valve. Exhaled air is vented to the atmosphere through another one-way valve. The combination of one-way valves minimises the mixing of inhaled and exhaled air, allows the SCBA to maintain positive pressure and preserves the seal between the environment and the firefighter. Standard methods of control and collection of exhaled air for volumetric breath analysis, however, is not incorporated into the design of the traditional firefighter facepiece.

The objective of this study was to develop and validate an accurate means of collecting metabolic data while the firefighter is breathing air from an open-circuit, positive pressure SCBA system. A design is presented for integrating common metabolic monitoring systems with a commercial SCBA. The modified SCBA facepiece was flow-tested to ensure that the modifications did not alter the National Fire Protection Association (NFPA) 1981 standard required mechanical characteristics (2013). The facepiece was then validated using a human subjects based variable-workload assessment with two metabolic measurement devices (portable Cosmed K4b$^2$ and stationary ParvoMedics Truemax 2400 metabolic cart) on an electrically braked cycle ergometer.
2. Methods

2.1 Facepiece modifications

The modern firefighting SCBA is designed to protect the wearer from environments which can be immediately dangerous to life and health, such as air that is potentially contaminated and/or at elevated temperatures. The SCBA seal prevents ambient air from entering the facepiece, and the nose cone ensures that all expired air is directed through the exhalation valve (Figure 1). The three one-way valves within the facepiece and standard nose cone separate inhaled and exhaled air to minimise mixing. The nose cone also helps to reduce dead space within the facepiece.

To allow for collection of metabolic data while breathing from an open-circuit SCBA, a commercially available facepiece worn by firefighters (Firehawk M7 Ultra Elite Facepiece, MSA Co., Cranberry Township, PA, USA) was modified to direct exhaled air through a metabolic breath-by-breath monitoring system (K4b², Cosmed S.r.l.). As the air flow within this SCBA is controlled through the nose cone similar to the commercial K4b² system, the major required modification was to replace the vented component housing beyond the exhalation valve with one that routes all exhaled air to the Cosmed data collection flow meter. To ensure that the SCBA maintained its positive pressure function, expired air was collected after exiting the existing exhalation valve within the SCBA facepiece (Figure 1). The modified component housing was first designed from a computer model (Inventor Professional, Autodesk, Inc., San Rafael, CA, USA) to replace the stock component housing and was then fabricated on a 3D printing system (Eden 350, Objet Geometries, Minneapolis, MN, USA) using Objet’s VeroBlack photopolymer resin material (Figure 2).

The modified component housing was designed with a $90^\circ$ turn so that exhaled gases were directed to the firefighter’s right (Figures 3 and 4). This turn prevented interference between the facepiece and turnout gear and allowed the firefighter to retain full movement of the head. Cross-sectional area of the modified housing flow path was constant throughout and a large turn radius was used so that flow properties were not significantly altered. Two rubber O-rings were utilised to ensure a tight seal between the housing and the metabolic measurement devices. A rubber gasket and silicone rubber sealant were used to prevent leaks between the facepiece and modified housing. Using 3D printing, this component can be produced rapidly and cheaply, yet provides a leak-free seal with the SCBA facepiece.

2.2 Testing protocols

Two series of tests were conducted to validate the modified component housing. First, the modified SCBA facepiece was bench top tested with an industry standard breathing mannequin to ensure that the modifications did not alter the SCBA seal or back pressure characteristics. Then, the metabolic data collected with the modified facepiece were validated against manufacturer provided breath collection devices on both the Cosmed K4b² and ParvoMedics Truemax 2400 metabolic cart.
Figure 2. Engineering drawing and solid model rendering of modified component housing used in 3D printing. Complete 3D design files and prints are available to the interested reader with the online version of the article at http://dx.doi.org/10.1080/00140139.2014.964783.

Figure 3. Front and side views of the MSA Firehawk M7 SCBA facepiece with modified component housing into which the Cosmed flow meter and gas sampling assembly is pressed.

Figure 4. (a) Complete modified SCBA facepiece assembly with Cosmed K4b² and SCBA regulator connected. (b) Modified SCBA facepiece with Cosmed K4b² system.
2.2.1 Positive pressure testing

To ensure that modification of the facepiece did not affect NFPA 1981 certified performance during normal breathing, the facepiece was tested with a commercial SCBA positive pressure testing system (PosiChek, Honeywell Analytics, Lincolnshire, IL, USA). To quantify breathing resistance performance, the PosiChek measures the pressure within the facepiece needed to open the exhalation valve. The facepiece passes the test if the pressure is within the manufacturer’s specifications (0.37–0.62 kPa (1.5–2.5 inches water column (in. WC)) for the MSA Ultra Elite). Static pressure within the facepiece is then measured when there is zero flow. Static pressure is required to maintain positive pressure, but the higher the static pressure, the greater the effort needed to exhale. Code of Federal Regulations (42 CFR 84.91(d)) limits this value to a maximum of 0.37 kPa (1.5 in. WC) (2010).

2.2.2 Metabolic data testing

2.2.2.1 Participants. Fourteen young adult males with no self-reported health issues were recruited to participate in this study. Subjects completed a physical activity readiness questionnaire (PAR-Q; Thomas, Reading, and Shephard 1992) prior to testing and all were determined to be eligible for physical activity (zero ‘YES’ responses to PAR-Q). All subjects were provided with the opportunity to ask questions and signed a written informed consent. Approval for this protocol was obtained from the University of Illinois institutional review board.

2.2.2.2 Procedure. Subjects were tested with two devices and two mask conditions for a total of four configurations: (1) Cosmed K4b$^2$ with the manufacturer provided silicone mask (Standard-Cosmed), (2) Cosmed K4b$^2$ with the modified SCBA facepiece (Modified-Cosmed), (3) ParvoMedics Truemax 2400 metabolic cart with the manufacturer supplied mouthpiece (Standard-Cart) and (4) ParvoMedics Truemax 2400 metabolic cart with the modified SCBA facepiece (Modified-Cart). To reduce the impact of fatigue on the results, each test configuration was evaluated during different test sessions, which were separated by a minimum of 48 h of rest. Test configurations were introduced to the subjects in a counter-balanced order.

For each of the four test configurations, subjects rode an electrically braked cycle ergometer (Corival Cycle Ergometer, Lode BV, Groningen, The Netherlands) repeating an identical stepwise 25-min exercise protocol, where power output was controlled by the research staff. The exercise protocol consisted of five defined steps, each 5 min long: (1) rest period sitting on the ergometer, and then riding at (2) 50 W, (3) 100 W, (4) 150 W and (5) 200 W. The ergometer automatically adjusted resistance based on the subject’s pedalling cadence to maintain constant work output. For each of the four work rates and test configurations, the subject maintained a cadence between 70 and 90 revolutions per minute (RPM), with a target cadence of 80 RPM. Subjects could monitor their own cadence with an electrical readout on the ergometer handlebars. Variations of this protocol have been extensively used in the validation of metabolic monitoring devices (Stuart et al. 1981; Armstrong and Costill 1985; McLaughlin et al. 2001; Keskinen, Rodríguez, and Keskinen 2003).

2.2.2.3 Data collection techniques. Data were collected continuously during the 25-min trial, either with the Cosmed K4b$^2$ (Software Version 3.9, Cosmed S.r.l.) or with the ParvoMedics metabolic cart (Truemax 2400, ParvoMedics, Inc., Sandy, UT, USA). For Standard-Cosmed trials, the K4b$^2$ was operated in its Standard mode, where both inhalation and exhalation data from the flow meter were used in computations of VO$_2$. For Modified-Cosmed trials, the device was used in its Exhalation-Only mode, since only expired air would be passing through the flow meter and gas sensors. During both Standard-Cart and Modified-Cart trials the metabolic cart was used in its Standard mode because the metabolic cart only required exhaled gases to perform all calculations. Following manufacturer recommendations, both systems were allowed ample warm-up time, gas sensors were calibrated to room air and standard gas concentrations (5% CO$_2$, 16% O$_2$ and 79% N$_2$), and the flow meters were calibrated with a 3-liter calibration syringe immediately prior to each data collection session.

Six parameters were analysed, which were either directly measured or derived from measurements by each system: consumption of oxygen per minute (VO$_2$, ml/min), fractional expired oxygen concentration (FE.O$_2$, %), fractional expired carbon dioxide concentration (FE.CO$_2$, %), ratio of carbon dioxide produced to oxygen consumed (R), respiration frequency (Rf, breaths/min) and tidal volume (TV, liters/breath). Both the ParvoMedics Truemax 2400 and the Cosmed K4b$^2$ sampled data on a breath-by-breath basis and then expressed the data as 30-s averages. The 30-s averages across the last 2 min of data from each workload were averaged for analysis (i.e. during the following data collection time points: 3–5, 8–10, 13–15, 18–20 and 23–25 min).

VO$_2$ is not directly measured but is a calculated value. VO$_2$ is derived from $V_{E}$, fractional concentration of expired oxygen (FE.O$_2$) and fractional concentration of expired carbon dioxide (FE.CO$_2$). $V_{E}$ is derived from the $TV$ and $R_f$. Both the Cosmed K4b$^2$ and ParvoMedics Truemax 2400 use automated algorithms to account for dead space, convert the gas
volumes from body temperature and pressure saturated to standard temperature and pressure dry, and include the Haldane transformation which negates the need for measurement of both inhaled and exhaled volumes of air under the assumption that nitrogen is neither consumed nor retained by the subject. Consolazio, Johnson, and Marek (1951) provide a full description of the methodology used to compute VO₂.

2.2.2.4 Statistical analysis. Each parameter (VO₂, FeO₂, FeCO₂, R, R₁ and Tᵥ) was analysed using a within-subject 5 × 2 × 2 repeated measures ANOVA (SPSS Statistics 21, IBM, Armonk, NY, USA). This analysis included five Workload conditions (Rest, 50 W, 100 W, 150 W and 200 W), two Device conditions (Cosmed K4b² and ParvoMedics TrueMax 2400) and two Mask conditions (manufacturer provided breath collection system for each device and the modified SCBA mask) being assessed within subjects. Statistical significance was adjusted to p < 0.008 for multiple ANOVAs of the six correlated parameters. A Tukey honestly significant difference analysis was conducted to examine workload by configuration interactions. To check for any non-statistically significant trends, Bland–Altman plots of the differences between configurations were examined (Bland and Altman 1986).

3. Results

3.1 Positive pressure testing

The SCBA facepiece modification allowing connection to the metabolic devices did not negatively impact the positive pressure attributes of the SCBA for use during normal breathing. The pressure needed to open the exhalation valve was 0.40 kPa (1.6 in. WC) for both trials, within the manufacturer’s requirement of 0.37–0.62 kPa (1.5–2.5 in. WC). The static pressure measured with the modified facepiece was below the 42 CFR 84.91(d) threshold of 0.37 kPa (1.5 in. WC) at 0.32 kPa (1.3 in. WC).

3.2 Metabolic data testing

Statistical analyses were based only on 12 test subjects who completed all 25 min of the protocol in each session. The two subjects unable to complete sessions reported fatigue in the legs as the reason for stopping, but no other medical conditions arose. The 12 subjects who did complete the protocol were a mean age of 24.0 ± 5.1 years, 1.8 ± 0.1 m tall, weighed 88.6 ± 12.3 kg and had a BMI of 26.1 ± 3.1 kg m⁻².

Typical VO₂ data from all four test configurations for a single subject are shown in Figure 5. As expected, the VO₂ clearly increases at each of the five workload stages every 300 s.

3.2.1 Oxygen consumption

For the main outcome of interest – VO₂ – an overview of the ANOVA statistical analysis is shown in Table 1. Significant main effects for Device and Mask configurations were found (p = 0.001 and p = 0.006, respectively). VO₂ significantly increased with each successive Workload level (p < 0.001), as expected with increasing exercise intensity (Table 2). Device × Mask (p < 0.001) and Workload × Device × Mask (p = 0.004) interactions were detected. Modified-Cosmed, Standard-Cart and Modified-Cart configurations were not significantly different from each other at any workload, with a mean difference of 4.1% (range 0.6–7.6%). Mean difference between Modified-Cosmed and Standard-Cart was 4.6% across all workloads. Furthermore, no trends were found in the difference between the Standard-Cart and Modified-Cosmed configurations (Figure 6) or between the Standard-Cart and Modified-Cart configurations (Figure 7) when examined with Bland–Altman plots. However, post hoc analyses revealed that the Cosmed K4b² and standard silicone mask (Standard-Cosmed) configuration estimated significantly greater (average 16.7%) VO₂ values relative to the other three configurations for all workloads except at Rest (Table 2). Deviations between the Standard-Cosmed and the other mask configurations increased in magnitude as the workload increased.

During further analysis, the regression equation proposed by Duffield et al. (2004) was applied to the VO₂ data collected in the Standard-Cosmed configuration, and the differences between configurations decreased from more than 15% to within 1% of that collected with the Standard-Cart.

3.2.2 Fractions of expired oxygen and carbon dioxide and the respiratory exchange ratio – FeO₂, FeCO₂ and R

Investigation into the fractional expired concentrations of both oxygen (FeO₂) and carbon dioxide (FeCO₂) revealed no significant main effects for Device or Mask configurations. As expected, significant main effects for Workload were found for FeO₂ (p = 0.002) and FeCO₂ (p < 0.001). There was a significant difference between all workloads for FeO₂ with the
exception of 50 W versus 100 W. \( F_eO_2 \) was highest at rest and lowest at 50 W, and then increased with increasing workload (Table 3). For \( F_eCO_2 \), there was a significant difference between workloads other than 50 W versus 200 W and 100 W versus 150 W. No interactions were found to be significant for \( F_eO_2 \). For \( F_eCO_2 \), which is not used in the calculation of VO\(_2\), a Workload × Device × Mask interaction was found at 50 W, 150 W and 200 W with the Standard-Cosmed significantly lower than the other configurations.

Figure 5. VO\(_2\) for a typical subject with four different test configurations (Standard-Cosmed, Modified-Cosmed, Standard-Cart and Modified-Cart). Workload was increased every 300 s (from rest, to 50 W, 100 W, 150 W and 200 W).

Table 1. \( p \)-Value, \( F \)-value and partial \( \eta^2 \) for VO\(_2\) (ml/min) for main effects, two-way interactions and three-way interactions.

| VO\(_2\) (ml/min) | \( p \)-Value | \( F \) | Partial \( \eta^2 \) |
|-----------------|-------------|-----|-----------------|
| Workload main effect | <0.001 | 908.7 | 0.998 |
| Device main effect | 0.001 | 23.01 | 0.677 |
| Mask main effect | 0.006 | 11.36 | 0.508 |
| Workload × Device interaction | 0.026 | 4.96 | 0.713 |
| Workload × Mask interaction | 0.308 | 1.43 | 0.417 |
| Device × Mask interaction | <0.001 | 52.00 | 0.825 |
| Workload × Device × Mask interaction | 0.004 | 9.51 | 0.826 |

Table 2. VO\(_2\) (ml/min) as a function of Workload for each Mask–Device configuration (mean (SE)).

| Workload | Standard-Cosmed | Modified-Cosmed | Standard-Cart | Modified-Cart |
|----------|-----------------|-----------------|--------------|---------------|
| Rest     | 459.4 (42.3)    | 387.5 (58.8)    | 366.3 (25.3) | 376.5 (29.8)  |
| 50 W     | 1352.5 (55.0)*  | 1105.8 (42.7)   | 1079.4 (35.0) | 1166.5 (36.6) |
| 100 W    | 1949.4 (80.6)*  | 1658.5 (43.7)   | 1563.3 (50.3) | 1649.2 (45.8) |
| 150 W    | 2578.5 (82.5)*  | 2274.2 (49.5)   | 2154.5 (50.7) | 2174.4 (52.5) |
| 200 W    | 3312.4 (129.1)* | 2984.7 (71.4)   | 2875.8 (59.7) | 2811.1 (47.5) |

Significant differences within each workload are indicated with an asterisk (*).
The respiratory exchange ratio (ratio of CO₂ produced/O₂ consumed, R) showed a significant main effect for Device ($p = 0.001$) and Workload ($p < 0.001$), with the Cosmed K4b² less than the metabolic cart. No significant interactions were found.

3.2.3 Tidal volume and respiration frequency

TV was not significantly different between any Mask and Device configuration and no significant interactions were detected (Table 4). Significant main effects for Workload were found for measurements of TV, which followed an increasing trend as Workload increased. Post hoc analyses revealed significant increases in TV across all levels ($p < 0.001$) as expected.

Main effects for $R_f$ were found to be significant for Device ($p = 0.001$), Workload ($p < 0.001$) and Workload $\times$ Device $\times$ Mask interaction ($p < 0.001$) (Table 5). Post hoc analysis revealed differences between all Workloads with the exceptions of Rest versus 50 W and 50 W versus 100 W, and that $R_f$ measured with the Standard-Cosmed configuration was significantly higher than the other three configurations at all workloads except Rest. No significant differences were measured between all other mask configurations.

4. Discussion

The goals of this study were to (1) characterise a newly designed modified firefighting SCBA facepiece by benchmarking metabolic data collected with a portable system and the modified SCBA facepiece against a stationary laboratory-grade metabolic cart with the commercial breath collection mouthpiece and (2) test the facepiece against industry standards for positive pressure SCBA. The most important result from this analysis is that the modified SCBA facepiece, when used with the Cosmed K4b² or the ParvoMedics Truemax 2400, is an accurate tool for the collection of metabolic data. In addition,
Figure 7. Bland–Altman plots of the difference between the Standard-Cart and Modified-Cart configurations as a function of the mean of the two configurations at various work outputs. Dashed lines represent ± 2 SDs difference in ml/min.

Table 3. Fractional expired oxygen concentration (FeO₂, %) as a function of Workload for each Mask–Device configuration (mean (SE)).

|         | Standard-Cosmed | Modified-Cosmed | Standard-Cart | Modified-Cart |
|---------|-----------------|-----------------|--------------|--------------|
| Rest    | 16.84 (0.15)    | 17.29 (0.24)    | 17.36 (0.22) | 16.93 (0.21) |
| 50 W    | 15.64 (0.22)    | 15.34 (0.36)    | 15.58 (0.33) | 15.47 (0.35) |
| 100 W   | 15.69 (0.26)    | 15.42 (0.36)    | 15.77 (0.32) | 15.65 (0.29) |
| 150 W   | 16.05 (0.18)    | 15.63 (0.35)    | 15.95 (0.29) | 15.92 (0.25) |
| 200 W   | 16.40 (0.20)    | 16.14 (0.35)    | 16.45 (0.29) | 16.31 (0.27) |

Note: No significant differences were found within each workload.

Table 4. Tᵥ (liters/breath) as a function of Workload for each Mask–Device configuration (mean (SE)).

|         | Standard-Cosmed | Modified-Cosmed | Standard-Cart | Modified-Cart |
|---------|-----------------|-----------------|--------------|--------------|
| Rest    | 1.04 (0.16)     | 0.95 (0.13)     | 0.98 (0.09)  | 1.18 (0.13)  |
| 50 W    | 1.59 (0.14)     | 1.82 (0.13)     | 1.62 (0.11)  | 2.01 (0.17)  |
| 100 W   | 2.05 (0.11)     | 2.29 (0.12)     | 2.11 (0.13)  | 2.48 (0.20)  |
| 150 W   | 2.49 (0.12)     | 2.73 (0.18)     | 2.65 (0.16)  | 2.73 (0.19)  |
| 200 W   | 2.79 (0.12)     | 2.91 (0.17)     | 3.06 (0.15)  | 2.92 (0.15)  |

Note: No significant differences were found within each workload.
these modifications did not alter the NFPA 1981 required static pressure or exhalation resistance characteristics of the facepiece.

For the main outcome of interest – VO₂ – there was a non-significant mean difference between Modified-Cosmed and Standard-Cart was 4.6% across all workloads (Table 2). In addition, the Modified-Cosmed, Standard-Cart and Modified-Cart configurations were not significantly different from each other at any workload, with a mean difference of 4.1%. No trends were found in the difference between these configurations when examined with Bland–Altman plots (Figures 6 and 7). These variations in measurements are similar to the 3–4% day-to-day variation demonstrated in previous research (Stuart et al. 1981; Armstrong and Costill 1985) and 3–7% differences reported for a modified swimming snorkel device used with the Cosmed system (Keskinen, Rodrı´ guez, and Keskinen 2003). Therefore, the modified firefighting SCBA facepiece can be considered a valid device for interfacing with portable and fixed laboratory-grade VO₂ measurement tools while breathing through firefighting SCBA system.

The accuracy of measurements made with the modified firefighting SCBA facepiece validates its use with the Cosmed K4b² in activities where metabolic data collection from firefighters has previously been limited. This includes training activities such as confined space or HAZMAT operations or during simulated firefighting activities in an environmental chamber, all while the firefighter breathes ‘on-air’.

The modified firefighting SCBA facepiece was also shown to be accurate when used with a commercial metabolic cart (ParvoMedics Truemax 2400) when compared with the manufacturer-supplied breath collection system. Quasi-static treadmill or ergometer protocols can be conducted with the firefighter breathing through the SCBA allowing for direct comparisons of maximal oxygen uptake to oxygen uptake during simulated firefighting activities. In addition to the primary result, we detected an overestimation of VO₂ with a stock Cosmed K4b² system, similar to that which has previously been reported (McLaughlin et al. 2001; Duffield et al. 2004). In this study, the difference between the Standard-Cosmed and Standard-Cart increased from 273 ml/min at 50 W to 436 ml/min at 200 W with average differences of 320 ml/min (Table 2). This variation between devices of nearly 15% is outside of the 3–4% day-to-day variation demonstrated in previous research (Stuart et al. 1981; Armstrong and Costill 1985) but can be corrected to 1% difference using a regression equation proposed by Duffield et al. (2004), thus corroborating the previous finding.

Further insight into this systematic over-prediction can be gathered by delving into the VO₂ measurement technique. VO₂ is calculated from other variables that are directly measured and variations in these measurements contribute to potential variations in the calculation of VO₂ with the Standard-Cosmed configuration compared to the other Mask–Device configurations. Examinations of FeO₂ and FeCO₂ suggest that all Mask and Device configurations resulted in consistent measurements of exhaled gas concentrations. All configurations recorded reduced oxygen and increased carbon dioxide concentrations in expired air following the rest phase. At the same time, no significant differences were measured in TV across the different Mask–Device configurations. However, significant differences were detected in measurement of Rf (Table 5). Post hoc analyses indicate that the Standard-Cosmed configuration estimated a higher number of breaths per minute than the other mask configurations. The differences in VO₂ magnitude increased with workload, likely due to Rf increasing with workload, resulting in greater overestimation of VO₂ with the Standard-Cosmed configuration. This was an interesting finding as the Standard-Cosmed configuration was the only test configuration which used both inhalation and exhalation to determine breath timing and hence Rf. The three other configurations all operated solely on exhaled air for both breath timing and gas analysis.

5. Summary and conclusions

The modified SCBA facepiece, when used with either the Cosmed K4b² (Modified-Cosmed) or the ParvoMedics Truemax 2400 metabolic cart (Modified-Cart), was determined to be an accurate tool (within 4.6% difference) for the collection of metabolic data across a wide range of workloads when compared with the metabolic cart with the commercial breath collection system (Standard-Cart). At the same time, these modifications have no negative effects on the positive pressure
attributes of the SCBA. The Cosmed K4b² in the standard configuration (Standard-Cosmed) was found to overestimate VO₂ relative to the Standard-Cart, an observation which has previously been reported in comparison to other measurement techniques and found to be acceptable (McLaughlin et al. 2001; Eisenmann et al. 2003). Component analysis of the variables used in the calculation of VO₂ indicates that this discrepancy appears to result from the measurement of respiratory frequency, which is different in the Standard-Cosmed configuration compared with the other three Device and Mask combinations.

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