2012

# Carbon dioxide re-breathing in respiratory protective devices; Influence of speech and work rate in full face masks

Carmen Lee Smith
*University of Wollongong*

UNIVERSITY OF WOLLONGONG

**Department of School of Health Sciences**

# Carbon dioxide re-breathing in respiratory protective devices; Influence of speech and work rate in full face masks

**Carmen Lee Smith**

**"This thesis is presented as part of the requirements for the award of the Degree of Masters of Science (Research) of the School of Health Sciences University of Wollongong"**

**November 2012**

## ABSTRACT

It is estimated that five million workers throughout the United States of America rely on Respiratory Protective Devices (RPDs) to protect their health. However, there are a number of factors that limit the wear time of RPDs in the workplace. This includes high breathing resistance, interference with vision, heat stress, difficulty communicating and re-breathing of carbon dioxide ($CO_2$). Of these factors there has been little research into the adverse affects to $CO_2$ re-breathing in RPDs. $CO_2$ is known to stimulate respiration, increase heart rate, dilate blood vessels and in higher concentrations produces symptoms of discomfort, anxiety, headache, fatigue, dizziness and shortness of breath. Previous investigations on $CO_2$ re-breathing are limited by small sample size and have not evaluated the relationship between $CO_2$ inhalation and phonic respiration (breathing during speech) in RPDs. This research was conducted in two parts, a pilot study at the University of Wollongong, New South Wales and a field study at a worksite in Mount Isa, Queensland. Participants took part in a graded exercise test on a bicycle ergonometer that increased in resistance every five minutes. During the third minute of each stage participants read aloud a prepared text. Measures of expired $CO_2$ ($PECO_2$), inspired $CO_2$ ($PICO_2$) and respiration were monitored. The results showed phonic respiration and low work rates contributed to significantly higher levels of $CO_2$ re-breathing. Aiming to reduce $CO_2$ re-breathing may result in improved wear time of RPDs. It is recommended that these findings be incorporated in technical specifications regarding human factors for RPDs.

## PUBLICATIONS AND PRESENTATIONS

Smith, C L, Whitelaw, J L and Davies, B 2012, Phonic respiration and its impact on carbon dioxide re-breathing in respiratory protective devices. *International Society of Respiratory Protection (ISRP) Conference,* Boston, United Sates of America, September 2012.

Smith, C L, Whitelaw, J L and Davies, B 2012, Speech and its impact on carbon dioxide re-breathing in respiratory protective devices. *Australian Institute of Occupational Hygienists (AIOH) Conference,* Adelaide, Australia, December 2012.

Smith, C L, Whitelaw, J L and Davies, B 2013, Carbon dioxide rebreathing in respiratory protective devices: influence of speech and work rate in full-face masks. *Ergonomics,* Taylor and Francis, London, United Kingdom.

## DEDICATION

I would like to dedicate this thesis to my partner, Tim Naylor, for his constant support. I would also like to dedicate this to my close friends and family who always encouraged me to do my best. I am so appreciative.

## ACKNOWLEDGEMENTS

This research was supported by a scholarship from the University of Wollongong funded by Safety Equipment Australia (The S.E.A Group). Thanks are due to the following people, without your assistance, this research would not have been possible:

- Jane Whitelaw for your support, upbeat enthusiasm and advice.
- Brian Davies for your words of wisdom, time and continuous guidance.
- John Henderson for your encouragement, input and humour.
- The management and staff of The S.E.A Group for their continual assistance.
- Vinodkumar Gopaldasani for your statistical advice and comments. You are a genius.
- Dan Warkander for your knowledge and recommendations.
- The volunteers who took part in the pilot and field studies.
- The School of Health Sciences at the University of Wollongong for their assistance and support.

## DECLARATION

I, Carmen Smith, declare that this thesis, submitted in the fulfilment of the requirements for the award of Masters in Science (Research) to the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This thesis has not been submitted for a degree or diploma in any other academic institution.

_____

Carmen Smith

Date: 26/11/2012

## TERMS AND DEFINITIONS

**Anaerobic (Exercise):** Short "rapid" duration exercise that is powered by metabolic pathways that do not use oxygen, e.g. sprinting

**Carbon Dioxide ($CO_2$):** Gaseous product of aerobic respiration

**Chemoreceptor:** A sensory receptor that is activated by binding of a chemical substance

**Dead Space:** Those portions of the respiratory system that do not exchange gases with the blood

**Dyspnoea:** A subjective feeling of not being able to breathe or get air

**End Tidal Carbon Dioxide ($P_{ET}CO_2$):** The concentration of $CO_2$ at the end of exhalation. Comparable to alveolar $CO_2$

**Hypercapnia (Hypercarbia):** Elevated concentration of $CO_2$ in the blood

**Hyperventilation:** An increase in alveolar respiration that is not associated with an increase in metabolic rate

**Hypoventilation:** A decrease in alveolar respiration without a change in metabolic rate

**Minute Ventilation ($V_E$ or $V_I$):** The volume of air expired (or inspired) in one minute

**Peak Inspiratory Air Flow (PIAF):** Highest flow rate that occurs during inhalation ($L\ min^{-1}$)

**Partial Pressure:** The pressure of a single gas

**Respiratory Acidosis:** Acidosis due to retention of $CO_2$

**Respiration:** Exchange of gases between the atmosphere and the cells

**Respiratory System:** Those structures involved in respiration and gas exchange

**Tidal Volume ($V_T$):** The amount of exhaled (or inhaled) air during normal respiration

**Work of Breathing (WOB):** The effort required to inspire into the lungs

## ABBREVIATIONS

| | |
|---|---|
| **ACSM:** | American College of Sports Medicine |
| **$A_{DU}$:** | Dubois body surface area |
| **AS/NZS:** | Australian & New Zealand standard |
| **$B_I$PAP:** | Bi-level positive airway pressure |
| **BP:** | Blood pressure, millilitres of mercury |
| **BTPS:** | Body temperature, ambient pressure, saturated with water vapour |
| **CE:** | *Conformité Européenne* meaning Eurpoean Conformity |
| **$CO_2$:** | Carbon dioxide |
| **ECF:** | Extracellular Fluid |
| **ECG:** | Electrocardiogram |
| **EN:** | European standard |
| **$FEV_1$:** | Forced expiratory volume in one second |
| **$f_R$:** | Breathing rate, breaths per minute |
| **FVC:** | Forced vital capacity, litres |
| **HR:** | Heart rate, beats per minute |
| **IDF:** | Israel Defence Force |
| **ISO:** | International Organisation for Standardisation |
| **JIS:** | Japanese Industrial Standards |
| **MBS:** | Modified Borg scale |
| **NASA:** | National Aeronautics and Space Administration |
| **NIOSH:** | National Institute for Occupational Safety and Health |
| **OSHA:** | Occupational Safety and Health Administration |
| **$P_ACO_2$:** | Alveolar partial pressure of carbon dioxide |
| **$PaCO_2$:** | Arterial partial pressure of carbon dioxide |
| **PAPR:** | Powered air purifying respirator |
| **$PCO_2$:** | Partial pressure of carbon dioxide |
| **$PECO_2$:** | Percentage of expired carbon dioxide |
| **$P_{ET}CO_2$:** | Partial pressure of end tidal carbon dioxide |
| **$PICO_2$:** | Percentage of inspired carbon dioxide |

| | |
|---|---|
| **PIAF:** | Peak inspiratory air flow, litres |
| **PIS:** | Participant information sheet |
| **ppm:** | Parts per million |
| **RPD:** | Respiratory protective device |
| **rpm:** | Revolutions per minute |
| **SCBA:** | Self contained breathing apparatus |
| **$V_E$:** | Minute ventilation (expired), litres |
| **$V_I$:** | Minute ventilation (inspired), litres |
| **$\dot{V}O_2$:** | Volume of oxygen uptake per minute, litres per minute |
| **$\dot{V}O_{2max}$:** | Maximal oxygen uptake, millilitres per minute per kilogram |
| **W:** | Watts |

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

# 1 INTRODUCTION

Respiratory protective devices (RPDs) are used in many environments to prevent the wearer from inhaling hazardous substances in the atmosphere, for example, gases, cement dust, welding fumes and bushfire smoke. According to the Occupational Safety and Health Administration (OSHA) approximately five million workers throughout the United States of America rely on RPDs to protect their health (OSHA 2011). However, according to a workplace survey by Laird et al. (1993) almost two thirds of the respondents stated they removed their RPD for some reason before they completed the work that required its use. The problem here is that if a RPD is removed in an area where protection is required, even for a short period of time, contaminants can enter the workers lung with adverse health effects. Therefore, it is important to research factors that limit RPD wear time to assist in resolving this problem.

There are a number of factors that limit the wear time of RPDs. This includes high breathing resistance, interference with vision, difficulty communicating, heat stress and facial discomfort (AS/NZS 1715: 2009). Research in the past has been heavily focused on evaluating these problems, although some studies such as Kloos and Lamonica (1966), Love et al. (1979) and Harber et al. (1982) have also examined the physiological stress of carbon dioxide ($CO_2$) re-breathing in RPDs.

$CO_2$ re-breathing occurs from inhaling expired air that gets trapped in the RPD, the amount of which is relative to the volume of the RPD (dead space). This can cause an increase in the arterial concentration of $CO_2$ ($PaCO_2$), also known as hypercapnia or hypercarbia, which can promote wearer discomfort. High $PaCO_2$ has been associated with symptoms of discomfort, fatigue, dizziness, headache, shortness of breath, muscular weakness, ringing in the ears and drowsiness (Kloos and Lamonica 1966).

The adverse affects of $CO_2$ re-breathing in RPDs has been known for some time. One of the earliest studies in this area was by Kloos and Lamonica (1966) who studied methods of measuring inspired $CO_2$ and its effect on breathing in RPDs. Consequently there are a number of standards established for the design of RPDs that

specify maximum allowable $CO_2$ concentrations in inhaled air. However, the understanding of the level of $CO_2$ re-breathing that occurs in RPDs and its impact on human wearers is limited. The reason for this lack of awareness may be due to $CO_2$ being an invisible problem and other issues such as, the effects of heat stress, being more recognisable.

A comprehensive review by Williams (2010) on physiological responses and limitations of $CO_2$ in RPDs found that exhaled $CO_2$ is not completely removed in the breathing space of RPDs and that more research in this area was warranted. Factors such as RPD type, size of person and exercise workload (increased metabolic $CO_2$) were identified as having probable effects on $CO_2$ re-breathing (Williams 2010). For instance, it appears than an increase in exercise workload may increase the chance of $CO_2$ re-breathing.

In regards to RPDs, the models available are extensive. There are two main types; air purifying respirators (APRs) and air supplying RPDs. Within this, APRs mainly include particulate or gas and vapour removing masks, powered or non-powered, half or full face masks. Whereas air supplied RPDs can include self contained breathing apparatus's (SCBA) and airline RPDs. In a review of 15 studies on the effects of $CO_2$ in RPDs (refer to Appendix A) less than half were on non-powered APRs. Even less research assessed $CO_2$ concentration in full face masks or how this problem may impact the wearer adversely. This research is concerned with $CO_2$ re-breathing in full face RPDs.

Moreover, the affect of phonic respiration, our breathing during speech, on $CO_2$ levels in RPDs has not previously been evaluated. Phonic respiration occurs primarily during exhalation and as a result decreases inhalation time (ISO/TS 16976-1: 2007). According to Boron and Boulpaep (2003) following the cessation of speech $f_R$ can increase by 25% and alveolar $CO_2$ ($PACO_2$) falls. Doust and Patrick (1981) proposed that hypercapnia could explain the above increase in respiration observed at the end of a speech. Many studies have focused on the impact of speech on air flow rate and respiratory minute volumes (Silverman et al. 1943, Berndtsson 2004 and Holmer, Kuklane and Gao 2007). However, there is little research in the literature on the influence of speech on $CO_2$ concentrations in RPDs.

## 1.1 Key Research Questions

The aim of this research was threefold;

- To determine the level of $CO_2$ re-breathed in a full face RPD during low to moderate intensity work.
- Evaluate the impact of phonic respiration (breathing during speech) on $CO_2$ re-breathing in RPDs.
- To examine if there was any association between other factors such as, body surface area (BSA) and gender on $CO_2$ re-breathing in RPDs.

## 1.2 Significance of the Study

In order to better understand $CO_2$ re-breathing, the invisible problem in regards to RPD use, this research aimed to address "how much $CO_2$ re-breathing occurs in a full face RPD?" Although many occupations require RPDs and communication in the workplace, it is not known if speech influences $CO_2$ re-breathing and if this is associated with symptoms of hypercapnia. An exercise assessment would allow for the assessment of whether $CO_2$ re-breathing is affected with increased workload. The measurement of dyspnoea is critical as this is one of the key causes of RPD non wear and also impacts the wearers work capacity.

For these reasons, this research focused on the level of $CO_2$ re-breathed in a full face RPD while the wearer performed work (exercise on a bicycle ergonometer). To our knowledge this is the first study to assess $CO_2$ re-breathing during both conditions of speech and no speech. Inclusion criteria for the study included workers familiar to wearing RPDs. Also a large sample size was selected for this study as it provided an opportunity to explore issues, for example the impact of BSA, which other studies have been too small to support.

Greater understanding of this research area will assist manufacturers in improving the design of RPDs so that they are more suited to the physiological

responses of the wearer. This will lead to increased wear time of RPDs with the outcome of improved respiratory protection in hazardous environments.

## 1.3 Research Hypothesis

Following a review of the literature and a pilot study it was hypothesised:

- Hypothesis one: There shall be a difference in $CO_2$ re-breathing in RPDs during periods of phonic respiration (breathing during speech).
- Hypothesis two: There shall be a difference in $CO_2$ re-breathing in RPDs at increased exercise workloads.

## 1.4 Limitations of the Study

There are a number of factors that limit this study. They are as follows:

- This study was limited in the amount of time and access to complete the exercise assessments at the worksite. Data collection for the field study was limited to five days. As a result participants did not have the opportunity to get used to, or train riding the bicycle ergonometer.
- There was an under representation of women in the sample, although a low percentage of women in the mining industry is customary. In addition the sample was mainly aged under 39 (68%).
- The mode of exercise chosen (bicycle ergonomter) often imposes lower limb fatigue which limits participants exercise capacity.
- The worksite was deliberately selected for the study as the workers were familiar with the use of full-face RPDs. Therefore, it is possible these workers sensitivity to $CO_2$ is diminished.
- Due to a lack of medical supervision, the level of $CO_2$ during maximal exercise was not assessed. Only low to moderate workloads were assessed.

## 1.5 Constraints of the Study

To make this study more manageable the following constraints were made:

- The field study aimed to collect data from 40 participants. This was calculated to be a manageable size.
- The study investigated dyspnoea (MBS), respiratory rate ($f_R$) and peak inspiratory air flow (PIAF). Other well known respiratory variables such as respiratory quotient (RQ), work of breathing (WOB), minute ventilation ($V_E$) and tidal volume ($V_T$) was excluded from analysis.
- The field study was restricted to workers familiar with the use of RPDs.
- In addition, only one level of breathing resistance was imposed on workers. Therefore, if higher resistance had been used, even larger concentrations of $CO_2$ may have been measured.

## 1.6 Statement of Assumptions

There were some unavoidable assumptions made in this study. These were as follows:

- Indoor (atmospheric) $CO_2$ was considered constant and to not contribute the level of $CO_2$ inhaled by the wearer.
- Oxygen uptake ($V\dot{O}_2$) was calculated using the leg cycling equation recommended by American College of Sports Medicine (ACSM) (2006). It was assumed that $V\dot{O}_2$ was the same during both conditions of speech and no speech, with and without the RPD. However there is evidence that working with RPDs reduces total energy expenditure and $VO_2$(Carretti et al. 2001).
- That the device used is representative of full face RPDs used in the workplace.

# 2 REVIEW OF THE LITERATURE

A review of the literature on the physiological effects of $CO_2$ and the implications this has in regards to RPDs was conducted. In addition methods used for evaluating $CO_2$ in RPDs and what factors may impact the results is also described. At the end of this section research recommendations for the pilot and field study are made.

## 2.1 Introduction

The aim of this research is to determine how the level of $CO_2$ re-breathed in RPDs impacts the wearer, especially in regards to their respiratory responses. It is thought that increased $CO_2$ re-breathing while wearing the device contributes to dyspnoea and may impact the wear time of the RPD. More research on this problem will provide information to assist in the design of RPDs that are more suited to the physiological responses of the wearer. This will assist in improving comfort of RPDs and increase respiratory protection in hazardous environments.

## 2.2 Physiological Effects of Carbon Dioxide

$CO_2$ is a "by-product of respiration" and is present in the atmosphere at very low levels (0.03% or 300 ppm) (ISO/TS 16976-3: 2011). At this level it has minimal physiological consequences and does not impair our day to day function. However, elevated $CO_2$ in the environment, such as in the dead space of RPDs, can have a significant impact on the respiratory system (ISO/TS 16976-3: 2011).

At rest "the chemical state of the blood exerts the greatest control of pulmonary respiration" (McArdle, Katch and Katch 2001). Changes in $CO_2$ concentration stimulate neural receptors (chemoreceptors) in the arterial system

which initiates changes to respiration. According to the International Organisation for Standardization (ISO) $CO_2$ is about 20-25 times more soluble in the blood than oxygen ($O_2$) (ISO/TS 16976-3 (2011). Therefore, it is not surprising that small changes in $CO_2$ concentration can have a powerful affect. For example, resting respiration doubles when $PaCO_2$ in humans increases to just 1.7 mmHg (0.22%) in inspired air (McArdle, Katch and Katch 2001). This is due to changes in blood acidity which is relative to the $CO_2$ content of the blood. A fall in blood pH (acidosis) is the result of $CO_2$ accumulation in the blood (McArdle, Katch and Katch 2001). This signals increased respiration to eliminate $CO_2$ from the blood to the alveoli.

$CO_2$ is removed from the blood to the alveoli by process of diffusion due to differences in partial pressures (McArdle, Katch and Katch 2001). For example, $CO_2$ is measured at 0.03% in atmospheric air (ISO/TS 16976-3: 2011). At sea level (where the atmospheric pressure is 100 kPa or 760 mmHg) this means the partial pressure of $CO_2$ is 0.03% x 100 kPa, equal to 0.03 kPa. The concentration of $CO_2$ in the alveolar air is 5.3%, giving a partial pressure of 5.3 kPa (ISO/TS 16976-3: 2011). The partial pressure of $CO_2$ in the blood stream is 6 kPa higher than alveolar air (ISO/TS 16976-3: 2011). As a result $CO_2$ moves down the partial pressure gradient from blood, to alveoli and is eventually breathed out.

Alternatively $CO_2$ retention can occur in the body if the level of $CO_2$ in the atmosphere (such as dead space in RPDs) exceeds the alveolar concentration. Figure 2.1 illustrates the acute effects of increased $PaCO_2$.

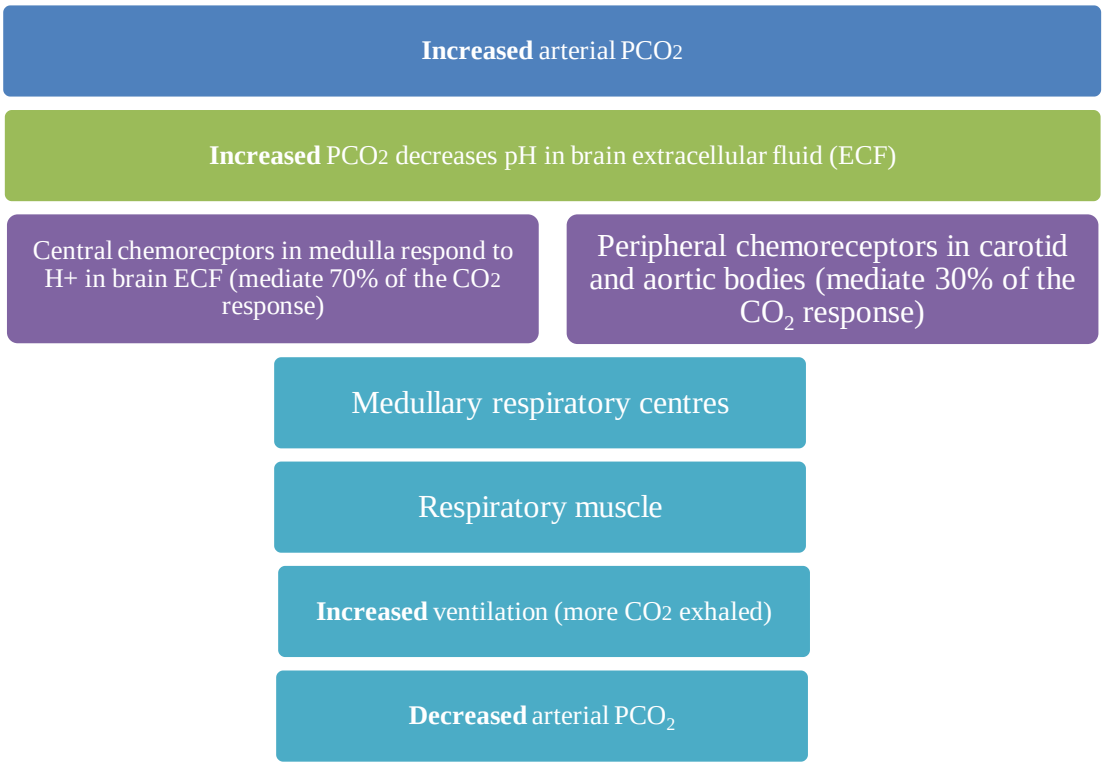



**Figure 2.1** Mechanism by which increased arterial carbon dioxide regulates ventilation by Marieb and Hoehn 2010

### *2.2.1 Hypercapnia*

High levels of inspired $CO_2$ ($PICO_2$) generally results in hypercapnia, when $PaCO_2$ is elevated above the normal range (4.5 kPa or >45 mmHg) leading to a blood pH of <7.38 (Silverthorn 2004). ISO states this "serves a protective purpose" due to its stimulatory effect on respiration (ISO/TS 16976-3: 2011). It not only increases $V\dot{O}_2$ (via increased respiration) but also increases cerebral blood flow (due to vasodilation or widening of blood vessels in the brain) (ISO/TS 16976-3: 2011).

However, there are adverse affects of $CO_2$ re-breathing which cause problems for the wearers of RPDs. Silverthorn (2004) describes $CO_2$ as a "toxic waste product" that must be removed from the lungs. The build up of which can produce symptoms of discomfort, fatigue, dizziness, headache, shortness of breath, muscular weakness, ringing in the ears, drowsiness, paralysis of the respiratory centre and even asphyxiation or death depending on length of exposure (Kloos and Lamonica 1966).

Early evidence that high $PaCO_2$ had negative effects was reported by Parker, Peters and Barnett (1963). They found, working on dogs, high $PaCO_2$ decreased compliance and increased work of breathing (Parker, Peters, and Barnett 1963).

In addition, several studies (Love et al. 1979, Takahashi et al. 2000 and Fletcher, Clarke and Stanley 2006) showed that breathing $CO_2$ resulted in increases in $V_E$. The National Institute for Occupational Safety and Health (NIOSH) (1976) reviewed 19 studies on $CO_2$ re-breathing and concluded that excess $V_E$ can occur as low as 1.1% inhaled $CO_2$. Even still, a study by the National Aeronautics and Space Administration (NASA) in 1971 (also cited in NIOSH 1976) showed that inspired $CO_2$ of 7.5 mmHg (0.99%) increased ventilation by 19%. Some outcomes have also linked high $PaCO_2$ with decreased exercise capacity (Bishop et al. 1999). Similarly, research by NASA (1971) (cited in NIOSH 1976) showed a significant reduction in maximal oxygen uptake ($\dot{V}O_{2max}$) (down 13%) when inhaled gas contained 15 mmHg $PCO_2$ (2% $CO_2$). $\dot{V}O_{2max}$ is used as a standard measure of cardiorespiratory fitness in exercise physiology.

Increased $PaCO_2$ can have multiple effects on the central nervous system. Yang, Sun and Sun (1997) demonstrated that 2.5% $CO_2$ in breathing air decreased participants ability to detect motion. Fothergill, Hedges and Morrison (1991) established that moderate 6.18 kPa to high 7.5 kPa (6.2-7.5%) levels of $CO_2$ impaired cognitive and psychomotor performance. Luksch et al. (2002) also found breathing $CO_2$ ranging from 2.5-8% decreased retinal blood flow (cited in ISO/TS 16976-3: 2011). It can be assumed such effects are more likely to increase cognitive errors and ability to perform tasks in the workplace.

In terms of determining an upper limit for $PaCO_2$, Maresh et al. (1997) showed that inhalation of 6-8% $CO_2$ caused an increase in $f_R$ (up 73%) and body sensations of dyspnoea, heart palpitations, sweating, dizziness, pressure in chest or blurred vision. There is also a condition known as extreme hypercarbia (supercarbia) where a blood level of 19.9 kPa (150 mmHg or 19.9% $CO_2$) occurs in individuals with respiratory disease (ISO/TS 16976-3: 2011). Lastly, a study by McArdle (1959) exposed individuals to 30% $CO_2$. This experiment resulted in ECG abnormalities, marked increase in blood pressure (BP) of 205/110 mmHg and unconsciousness. Essentially to test this level of $CO_2$ exposure would be unethical in present day

research. However, from these studies it is evident that a wide range of acute $CO_2$ conditions can be tolerated. Table 2.1 is a summary of these cited effects.

**Table 2.1** Cited acute physiological effects of carbon dioxide re-breathing on humans

| $PICO_2$ (%) | Physiological Effects | Reference |
|---|---|---|
| **1** | ↑ $f_R$ by 19% | NASA (1971) |
| **1.1** | ↑ $V_E$ | NIOSH (1976) |
| **2** | ↓$\dot{V}O_{2max}$ | NASA (1971) |
| **2.5** | ↓ ability to detect coherent motion | Yang et al. (1997) |
| **2.5-8** | Decreased retinal blood flow | Luksch et al. (2002) |
| **3** | ↑ $V_E$ & $PECO_2$ | Craig et al. (1970) |
| **4-5** | Breathlessness and Headache | Love et al. (1979) |
| **6-8** | ↑ $f_R$, dyspnoea, heart palpitations, sweating, pressure in chest, wobbly legs, dizziness and blurred vision | Maresh et al. (1997) |
| **30** | ↑BP, ECG abnormalities and unconsciousness | McArdle, (1959) |

The health effects of long-term elevated $CO_2$ in the atmosphere have been reported on to a lesser extent. Yet, this is an important factor to consider, especially for workers who are exposed to elevated $CO_2$ on a daily basis. Many studies show that participants become adapted to $CO_2$ following chronic exposure. For example, submariners exposed to high $CO_2$ over a period of 11 days in a study by Margel, White and Pillar (2003) showed reduced respiratory disturbance during the collection of sleep and breathing data. However, there is evidence to suggest that long-term high $CO_2$ exposure does have serious health implications. Drummer et al. (1998) exposed participants to 1.2% $CO_2$ in a deep diving chamber for 25 days. Follow up measures showed elevated concentrations of serum calcium and slightly lower biomarkers of bone formation and increased bone re-absorption in participants. Further research regarding the impact of long-term exposures to $CO_2$ is needed.

### *2.2.2 Carbon dioxide re-breathing in respiratory protective devices*

Physiological responses to $CO_2$ are well documented. Yet, there is little scientific literature available regarding $CO_2$ re-breathing in RPDs. This present study aimed to assess the impact of $CO_2$ re-breathing in a full face non-powered air purifying RPD. From the research examined it was evident that even less information was available on this topic. Refer to a detailed summary of studies on $CO_2$ re-breathing in different types of RPDs and the variables that were measured in Table 5.1 (Appendix A). These studies have produced mixed results.

Love et al. (1979) studied respiratory responses to inhaled $CO_2$ under work conditions using a device that had similar breathing resistances to a standard filter self rescuer. Self rescuers are emergency RPDs often used for protection against carbon monoxide, it is not self contained or oxygen supplying. The study found that the symptoms of breathlessness and headache occurred at 4% and 5% $PICO_2$. Love et al. (1979) concluded that $CO_2$ was not well tolerated at concentrations above 3% in RPDs. Similarly Craig et al. (1970) studied $CO_2$ re-breathing in M9 Protective Masks and found that concentrations of 3% $PICO_2$ or above produced a significant reduction in endurance. A recent study by Takahashi et al. (2000) showed that participants breathing 3% $CO_2$ from a half mask had higher $V_E$ and percentage of expired $CO_2$ ($PECO_2$) than participants breathing room air and that these responses were augmented during moderate exercise. Consequently Takahashi et al. (2000) recommended a minimum level of 2% $CO_2$ as a safer limit with present day RPDs. From these findings it is clear that increased $PCO_2$ causes dyspnoea in RPDs. However, these studies have a number of limitations including that $CO_2$ was administered to the participants. Further research is required to demonstrate the level of $CO_2$ re-breathing that occurs in the dead space of a RPD due to the incomplete removal of exhaled air.

Arad et al. (1992) found that increased $PICO_2$ was linked with increases in $f_R$ in powered air-purifying respirators (PAPRs). A total of 10 participants (five women) were involved in two exercise sessions wearing a full face RPD with and without a blower. Each session involved six minutes at rest and six minutes of walking on a treadmill at 5.1 km hr (3.2 miles hr) and 10% incline. Results indicated that the blower significantly decreased $PICO_2$ (0.4±0.4% and 1.3±0.7%) There was some evidence that these changes were associated with improved RPD comfort.

Arad et al. (1992) study also revealed female participants showed significantly lower $PECO_2$.

Roberge et al. (2010) examined the physiological impact of N95 filtering face piece RPDs. Ten adults (seven women) conducted two 60 minute treadmill assessments walking at 2.74 km hr (1.7 miles hr) and 4.02 km hr (2.5 miles hr) while wearing the RPD. Data collected showed that the RPD did not have a significant physiological impact on the wearer. However, the dead space $CO_2$ levels ranged from 2.5-3.5% which is significantly above design standards (1%). This suggests that $CO_2$ re-breathing has the potential to occur in RPDs. The results indicated that only modest elevations in transcutaneous $CO_2$ ($P_{cut}CO_2$), equivalent to $PaCO_2$, occurred. However, two participants did have $P_{cut}CO_2$ equal to or greater than 50 mmHg (6.7%). In addition only mixed inhaled and exhaled $CO_2$ was measured rather than measured separately. This could overestimate the level of $CO_2$ re-breathing. Further research using a more representative sample and measurement of inspired $CO_2$ only is needed.

In contrast, other studies on RPDs have examined the physiological impact of dead space which is well known for contributing to $CO_2$ re-breathing. A study by Johnson et al. (2000) showed for each 350 mL of external dead space imposed on the participants a 19% decrease in performance time and an 18% decrease in breathing comfort occurred. Warkander and Lundgren (1995) conducted a study on the impact of dead space in three diving RPDs. Experiments were performed on a bicycle ergonometer at three different workloads. Warkander and Lundgren (1995) found that dead space was not constant in RPDs and increased with increased ventilation during exercise. High $PICO_2$ levels also occurred during periods other than rest.

The effect of breathing resistance in RPDs is also viewed as a key factor in $CO_2$ re-breathing. Harber et al. (1982) showed dead space ($CO_2$ re-breathing) had "effects similar to those of exercise", this includes increased $V_E$ and $f_R$, yet breathing resistance led to hypoventilation. Furthermore, studies by Johnson, Dooly and Dotson (1995) and Warkander et al. (1992) demonstrated that increased $PCO_2$ in RPDs was largely associated with breathing resistance. According to ISO the normal response of increased respiration due to $CO_2$ re-breathing is blunted when in the presence of breathing resistance (ISO/TS 16976-3: 2011). Resistance is a problem in most RPDs as the wearer has to overcome the filter resistance when breathing (the

majority of RPDs have some sort of filter to capture particles or gas). Breathing through RPD resistance stimulates a "negative cycle" of hypoventilation, which can cause increased $CO_2$ partial pressure (Craig et al. 1970, Johnson et al. 2005 and ISO/TS 16976-3: 2011). This stimulates respiration and potentially even further $CO_2$ re-breathing. This will increase the level of hypercapnia to the point that it can cause physiological stress or dyspnoea for the wearer. In turn this will result in decreased wear time of the RPD.

From the research examined it is evident that multiple factors contribute to increases in $PCO_2$ in RPDs. Louhevaara et al. (1985) results suggest that symptoms of hypercapnia (increased $V_E$) may be influenced by the interaction of dead space (volume of the RPD), breathing resistance as well as the weight and psychological stress of the RPD. Suzuki, Ogawa and Matsumura (2004) put forward that factors such as filtering face pieces that contained carbon, replaceable particulate RPDs and gas masks without an inhalation valve or gas masks with inhalation valves with "lack of air tightness" may also give rise to $CO_2$ re-breathing. Sinkule and Turner (2004) also found that the degree of $PCO_2$ varied considerably between devices, body weight and gender (2004). More research into $CO_2$ re-breathing in RPDs is required to evaluate these factors.

## 2.3 Occupational Exposure Standards

The adverse effects of $CO_2$ have been known for some considerable time. As a result there are several occupational exposure standards that specify the maximum allowable concentrations of $CO_2$. Safe Work Australia (SWA) specify a exposure limit for $CO_2$ of 0.5% (5, 000 ppm) over an eight hour time weighted average (SWA 2012). Similarly, OSHA has also set the same limit (OSHA 2011). NIOSH (2011) state a maximum concentration of 0.5% (5, 000 ppm) for the workplace (40 hr week). In respect to short term exposure limits for $CO_2$, SWA (2012) stipulates 3% (30, 000 ppm) for 15 minutes as a limit. NIOSH (2011) also consider a $CO_2$ value of 4% (40, 000 ppm) to be immediately dangerous to life or health.

In regards to specifications for maximum concentrations of inhaled $CO_2$ in the design of RPDs, standards generally vary between 1% and 3% in different countries (summarised in Table 2.2). In Australia the main organisation that governs these standards is Standards Australia. The Australia/New Zealand Standard: 1716 (AS/NZS 1716: 2003) "Respiratory Protective Devices" states $CO_2$ concentration of inhaled air (including dead space) in full face pieces and head coverings (excluding self rescuers and smoke masks) must not exceed a 1% average. This specification is also applied in the Occupational Safety and Health Standards of OSHA: 1910.134 "Respiratory Protection" and European Standards: EN 13274-6: 2001 for respirator classification. The Israel Defence Force (IDF) regulations state the fraction of inspired $CO_2$ should not exceed 2% for longer than one consecutive minute in RPDs (as cited in Luria et al. 2004). Japan International Standards (JIS) however, recommends a maximum of 3% (Takahashi et al. 2000). In regards to the mentioned IDF and JIS standards English versions of these documents could not be accessed at the time of the literature review.

**Table 2.2** Summary of maximum allowable concentration of carbon dioxide in inspired air in respiratory protective devices

| Standard | Maximum Allowable Concentration (%) | RPD Type |
|---|---|---|
| AS/NZS | 1.0 | Full face pieces and head coverings |
| AS/NZS | 1.5 | SCBA |
| AS/NZS | 2.0 | Smoke masks |
| EN | 1.0 | Independent air supply |

Interestingly many of these current standards, such as AS/NZS 1716: 2003 and EN 13274-6: 2001 test for $PCO_2$ using a "Sheffield" dummy head attached to a breathing simulator. In AS/NZS 1716: 2003 the $f_R$ of the machine is fixed to 20 breaths per minute with a tidal volume of 2.0 L. A 5% $CO_2$ air mixture is exhaled into the face piece and inhaled $CO_2$ is analysed. It is therefore, important to research the respiratory responses to $CO_2$ during exercise (greater than 20 breaths per minute). Furthermore it is essential to evaluate $CO_2$ re-breathing in a human wearer.

## 2.4 The Physiological Impact of Respiratory Protective Devices

There is a vast range of RPDs available. According to NIOSH (2011) RPDs belong in two main categories:

1. Air purifying: These filter air before it is inhaled by the wearer and can be disposable or non-disposable.
    - Particulate RPDs
    - Vapour and gas removing cartridges and canisters
    - Non-powered air-purifying respirators
    - Powered air-purifying respirators (PAPRs)

2. Air supplying: These RPDs independently supply air to the wearer.
    - Self contained breathing apparatus (SCBA)
    - Closed circuit
    - Open circuit
    - Supplied-air RPDs
    - Airline RPDs
    - Hose masks

Within this, there are numerous types of filters which include particulate (filter out particles), vapour and gas removing masks and filter effectiveness (e.g. 95%, 99% and 100%) (NIOSH 2011). After reviewing 15 studies on $CO_2$ re-breathing (refer to Appendix A) less than half focused on non-powered air purifying RPDs, three used SCBAs, two used full face masks used in diving and two were on PAPRs. The remaining studies used apparatuses to simulate RPDs.

Many studies reported a range of $PCO_2$ levels and physiological responses to RPDs (for example Harber et al. 1991, Luria et al. 2004 and Sinkule and Turner 2004). Harber et al. (1991) studied the effect of three alternative RPD designs and found that powered air-purifying RPDs had less physiologic impact than the non-powered models. However, they found no differences between RPDs with and

without a nasal deflector in place (a device that directs air flow in RPDs). Similarly, Luria et al. (2004) found that despite using two very similar RPDs during rest and exercise, very different levels of $CO_2$ accumulation and work of breathing was observed.

Given the above evidence, it is not surprising to assume each type of RPD will exert different physical effects on the wearer. Table 2.3 below is modified from Szeinuk et al. (2000) and provides a summary of some of these physiological-based stressors.

**Table 2.3** Summary of the physiological effects of respiratory protective devices by Szeinuk et al. 2000

| RPD | Respiratory | Cardio-vascular | Discomfort | Ergonomics | Psychosocial | Skin | Senses |
|---|---|---|---|---|---|---|---|
| Air-Purifying (Negative Pressure) | Little breathing resistance; difficulty in cough; full-face mask; increased dead space | Few | Thermal load; Tightness; Pain | Few | Yes | Yes | Speech communication difficult; smell interference; full face mask may interfere with vision |
| Powered Air Purifying (Continuous Flow) | Little breathing resistance; cough difficulty | Few; some models add load | Thermal load (less than negative pressure); tightness; pain | Few; Some models add load to face and belt | Yes | Yes (for tight fitting) | Speech communication difficult; smell interference; full face mask may interfere with vision |
| Airline; Compressor or Tanks | Cough difficulty; demand regulator (negative pressure) may increase breathing resistance; full face mask increase dead space | Few | Thermal load (less than negative pressure); tightness; pain | Air hose may be heavy and cumbersome | Yes | Yes (for tight fitting) | Speech communication difficult; smell interference; full face mask may interfere with vision |
| SCBA | Cough difficulty; Full face mask increases dead space | Yes; heavy load | Thermal load (less than negative pressure); tightness; pain | Unit add weight and volume to user | Yes | Yes (for tight fitting) | Speech communication difficult; smell interference; full face mask may interfere with vision |

From Table 2.3, the most important of these differences is the level of breathing resistance and dead space of the RPD. Any breathing resistance at all will impede breathing (Johnson et al. 2000) and thereby increase $PaCO_2$. In a similar way increased dead space will result in $CO_2$ re-breathing and hence elevated $PaCO_2$. It is these differences that may contribute to the mixed results observed in the literature review.

Where dead space varies between RPDs, breathing resistance is standardised. According to AS/NZS 1716: 2003, exhalation for air filtering RPDs is 200 Pa for full face pieces and 120 Pa for half face pieces. In regards to inhalation resistance this varies with the filter efficiency. Table 2.4 is extracted from AS/NZS 1716 standard 4.3.4 and defines the levels of maximum inhalation resistances that can be imposed by an RPD (except PAPRs). These levels can be measured using a pressure transducer.

**Table 2.4** Inhalation resistance in respiratory protective devices (AS/NZS 1716)

| Filter class | Filter assembly only maximum resistance (Pa) | | Assembled RPD maximum resistance (Pa) | |
|---|---|---|---|---|
| | 30 ± 1 L $min^{-1}$ | 95 ± 1 L $min^{-1}$ | 30 ± 1 L $min^{-1}$ | 95 ± 1 L $min^{-1}$ |
| P1 | 60 | 210 | 110 | 340 |
| P2 | 70 | 240 | 120 | 370 |
| P3 | 120 | 420 | 170 | 570 |

For this research a full face non powered air purifying RPD was used with a Sundstrom SR P510-310 P3 particulate filter (see Figure 2.2). Hence by only using one RPD model the variability associated with dead space and breathing resistance will be minimised.

**Figure 2.2** The full face non powered air purifying respirator

## 2.5 Evaluation of Research Methods

The assessment of $CO_2$ re-breathing in RPDs is quite complex. Firstly, the RPD needs to be altered for the collection and analysis of inspired and expired gases. In addition, the methods and equipment used to test RPDs all vary. Table 5.1 (Appendix A) attempts to document studies on $CO_2$ re-breathing. The following sections considers the different research methods and equipment used to study $CO_2$ re-breathing in RPDs.

### *2.5.1 Analysis of arterial carbon dioxide*

One method to assess $PCO_2$ in RPDs is to measure the accumulation of $CO_2$ in the individual's blood. In the past a standard technique to do this was by obtaining

arterial blood samples ($PaCO_2$). However, in recent times the indirect analysis of $PECO_2$ or end tidal $CO_2$ ($P_{ET}CO_2$) gas samples has replaced this method, especially in laboratory settings (ACSM 2006). $P_{ET}CO_2$ is the final and highest $CO_2$ reading recorded at the end of exhalation (John 2003). In discussing $P_{ET}CO_2$ John (2003) noted that this method was: "a non-invasive estimate of alveolar ventilation status by its close correlation with $PaCO_2$". Hence a benefit of analysing respiratory gases includes that arterial blood does not need to be drawn from the participant regularly, such as every minute (Wanger 1996).

Transcutaneous $CO_2$ monitoring is another practice that is non-invasive in blood $CO_2$ analysis. Electrodes are placed on the surface of the skin, such as the forearm, chest, abdomen or earlobe and indirectly measures $PaCO_2$. This was used in the study by Roberge et al. (2010). These findings suggest analysis of $CO_2$ via non invasive methods is an acceptable method for the study of $CO_2$ exposure in RPDs. These methods are preferred for this research as it is a field based study.

### *2.5.2 Measurement of inhaled carbon dioxide*

As expired $CO_2$ may not completely leave the RPD the level of $CO_2$ inhaled is a key parameter in this research. A study by Mojoli et al. (2008) found that the concentration of $CO_2$ re-breathed was dependent on the level of $PECO_2$. Mojoli et al. (2008) conducted a series of tests to assess the most convenient method to monitor $PICO_2$ by sampling $CO_2$ at different sites within a helmet. Their results showed that $PICO_2$ is best measured at either a "quiet" point inside the device or at the airway opening. Mojoli et al. (2008) observed that $CO_2$ concentration was not static within the helmet, for example measurement of end $PICO_2$ at the airway opening grossly underestimated $PICO_2$.

Similarly, ISO/TS 16976-3: 2011 noted that $CO_2$ in the breathing zone of RPDs varies. At the end of exhalation ($P_{ET}CO_2$) can be as high as 8%, yet this concentration will decrease rapidly at the start of the following inhalation to approximately 1%, especially in a device with small dead space (ISO/TS 16976-3: 2011). Due to this variability separate collection and analysis of the level of $CO_2$ in both inspired and expired air in RPDs is necessary. According to the European Standard, EN 13274-6: 2001 on determination of $CO_2$ inhalation in RPDs a $CO_2$

sample probe should be placed at a point 50 mm in front of the device inlet. Hence measurement of $PICO_2$ should occur as close to the breathing port as possible. John (2003) also supported this sampling technique.

### *2.5.3 Carbon dioxide gas analysis*

There are several types of analysers (chemical sensors) used for the measurement of $CO_2$ (refer to Appendix A for a table of equipment used in past research). This includes gas chromatographs, infrared absorption analysis or mass spectrometers. According to Wagner (1996) gas chromatography was a technique used more in the past. This involves a sample of expired air being collected and analysed for $CO_2$. However, this process is quite expensive and requires several technicians.

The infrared analyser has been the preferred analyser for quite some time in $CO_2$ analysis (Wagner 1996). Louhevaara et al. (1984), Mador et al. (1992), Sidney and Poon (1995), Luria et al. (2004) and Fletcher, Clarke and Stanley (2006) all measured inspired $CO_2$ using infrared analysers. This is a less accurate method compared to mass spectrometry, however, preferred as it is less expensive and allows analysis of many participants (Wagner 1996).

From the research examined mass spectrometers were used less frequently in $CO_2$ analysis despite reported rapid response and increased accuracy. According to Wagner (1996) mass spectrometers are limited by its relatively large size and are the most expensive to use. Some studies that measure $CO_2$ in RPDs with mass spectrometers include Mador et al. (1992), Stromberg and Eklund (1996) and Caretti et al. (2001).

In relation to $CO_2$ collection, there are also two main approaches. There is the breath by breath method which measures data continually during each breath. According to Wagner (1996) and Goodman and Curnow (1995) this method is quite fast which allows for more data points to be collected. Secondly, there is the mixing chamber method which uses a small compartment to collect gas samples, where $CO_2$ is later analysed downstream. Wagner (1996) states this method does not require high speed analysers or adjustment for time delays as in the breath by breath method. However, it is limited by the fact that samples, such as expired air or air in the

mixing chamber cannot be analysed at the same time. Despite this the results of the literature review show that both these methods are acceptable in RPD research.

### *2.5.4 Measurement of dead space*

One of the main issues that cause $CO_2$ re-breathing is the volume of dead space. Dead space refers to the portion of each breath that does not take part in gas exchange (Brooks, Fahey and Baldwin 2005). According to McArdle, Katch and Katch (2001) dead space in humans (anatomical) ranges between 150-200 mL or is equal to 30% of resting $V_T$. With a RPD, the dead space involved in respiration increases, which can lead to the build up of $CO_2$ as there is more potential for expired air to be re-inhaled. As a result, some studies focused on the physiological impact of dead space when evaluating $CO_2$ re-breathing in RPDs. Stromberg and Eklund (1996) calculated dead space by using indirect measurements of inspiratory volumes using a calibrated inductive plethysmograph and measurements of $PCO_2$ with a mass spectrometer. However, this method had an error rate almost equal to 20% (Stromberg and Eklund 1996).

Alternatively the study by Warkander and Lundgren (1995) measured dead space of the device by filling it with water and measuring volume. This research shows the measurement of dead space in the assessment of $CO_2$ re-breathing in RPDs is an important aspect that could be included in this research.

### *2.5.5 Measurement of respiratory parameters*

The measurement of respiratory parameters is standard practice in this research area. Common respiratory variables such as $f_R$, $V_T$, minute volume ($V_E$) and lung function variables such as forced vital capacity (FVC) and total lung capacity (TLC) was included in some way in all the literature reviewed (refer to Appendix A).

There are two commonly used devices for the analysis of respiratory parameters, these are pneumotachometers and plethsymographs. A pneumotachometer is a device that measures air flow directly from the mouth. Of the 15 studies that looked at $CO_2$ re-breathing in RPDs more than half used a form of pneumotachography (refer to Appendix A). The advantage to using pneumotachometers is that they are considered to be more precise (Harber et al.

1991). However, as this is measured at the mouth, the RPD is often modified to allow the collection of expired air. This change alone could decrease the accuracy of the results.

Alternatively, Harber et al. (1991), Butcher et al. (2006) and Bansal et al. (2009) used plesthmography. This method involves placing elastic bands around the participants trunk. During respiration the changes in the diameter of the chest wall generates electrical signals that can provide data on respiratory volumes and flow rates. The benefit of this method is that these calculations can be made without the need to sample air flow at the mouth.

Berndtsson (2003) also published a paper on a new technique for measuring PIAF. PIAF can be three to ten times higher than $V_E$ and refers to the maximal speed achieved during a full inspiration (AS/NZS 1715: 2009). There has been research that has suggested that analysis of PIAF may be a more important factor when testing respiratory responses in RPDs (including Silverman et al. 1943 and Berndtsson 2004). In addition the flow meter used to measure PIAF is light weight, accurate, does not add to the inhalation resistance of the RPD or have any problems with lag (Berndtsson 2003). The flow meter is preferable for this research as it does not impact on breathing resistance or increase dead space significantly, which could increase $PCO_2$.

### *2.5.6 Measurement of work of breathing*

Stimulation of respiration due to $CO_2$ re-breathing will result in increased work of breathing (WOB). According to Butcher et al. (2006) the potential consequences of increased WOB is reduced cardiac output, peripheral muscle fatigue and diminished exercise capacity. Assessing only respiratory variables in this research may fail to show significant increases in WOB. For example, Lofaso et al. (1995) evaluated $CO_2$ re-breathing in BiPAP devices and found a 1.3% increase in $V_E$ but nearly two fold increase in the WOB (J L).

The measurement of WOB is the product of oesophageal pressure change and lung volume ($WOB=P.V_T$) (Butcher et al. 2006). To measure this directly an oesophageal balloon is inserted and is impractical in some research settings.

Alternatively WOB can be calculated by using pressure and flow recordings (Shykoff and Warkander 2011)

Increased WOB will also result in higher values of $\dot{V}O_2$. $\dot{V}O_2$ is an indirect measure of calculating the demands of energy expenditure (ACSM 2006). By definition $\dot{V}O_2$ is the volume of oxygen used by the body to produce energy (ACSM 2006). Therefore, $\dot{V}O_2$ can indirectly represent WOB. The calculation of $\dot{V}O_2$ is a much less invasive and straightforward approach to measure the demands of work. There are a number of ways to accurately calculate $\dot{V}O_2$. One method for calculating $\dot{V}O_2$ is to use ACSM (2006) metabolic calculations. For instance the leg cycling equation for $\dot{V}O_2$ is as follows:

$$\dot{V}O_2 \text{ (mL kg}^{-1} \text{ min}^{-1}) = \frac{1.8 \text{ (work rate)}}{\text{(body mass)}} + 3.5 \text{ mL kg}^{-1} \text{ min}^{-1} + 3.5 \text{ mL kg}^{-1} \text{ min}^{-1}$$

For the context of this research the above equation was the preferred method to represent WOB.

## 2.6 Variables that Influence Carbon Dioxide Re-breathing

There are a number of factors that influence the assessment of $PCO_2$ in RPDs. These are important considerations when conducting research on RPDs. Some of these issues will be mentioned in the section below.

### *2.6.1 Facial fit*

RPD fit testing is an important procedure to ensure that a good face seal is achieved and that the device protects the wearer from inhaling hazardous substances. For this research RPD fit is important to ensure leakage factors do not limit results. According to AS/NZS 1715: 2009 fit testing procedures include either a qualitative or quantitative fit test. Qualitative fit testing generally involves the wearer detecting the presence of a chemical agent either by taste or smell within the RPD. Quantitative tests involve precise measurement of the amount of leakage that occurs in an RPD by a contaminant. Measurement of leakage is undertaken using an

instrument such as a "Portacount" which is considered to be one of the fastest and easiest ways to do this. In addition this device is approved by OSHA (OSHA 2011). In regards to fit testing both qualitative and quantitative fit tests are acceptable (AS/NZS 1716: 2003). Some studies have mentioned checking for face fit to eliminate leaks before carrying out research (Jones 1991, Caretti et al. 2001, Rebar et al. 2004 and Johnson et al. 2005).

### *2.6.2 Human variability*

There are many variables that will affect participants level of $CO_2$ re-breathing and response to $CO_2$. For example, participants sensitivity to $CO_2$ can vary greatly. A study by Takahashi et al. (2000) showed that the respiratory response ($f_R$, $V_E$) of the most sensitive person to $CO_2$ was 10 times as high as that of the least sensitive person. This may account for the Warkander et al. (1992) results which showed that high levels of $P_{ET}CO_2$ did not cause dyspnoea in some participants. In addition it has been noted repeated exposure to $CO_2$ will reduce an individual's sensitivity (Silverman et al. 1951).

Exercise has also been shown to impact $PICO_2$. Firstly, during light and moderate exercise respiration is proportional to $V\dot{O}_2$ and $PECO_2$ (McArdle, Katch and Katch 2001). At these intensities it can be expected to see increases in $CO_2$ re-breathing with increased work. Warkander et al. (1995) showed a mean increase of 0.3 kPa (0.3%) $CO_2$ when participants workload was increased from 50 W to 100 W on a bicycle ergonometer. Secondly, two participants working at the same $V\dot{O}_2$ will have different levels of $PECO_2$ and respiration (Kyriazi 2011). These differences may be related to differences in body size, gender and fitness.

It is these reasons that Body and Metabolic Simulator (BMS) machines are often used to test RPDs as there is better repeatability (Kyriazi 2011). BMS machines simulate mechanical breathing and metabolism of humans. However, it is important to realise these machines are not without limitation. A study by Kyriazi (2011) tested two different BMSs against each other and found notable differences in $PICO_2$.

To control for human variability, the aim of this research is to recruit a large sample size to explore these issues further. It is worth noting that of the literature

reviewed few studies had a sample size large enough to determine if for example gender or body size had an influence on $CO_2$ re-breathing in RPDs.

### *2.6.3 The impact of speech*

Speech production, sometimes called phonic respiration is a particular act that affects the dynamics of breathing even though it has nothing to do with gas exchange (Boron and Boulpaep 2003, p733). The process of breathing provides air flows and pressures that interact with the respiratory tract to create speech. Speech occurs primarily during exhalation and as a result decreases inhalation time (ISO/TS 16976-1: 2007).

According to Boron and Boulpaep (2003) when persons read aloud, $f_R$ can increase by 25% and $PACO_2$ falls. During heavy work the demand for alveolar ventilation increases and as a result the ability to speak becomes increasingly difficult.

It appears speech under conditions of high ventilatory demands (such as exercise) has been well researched. For example, studies by Doust and Patrick (1981) and Barker et al. (2008), found that $V_E$ and $f_R$ is significantly lower during simultaneous speaking and exercise tasks compared to non speech exercise tasks. It is thought that this decrease in respiration is due to competition between the breathing patterns required for speech and the breathing patterns typically used for exercise. In addition both studies noted that $\dot{V}O_2$ did not significantly differ between the speech and non speech tasks.

Doust and Patrick (1981) also noted respiration overshot by 14% immediately after the speech period. It was proposed that hypercapnia could explain the above increase in respiration observed at the end of speech.

Research by Raczek and Asamczyk (2004) evaluated changes in speaking fluency and the concentration of expired $CO_2$. This study found that stutterer's whose speech is impaired, is linked to increases in $CO_2$ concentration in exhaled air. Therefore, there is reason to believe that speech may cause changes to the concentration of $CO_2$ in the breathing atmosphere of a RPD, particularly if speech is obstructed (such as breathing resistance or increased work rate).

In addition, a study by Hoit and Lansing (2007) looked into speech related dyspnoea while breathing high levels of $CO_2$. Results showed that speech breathing behaviours changed with inspired $CO_2$. This included increased $P_{ET}CO_2$, increased lung volume expended per syllable and more non speech exhalations.

There is considerable research on the impact of RPDs and speech intelligibility. All RPDs impact on communication by attenuation or distortion of sound by some degree. Studies, for example by Caretti and Strickler (2003) have revealed that interference with communications is regarded as one of the most important factors limiting RPD compliance (Caretti and Strickler 2003).

Other studies have measured the effects of speech in RPDs under work conditions including Silverman et al. (1943) and Berndtsson (2004). Results indicated breathing during speech was altered and led to significant increases in PIAF. However, the impact of speech on $CO_2$ levels in RPDs has not previously been evaluated to our knowledge. Hence further studies measuring $CO_2$ re-breathing during speech in RPDs seems worthwhile.

## 2.7 Summary

Following a review of the literature it is possible to conclude that $CO_2$ re-breathing is a problem regarding the wear of RPDs. Dead space has long been regarded as a primary cause for $CO_2$ re-breathing in RPDs. However, breathing resistance, a common difficulty in all RPDs also contributes to this. Other factors that appear to influence $CO_2$ re-breathing in RPDs include increased $CO_2$ production, for example during exercise, BSA, gender and individual sensitivity to $CO_2$.

A lack of published papers suggests that $CO_2$ re-breathing in RPDs is an under researched topic. Of 15 studies that measured $PCO_2$ in RPDs few measured PIAF, WOB, or changes to cognitive function. In addition no studies have specifically focused on the effects of speech on $PCO_2$. Many studies on $CO_2$ re-breathing were limited by small sample size, consequently the effects of body size and gender appear unclear. It is apparent the level of $CO_2$ re-breathing that occurs in RPDs and its impact on human wearers could be better understood.

Therefore, with these factors in mind this research aims to measure the level of $CO_2$ re-breathing that occurs in RPDs while performing work and to investigate its impact on the wearer (for example dyspnoea). In addition, the impact of speech, gender and BSA will be investigated using a more representative sample. This information will assist manufacturers in improving the design of RPDs so that they are more suited to the wearer's respiratory responses. This potentially will lead to improving RPD comfort and wear time.

# 3 METHODOLOGY

## PILOT STUDY

A pilot study was conducted between February and March 2012 at the University of Wollongong (UOW), New South Wales. The pilot study provided an opportunity to test the assessment process with a group of volunteers before conducting the field study. From this, methodological limitations were identified and overcome and assessment procedures improved.

As a result of the information gained in the literature review it was hypothesised that speech, BSA, gender and workload would influence $CO_2$ re-breathing in RPDs. Also, it was apparent that $CO_2$ re-breathing stimulates a range of physiological and psychological effects including increased respiration and dyspnoea. This may contribute to decreased RPD wear time and comfort.

The pilot study was approved by the Human Research Ethics Committee of the UOW/South Eastern Sydney and Illawarra Area Health Service (Reference Number: HE11/437 and Appendix B).

### 3.1 Participants

Participants were recruited for the pilot study from the School of Health Sciences at the UOW. Participants were approached or recruited via verbal announcements and email. Participation was voluntary and no incentives were offered. Participants were informed of potential psychological and physiological discomforts of wearing a RPD. A participant information sheet (PIS) further outlined the aim and potential risks and benefits of the study (refer to Appendix C).

Participants were required to be aged between 18 and 69 years, clean shaven and pass a TSI Portacount fit test. The principle of this latter constraint was to ensure that the RPD achieved an acceptable face seal on the wearer. Participants were excluded if pregnant, suffering from severe illness or injury, diagnosed with severe anxiety or problems with claustrophobia (refer to Appendix D for more information regarding inclusion and exclusion criteria). In addition participants were required to avoid exercise and smoking on the day of testing (refer to Appendix E for appointment confirmation letter). If no contraindications to exercise were identified using the screening materials detailed in section 3.1.3, participants were requested to complete an informed written consent (refer to Appendix F).

## 3.2 Equipment and Instruments

The equipment used for the pilot study is illustrated schematically in Figure 3.1. The apparatus was arranged with the following components:

- S.E.A Full Face Mask (1)
- A Validyne Pressure Transducer (2)
- Data Acquisition Board (DAQ) (3)
- Personal Computer (PC) (4)
- Valve Controller (5)
- $O_2$/$CO_2$ analyser (6)
- Pump(s) (7 and 8)
- Accumulator(s) (9 and 10).

The system was designed to collect separate volumes of exhaled and inhaled gas concentrations by using three sampling probes located in the oronasal space of the mask. The apparatus developed was comparable to the preferred example for determination of $CO_2$ content in RPDs described in Australian/New Zealand Standards (AS/NZS 1716: 2003). However, in this study a human wearer donned the RPD rather than using a BMS machine to simulate respiration. The distinction here is that where the BMS is set to exhale a 5% $CO_2$ mixture, a human can exhale as

much as 8% $CO_2$ during exercise (ISO/TS 16976-3: 2011). A summary of the equipment used is described below.

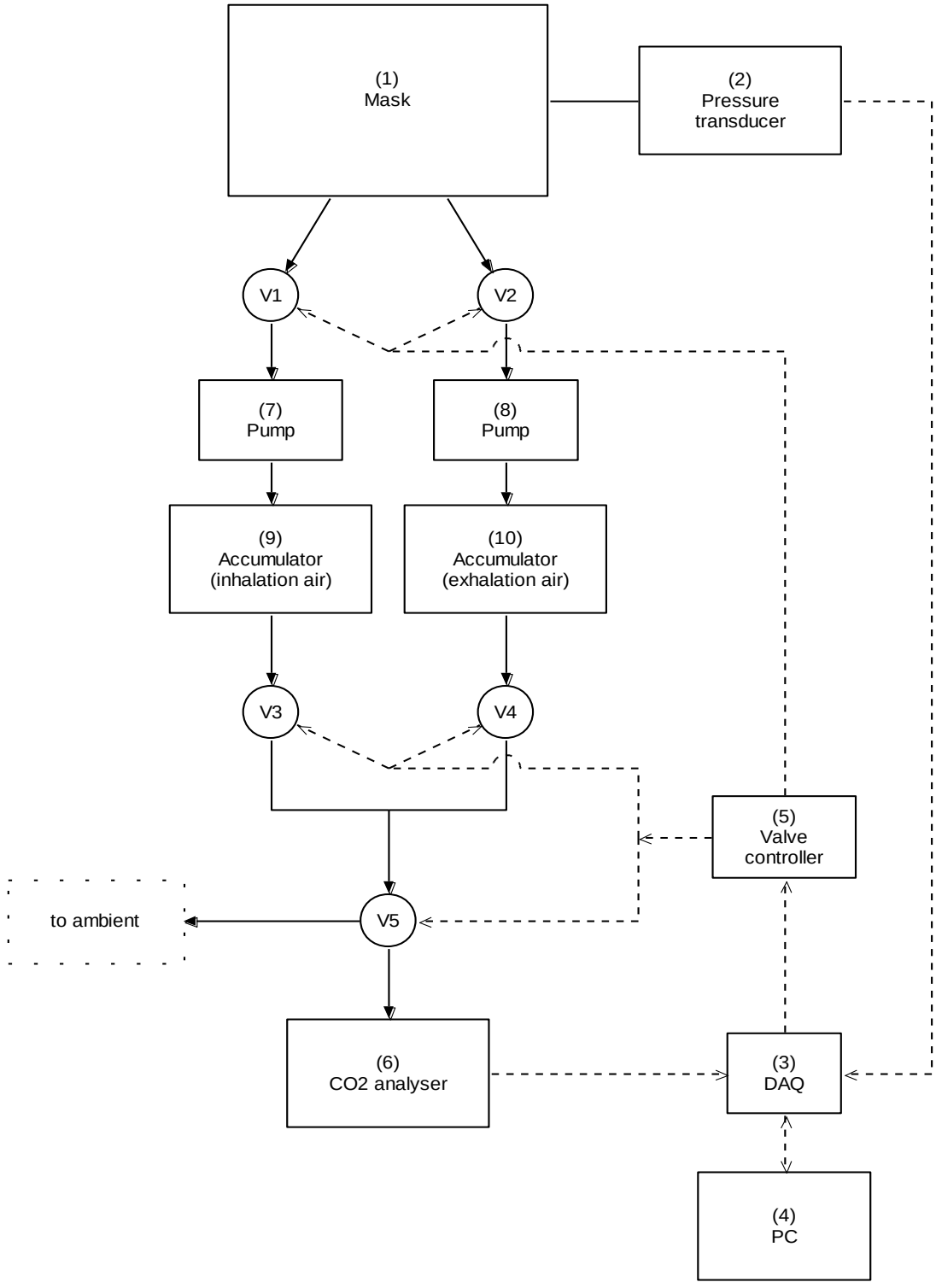



**Figure 3.1** Schematic diagram of the test equipment by Crain and Kazakov 2011

### *3.2.1 S.E.A Full Face Mask*

A full face S.E.A Pty Ltd mask (SMF-L model, The S.E.A Group, Warriewood, NSW) with a Sundstrom SR P510-310 P3 particle filter was selected. The RPD was modified to allow for the analysis of respiratory parameters. This was done via three independent probes located in the oronasal space of the RPD. One probe detected flow and pressure, the remaining two sampling lines collected inhalation and exhalation air samples via two valves (V1 and V2 in Figure 3.1). These valves operated as one way valves and measured $PICO_2$ and $PECO_2$ separately downstream. The participants breathed normal atmospheric air and were exposed to minimal breathing resistance. The device was calibrated and validated by S.E.A Pty Ltd using CE standards for RPDs. The full face RPD was worn as shown in Figure 3.2.

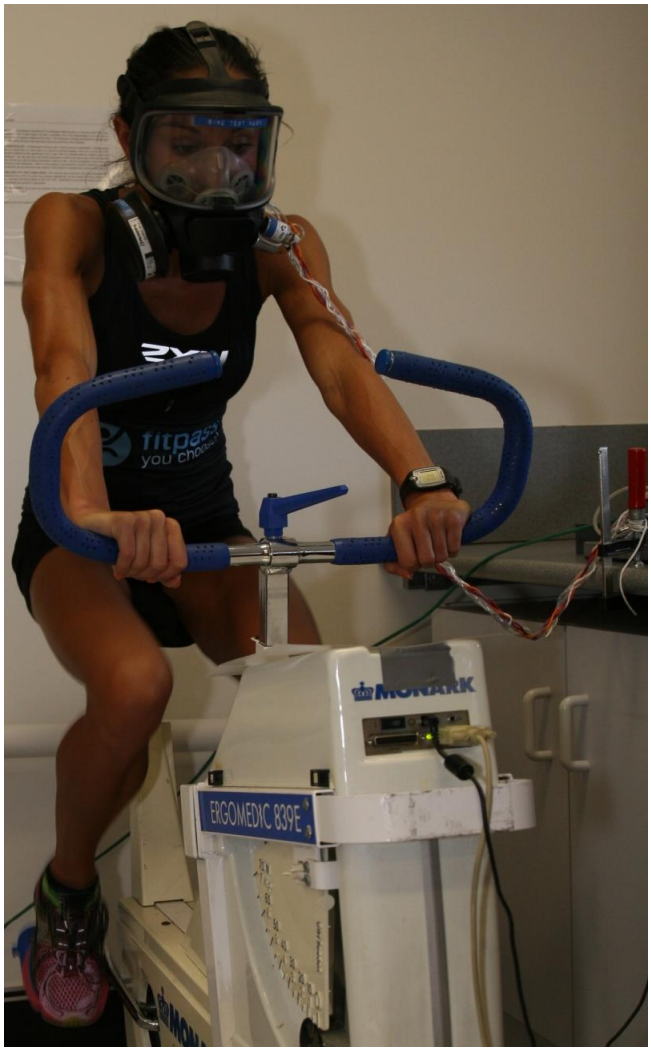



**Figure 3.2** Participant seated on the bicycle ergonometer

### *3.2.2 Flow measurement*

A Validyne Differential Pressure Transducer (Model P55D, Validyne Engineering Corporation, Northridge, California) (accuracy ±0.25b FS) was connected to the RPD to measure PIAF. It was designed to measure a pressure drop in combination with a standard Sundstrom SR 510-310 P3 particulate filter. The device was calibrated and validated by S.E.A Pty Ltd prior to testing. The PIAFs published in this report was modelled after Berndtsson (2004). PIAF was calculated as the mean of all breaths during 30 seconds of each measurement period. The values were then corrected to body temperature and pressure saturated with water vapour (BTPS).

### *3.2.3 Gas analyser*

An $O_2/CO_2$ analyser ($O_2$Cap, Oxigraph, Mountain View, US) single channel (5-100% $O_2$; 0-10% $CO_2$ range) measured the concentration of $PICO_2$ and $PECO_2$. The analyser sampled air samples at a sample rate of 50 Hz, 250 mL $min^{-1}$. The manufacturer listed ±0.1% stability for $CO_2$. Gas samples were taken from two separate probes located in the sampling port of the RPD and connected to the analyser via two separate lines. The $CO_2$ analyser was calibrated at regular intervals using certified reference gases (0% $CO_2$ and 5% $CO_2$).

### *3.2.4 Personal computer*

A Data Acquisition (DAQ) board was connected to personal computer (PC) to perform $O_2$ and $CO_2$ management, valve control and collect pressure and flow measurements. Data was stored in a S.E.A software program as CSV files. These results were imported into a Microsoft Excel 97 (Microsoft Corporation) spreadsheet for further analysis.

### *3.2.5 Bicycle ergonometer*

The exercise test was performed on a calibrated bicycle ergonometer (Monark Bodyguard AB, Varberg, Sweden) with Monarch analysis software. The seat height was adjusted to the preference of the user, ideally so that their knee had a five degree

bend when extended. Participants were instructed to maintain a pedal rate of 60 revolutions per minute (rpm). The Monark software was used to convert kilopond to watts, to adjust workload automatically and record test data.

### *3.2.6 TSI Portacount*

A calibrated TSI Portacount Plus (TSI Incorporated, Shoreview, MN, USA) quantitatively calculated RPD fit. This instrument works by measuring the particle concentration in an ambient air sample and comparing this to inside the mask to provide an estimate of RPD fit (TSI 2011). The ratio of these two variables is called a fit factor. For the full face mask an overall fit factor of greater than 500 is required. The TSI Portacount was pre-programmed with eight one minute exercises contained in the OSHA regulations (OSHA 2011). Participants were required to obtain a pass for each exercise to be included in the study.

A HP Pavilion G series laptop with TSI software was in command of the TSI Portacount during fit testing. Daily checks were performed on the TSI Portacount at the start, middle and end of each day of testing to ensure it operating accurately. This was done by following the instructions provided by the manufacturer. This equipment and method was chosen to carry out the fit test as it is commonly conducted in many workplaces.

### *3.2.7 Heart rate monitor*

Participants HR was measured throughout the exercise test using a Polar HR monitor (Polar FT1, Polar Electro, Kempele, Finland). The chest belts were moistened and fixed around or just below nipple line of participants.

### *3.2.8 Modified Borg Scale*

$CO_2$ produces symptoms of shortness of breath and dyspnoea. A visual analogue scale to gauge participant's level of dyspnoea is therefore, a valid and useful tool for this research. The Modified Borg Scale (MBS) is a visual analogue scale which allows participants to communicate their level of breathlessness and can be accessed

from the Australian Lung Foundation (2011). A well known study by Kendrick, Smith and Baxi (2000) was able to demonstrate that this scale correlated well with respiratory variables and can be used to measure dyspnoea.

The MBS allows participants to rate their level of breathlessness from 0 (Nothing at all) to 10 (Maximal). Scores 7 or greater (very severe) was considered termination criteria for the assessment. Refer to Appendix H for more termination criteria in regards to the exercise test.

### 3.3 Screening materials

Prior to testing the participants were requested to complete the Physical Activity Readiness-Questionnaire (PAR-Q) (Appendix I). This form consists of seven questions that can detect medical contraindications to exercise. ACSM recommends the use of this questionnaire as a safe pre-screening tool to identify adults who should not participate in exercise (ACSM 2006). If participants answered no to all PAR-Q questions they were permitted to take part in the exercise test.

A pre-screening questionnaire (Appendix J) was also designed to collect participants demographic data, it asked for information such as age and gender as well as smoking status, history of lung problems, issues with anxiety or claustrophobia, physical activity levels and experience with RPDs. This was adapted from the Occupation Safety and Health Administration (OSHA) Respirator Medical Evaluation Questionnaire. According to OSHA (2011) this information is important when evaluating an individual's suitability for the use of RPDs.

Lastly, the State-Trait Anxiety Inventory (STAI) (Appendix K) was used to measure participants symptoms of state and trait anxiety (Spielberger et al. 1983). In a review of the literature it was apparent that RPDs can increase symptoms of anxiety. Williams (2010) highlighted that individual's diagnosed with anxiety or problems with claustrophobia are more susceptible to the adverse effects of $PCO_2$. The Speilberger State- Trait Anxiety Inventory (STAI) is a widely used assessment tool to evaluate how anxiety can interfere with RPD use (Caretti et al. 2001, Johnson

et al. 2005 and Koh et al. 2006). Some studies have also used the STAI to exclude participants who are prone to anxiety in RPD trials.

Therefore the STAI was used as an additional pre-screening tool for participants at risk of test associated discomfort. The first 20 items of this questionnaire, S-Anxiety scale (STAI Form Y-1) measure how the respondent feels "right now, at this moment". Each item consisted of a direct statement (e.g. "I feel calm") and participants were instructed to rate the strength of their agreement on a scale from 1 (not at all) to 4 (very much so). Scores for each item ranged between 1 and 4.

The last 20 items, the T-Anxiety Scale (STAI Form Y-2) in the questionnaire measured how participants "generally feel". Each item comprised of a statement (e.g. "I feel pleasant"). Participants were instructed to rate their level of agreement of each item on a scale from 1 (almost never) to 4 (almost always). Similarly each item scores ranged between 1 and 4.

Final scores for each scale could range between 30 and 80. If participants scored in the 90$^{th}$ percentile or above, this was indicative of severe anxiety and they were excluded from the study. According to Szeink et al. (2000) a questionnaire to identify a psychological condition, such as severe anxiety can be utilised to determine whether an individual will be suitable to wear a RPD. The STAI was chosen as it is a definitive instrument for measuring anxiety in adults and has also been used effectively as a pre-screening tool in past RPD research (for example Johnson et al. 2000).

## 3.4 Procedures

The testing for the pilot study took place in the Occupational Health and Safety laboratory at UOW, New South Wales, Australia. The laboratory temperature and relative humidity was recorded before testing. Participants were instructed to wear comfortable sporting clothes and running shoes, be clean shaven, to not exercise on the day of the appointment or consume any alcohol, caffeine, cigarettes or heavy meals three hours prior to the appointment.

### *3.4.1 Anthropometric measurements*

Following completion of the questionnaires and pre-screening materials participants initial anthropometric measurements (without shoes and heavy clothes) were taken. The height of each participant was recorded with a stadiometer to the nearest 0.5 cm. The weight of each participant was measured with a calibrated, electronic portable scale to the nearest 0.5 kg. Participants BSA was calculated using the Dubios formula highlighted in the ISO/TS 16976-1: 2007 specifications.

### *3.4.2 TSI Portacount fit test*

In order to be included in the study the participants were required to pass a Portacount fit test (refer to Figure 3.3). This procedure was important to ensure that the RPD achieved a good face seal on the wearer and that no leakage factors limited the results. A minimum fit factor pass level of 500 was necessary.

Participants were asked to put on a large RPD which was connected via an adapter to the TSI Portacount. The participant was allowed enough time to feel comfortable wearing the device and the fit around the eyes, nose and cheeks was checked.

Participants were then asked to perform a series of eight exercises lasting one minute each while wearing the RPD. During each exercise the TSI Portacount would measure face seal leakage. The eight exercises consisted of normal breathing, deep breathing, turning the head side to side, moving head up and down, talking (loud reciting of a written passage), grimacing (smiling or frowning), bending over and normal breathing.

The TSI Portacount was able to show in real time if the participant passed or failed at the conclusion of the test. The result was coded and the participant was prepared for the exercise test.


**Figure 3.3** Participant completing the respirator fit test

### *3.4.3 The exercise test protocol*

In preparation for the exercise test participants resting HR and BP was obtained while seated on the bicycle ergonometer. The seat height of the bicycle ergonometer was adjusted and the procedures for the test described. To study the effects of exercise on the outcome parameters a range of exercise intensities were selected (75 W, 100 W, 125 W, 150 W and 175 W). Appendix O depicts the exercise protocols and record forms (low and high level).

The test began with a sufficient minute warm up at 50 W and a pedal rate of 60 rpm. The starting pedal resistance began at 75 W or 100 W depending on the participant's body size, gender or estimated fitness. The protocol consisted of 25 W increments every five minutes or after a steady state HR was reached (two heart rates within 5 beats $min^{-1}$). Steady HR was deemed to be obtained when there was no variation in HR of more than five beats per minute. Participants were encouraged not to talk for the first three minutes. At the end of third minute they were asked to read the from the rainbow passage for one minute (refer to Appendix L for the Rainbow Passage).

During minute two (no speech) and minute three (speech) of each stage gas analysis and measurement of the physiological parameters (HR, MBS, PIAF) was

conducted. During the fourth minute participants were encouraged not to speak to allow their breathing and HR to normalise.

Each assessment was approximately 8-22 minutes in length depending on the participants fitness levels and signs or symptoms. All participants could voluntarily halt the assessment process at any time. The test was terminated after four stages, volitional fatigue or when the participant reached 85% of their predicted maximum HR. Refer to Appendix H for further termination criteria.

At the end of the test, resistance was reduced to 50 W or lower and the participant was allowed time to cool down for a minimum of two minutes. The participants results were immediately coded and filed. When the test was stopped the participant removed the RPD which was subsequently cleaned in preparation for the next assessment. Participants were also asked to provide any feedback on any test or RPD related discomfort experienced during the assessment. Participants were thanked for their participation.

## FIELD STUDY

The field study was conducted over one week between April 16 and 20, 2012 at a worksite in Mount Isa, Queensland. The logistics, promotion, administration and delivery of the field study will be described in the following sections. The goal of the field study was to identify and understand the impact of $CO_2$ re-breathing in workers who use RPDs as part of their employment duties. A large sample size was a key goal of the field study and would provide a more detailed analysis of the problem and its impact.

The field study was approved by the Human Research Ethics Committee (HREC) of the UOW/South Eastern Sydney and Illawarra Area Health Service (Reference Number: HE11/437 and Appendix B). A process map for the field study is provided in Figure 3.4.

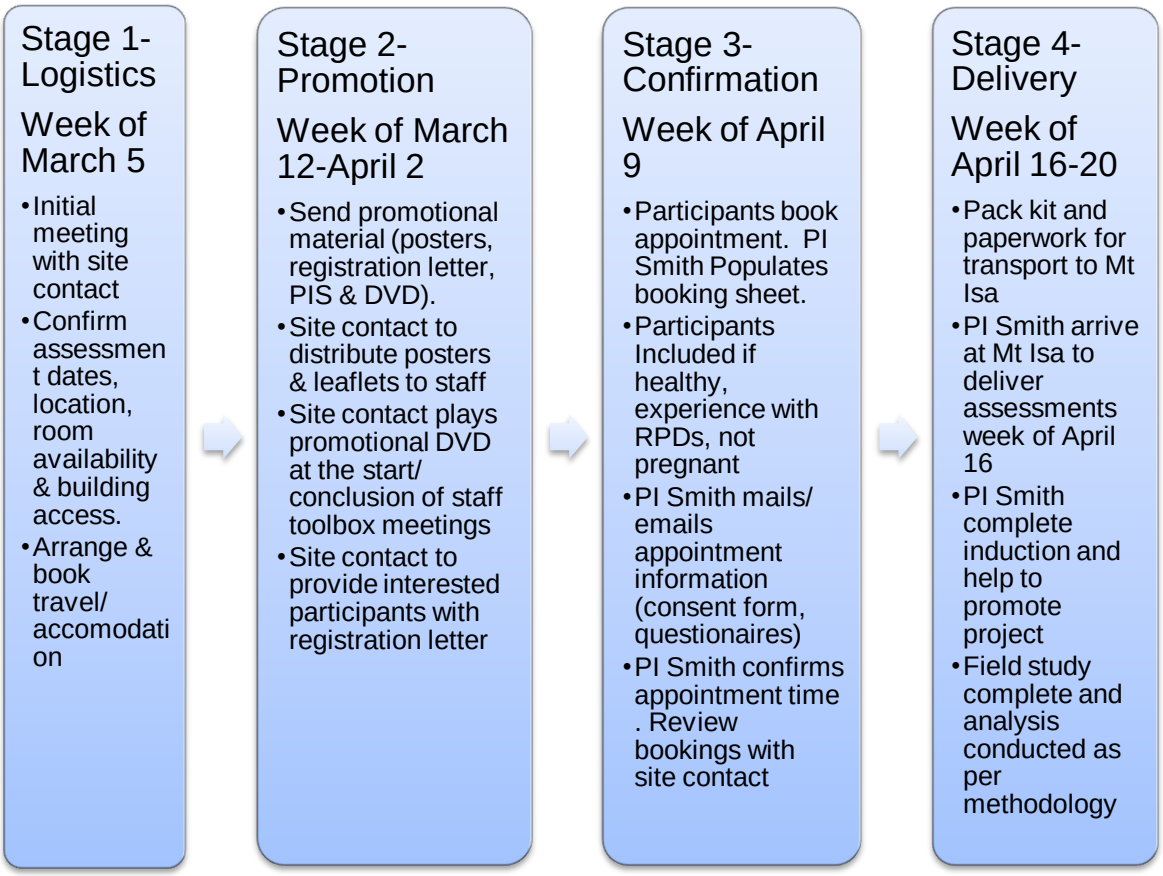



**Figure 3.4** Process map for administration and delivery of the field study

## 3.5 Logistics

The population of interest for the field study was workers who used RPDs on a regular basis. The first stage of the field study involved several logistical meetings to make plans for the promotion and delivery of the research project at the worksite. These meeting were between UOW research supervisors and the worksite site program champions. The meeting involved discussions via telephone and email regarding the research goals, explanation of the risks and benefits of being involved, confirmation of the assessment dates and responding to any questions that the worksite may have. PISs, consent forms, questionnaires and promotional materials were forwarded to the worksite to assist with informing them of the assessment process and procedures (refer to Appendix C to Appendix N).

## 3.6 Promotion

Participants were recruited for the field study from a worksite in Mount Isa, Queensland. Dissemination about the research project to the workers was undertaken using various strategies from word of mouth to the use of multi-media. Participation was voluntary and no incentives were offered. Once the assessment dates, location and times were confirmed the promotion phase began. The promotion strategies used for the field study are described in section 3.6.1 to 3.6.3.

### *3.6.1 Posters and leaflets*

Posters and leaflets were distributed to the worksite to display the assessment date, time and location (Appendix M). Logistically this was an inexpensive way to promote the research. In recognition of the HREC advice, the promotional materials prompted that only the principal investigator (PI) or co-investigators (CIs) at UOW were to be contacted by prospective participants to register their interest.

### *3.6.2 Promotional DVD and information sessions*

In conjunction with the distribution of posters and leaflets a promotional 30 second DVD was produced. The DVD was designed so participants could be better informed regarding the test procedures and who will be conducting the research. The DVD was provided to the site contacts and workers as a more compelling and personalised way than using posters and written formats to explain and encourage participation.

The site contacts had the opportunity to play this DVD at staff meetings leading up to the onsite assessments. Similarly, in recognition of the HREC advice, the DVD encouraged that only PI Smith and CI Whitelaw were to be contacted in regards to the research project. Refer to Appendix N for a copy of the recruitment script.

### *3.6.3 Mail out*

A contact details form, PIS and self addressed envelope marked "Private and Confidential" was circulated to the workers. Again, participants were instructed to complete and return the form to PI Smith or CI Whitelaw in order to volunteer for the project.

## 3.7 Confirmation

A total of 46 workers from a worksite in Mount Isa, Queensland were recruited for the project. All volunteers were booked into an appointment during their normal working hours. All participants received a PIS, pre-screening questionnaire and appointment confirmation letter (refer to Appendix C, J, and E respectively).

Participants were required to be aged between 18 and 69 years, clean shaven and pass a quantitative RPD fit test with a TSI Portacount. Participants were excluded if they had apparent health concerns or musculoskeletal injury (refer to Appendix D for more information regarding inclusion and exclusion criteria). In addition participants were required to avoid exercise and smoking cigarettes or cigars on the day of testing (refer to Appendix E for appointment confirmation letter). If no contraindications to exercise were identified following a complete health history, resting HR and BP screening, participants provided their written informed consent to participate (Appendix F).

## 3.8 Equipment and Procedures

The apparatus and procedures used in the field study were conducted under the same protocols as those used in the pilot study which is described in section 3.2 – 3.4.3.

## 3.9 Outcome Parameters

The key cardio-respiratory variables obtained were heart rate (HR), breathing frequency ($f_R$), peak inspiratory air flow (PIAF), dyspnoea (MBS), percentage of inspired $CO_2$ ($PICO_2$) and percentage of expired $CO_2$ ($PECO_2$). Oxygen uptake ($\dot{V}O_2$) was calculated using the metabolic equation for the total oxygen cost of cycling (ACSM 2006). These parameters were measured against both conditions of no speech and speech during each exercise stage.

## 3.10 Data Analysis

### *3.10.1 Data handling and management*

Data was compiled into a Microsoft Excel 97 (Microsoft Corporation) spreadsheet post assessment this included pre-screening instruments and the physiological parameters measured. The data was screened in this format for any potential problems or errors. All analyses were completed using Statistical Package for the Social Sciences (SPSS) version 19.

### *3.10.2 Statistical analysis*

Descriptive statistics were used to report the physiological and demographic data (age, weight, height and BSA) as mean and standard deviations. To determine whether there were any outliers the box-plot method was used for the six workloads. Data points outside of the interquartile range (size of the box) were checked for processing errors and subsequently remained in the data set for statistical analysis.

This was followed by inferential statistics using $PICO_2$ as the dependent variable. The main test results were paired into speech and no speech and comparisons were made across each of the six workloads (rest, 75 W, 100 W, 125 W, 150 W and 175 W). Independent variables included breathing condition (speech and no speech), HR, gender, BSA, $\dot{V}O_2$, PIAF, $PECO_2$ and MBS scores.

To analyse the differences between the experimental conditions, speech and no speech a paired *t*-test was used. Linear mixed models analysis was used to determine whether significant differences existed in $V\dot{O}_2$ and $PICO_2$ across the six exercise workloads. A significance level of $p<0.05$ (two tailed) was used for all statistical analysis.

# 4 RESULTS

## PILOT STUDY

The aim of the pilot study was to assess the accuracy of the preliminary hypothesis. In addition, it allowed for any methodological problems to be identified and resolved in preparation for the field study. The results of the pilot study are provided in the following sections.

### 4.1 Participants

A total of 22 participants (eight females) volunteered for the pilot study. Testing was carried out in the Occupational Health and Safety laboratory at UOW, New South Wales, Australia at an ambient temperature of 24°C, with an average relative humidity of 60%. The ages ranged from 18 to 58, with a mean age of 33 (SD=±12.4). The majority of these participants were non-smokers (n=20) and 59% (n=13) reported that they were physically active or exercised on a regular basis.

State and trait anxiety scores were converted into percentile scores for a normal adult population. The mean was 37% for state (participants anxiety at the moment of testing) and 54% for trait (participants anxiety proneness). No participants were identified with severe or clinically severe levels of state and trait anxiety which was additional exclusion criteria.

Of the 22 volunteers, all participants passed the medical clearance however, 23% (n=5) did not pass the TSI Portacount fit test. This data has been excluded from the report unless otherwise specified. Refer to Table 4.1 for more demographic information.

**Table 4.1** Demographic characteristics of the pilot participants

| *Participant* | *Gender* | *Age (years)* | *Weight (kg)* | *Height (m)* | *BSA ($m^2$)* | *RPD Fit* |
|---|---|---|---|---|---|---|
| **1** | M | 27 | 75.0 | 1.74 | 1.89 | PASS |
| **2** | M | 26 | 75.0 | 1.81 | 1.95 | PASS |
| **3** | F | 32 | 49.0 | 1.71 | 1.56 | FAIL |
| **4** | F | 33 | 60.0 | 1.76 | 1.73 | PASS |
| **5** | F | 30 | 66.0 | 1.63 | 1.71 | FAIL |
| **6** | M | 39 | 85.0 | 1.85 | 2.08 | PASS |
| **7** | M | 35 | 87.5 | 1.79 | 2.06 | PASS |
| **8** | M | 56 | 78.5 | 1.78 | 1.96 | PASS |
| **9** | F | 53 | 63.0 | 1.53 | 1.60 | PASS |
| **10** | M | 58 | 78.0 | 1.73 | 1.91 | PASS |
| **11** | F | 56 | 78.5 | 1.68 | 1.88 | FAIL |
| **12** | F | 25 | 66.0 | 1.59 | 1.68 | FAIL |
| **13** | F | 26 | 70.0 | 1.69 | 1.80 | PASS |
| **14** | M | 29 | 68.2 | 1.85 | 1.90 | FAIL |
| **15** | M | 41 | 111.0 | 1.66 | 2.16 | PASS |
| **16** | F | 20 | 66.0 | 1.72 | 1.78 | PASS |
| **17** | M | 22 | 92.0 | 1.69 | 2.02 | PASS |
| **18** | M | 18 | 68.0 | 1.75 | 1.82 | PASS |
| **19** | M | 18 | 74.4 | 1.79 | 1.92 | PASS |
| **20** | M | 28 | 71.1 | 1.82 | 1.91 | PASS |
| **21** | M | 27 | 86.8 | 1.83 | 2.09 | PASS |
| **22** | M | 29 | 65.5 | 1.77 | 1.81 | PASS |
| **Mean** | | 33.1 | 73.7 | 1.73 | | |
| **SD** | | 12.4 | 12.9 | 0.08 | | |

**M, Male; F, Female; BSA, Body Surface Area; SD, Standard Deviation**

In regards to the exercise assessment, four participants did not reach 85% of their maximal HR. Reasons participants requested to stop the exercise test before target HR was reached included headache (n=1), development of lower back discomfort (n=1) and general leg fatigue (n=2). Two participants speech fluency and quality was reduced due to reported difficulty reading the prepared text during the exercise assessment (participant 10 and 11). Post assessment all participants stated speech increased symptoms of dyspnoea while wearing the RPD.

The duration that participants were able to complete the exercise assessment varied from 8-21 minutes. $PECO_2$ was higher than 7% in three participants which

equates to a high $PACO_2$ value (John 2003). One of these participants mentioned feeling the onset of a headache and removed the RPD prematurely. Figure 4.1 is a flow chart of the study cohort.

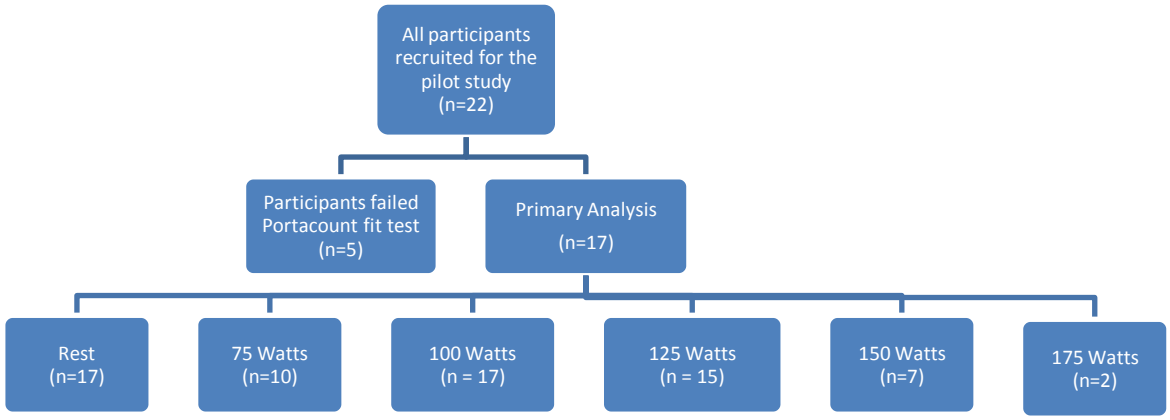



**Figure 4.1** Flowchart of the pilot study participants

## 4.2 Preliminary Results

The results of the pilot study are displayed in Table 4.2. The mean and standard deviations (SD) for all the parameters measured at rest and different workloads can be compared. The recorded outcome parameters included percentage of inspired $CO_2$ ($PICO_2$), percentage of expired $CO_2$ ($PECO_2$), heart rate (HR), peak inspiratory air flow (PIAF), dyspnoea (MBS) and oxygen uptake ($V\dot{O}_2$). The variables were calculated across all six workloads (rest, 75 W, 100 W, 125 W, 150 W and 175 W) and the two breathing conditions (speech and no speech).

**Table 4.2** Effects of speech on respiratory parameters during rest and exercise wearing a full face respiratory protective device

| | *Rest* (n=17) | | | | *75 W (n=10)* | | | | *100 W (n=17)* | | | | *125 W (n=15)* | | | | *150 W (n=7)* | | | | *175 W (n=2)* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | |
| | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD |
| $PICO_2$ (%) | 1.6 | 0.41 | 2.5 | 0.51 | 1.3 | 0.37 | 2.0 | 0.63 | 1.1 | 0.27 | 2.1 | 0.56 | 1.2 | 0.39 | 2.0 | 0.56 | 1.1 | 0.51 | 2.0 | 0.69 | 0.8 | 0.25 | 2.0 | 0.30 |
| $PECO_2$ (%) | 4.1 | 0.86 | 3.9 | 0.67 | 4.6 | 0.49 | 4.4 | 0.71 | 5.2 | 1.42 | 4.8 | 1.07 | 5.3 | 1.39 | 5.0 | 1.08 | 5.4 | 1.48 | 4.9 | 0.99 | 4.5 | 0.22 | 3.9 | 0.04 |
| HR (bpm) | 77 | 11 | 82 | 11 | 112 | 10 | 119 | 9 | 119 | 18 | 130 | 17 | 135 | 16 | 143 | 17 | 139 | 16 | 146 | 18 | 163 | 9 | 167 | 9 |
| $\dot{V}O_2$ (mL kg $min^{-1}$) | 7 | 0 | | | 19.8 | 2.28 | | | 24.3 | 2.71 | | | 28.2 | 3.36 | | | 33.6 | 3.85 | | | 37.4 | 5.94 | | |
| PIAF (L $min^{-1}$) | 61.25 | 10.91 | 114.00 | 25.01 | 116.75 | 20.65 | 198.00 | 0.71 | 143.00 | 22.40 | 228.25 | 45.45 | 179.25 | 25.01 | 263.50 | 40.25 | 211.25 | 40.66 | 308.25 | 51.78 | 275.75 | 68.59 | 431.75 | 3.39 |
| MBS (0-10) | 1 | - | 1 | - | 2 | - | 4 | - | 2 | - | 4 | - | 3 | - | 5 | - | 3 | - | 4 | - | 3 | - | 4 | - |

**M, Mean, SD, Standard Deviation, $PICO_2$, Percentage of Inspired Carbon Dioxide, $PECO_2$, Percentage of Expired Carbon Dioxide, HR, Heart Rate, bpm, Beats per minute, $\dot{V}O_2$, Oxygen Uptake, PIAF, Peak Inspiratory Air Flow , MBS, Modified Borg Dyspnoea Scale.** Statistical significance ($p$<0.05).

### *4.2.1 Effects of phonic respiration (speech)*

Multiple paired-samples *t* tests were conducted to compare $PICO_2$ in the two breathing conditions (no speech and speech) across the six exercise workloads (rest, 75 W, 100 W, 125 W, 150 W and 175 W) (alpha level was set to 0.05). Consistent with the preliminary hypothesis, there was a significant difference in $PICO_2$ between periods of speech and no speech at rest ($t(32)=19.2$, $p=0.00$), 75 W ($t(19)=9.72$, $p=0.00$), 100 W ($t(33)=14.8$, $p=0.00$), 125 W ($t(29)=12.3$, $p=0.00$), 150 W ($t(13)=6.5$, $p=0.00$) and 175 W ($t(3)=7.50$, $p=0.01$).

These results suggest that speech in fact does have an impact on $CO_2$ re-breathing in RPDs. These differences are visible in the following graph (Figure 4.2).

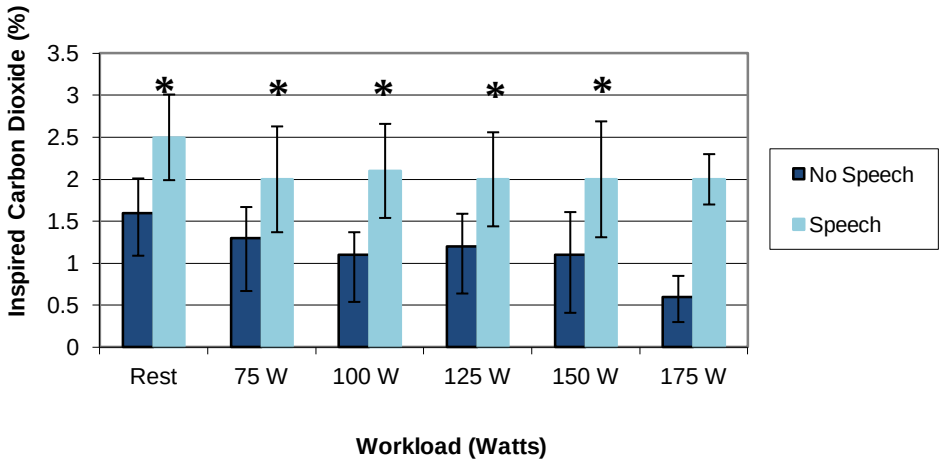



**Figure 4.2** Mean and standard deviations of inspired carbon dioxide during speech and no speech wearing a full face respiratory protective device. The asterisk represents significant differences at each workload ($p<0.05$).

Speech increased $PICO_2$ at any given workload, however, the highest mean $PICO_2$ occurred at rest for both breathing conditions. At rest, $PICO_2$ dramatically increased by 56% during speech compared to no speech (from 1.6% to 2.5% $PICO_2$). In addition, $PICO_2$ appeared to reduce with increased workload. On average, $PICO_2$

was 24% higher during speech at rest, than at end exercise for participants. Mean resting and end exercise values for $PICO_2$ are compared in Table 4.3.

**Table 4.3** Mean carbon dioxide inspired at rest and end exercise for speech and no speech

| | *Rest* | | *End Exercise* | |
|---|---|---|---|---|
| | No Speech | Speech | No Speech | Speech |
| $PICO_2$ (%) | 1.6 | 2.5 | 1.1 | 1.9 |
| SD | 0.41 | 0.51 | 0.38 | 0.60 |

**SD, Standard Deviation, $PICO_2$, Percentage of Inspired Carbon Dioxide**

### *4.2.2 Effects of oxygen uptake*

$CO_2$ re-breathing appeared to decrease as workload or $V\dot{O}_2$ increased. Figure 4.3 shows a decrease in $PICO_2$ with increasing $V\dot{O}_2$ for both conditions. From this, it was hypothesised that $V\dot{O}_2$, actually does not induce $CO_2$ re-breathing and may very well reduce $PICO_2$.

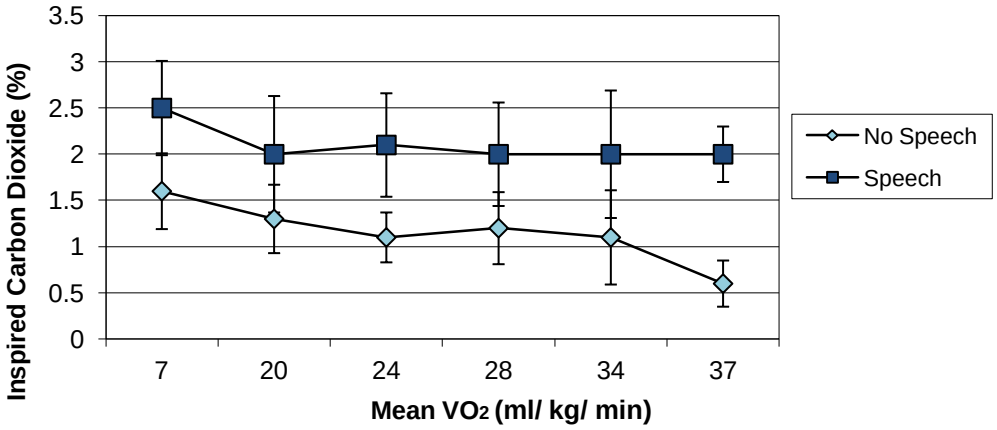


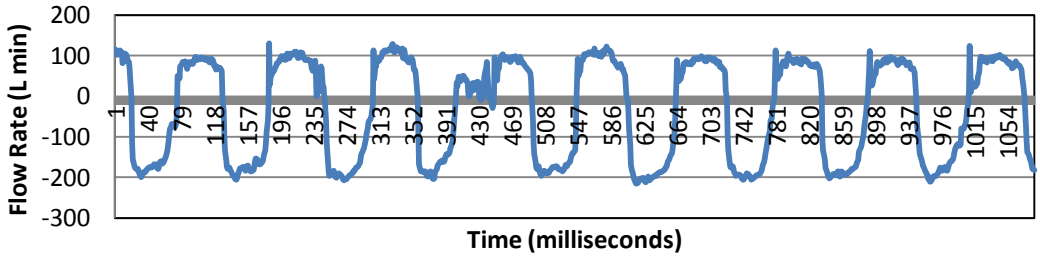

**Figure 4.3** Mean and standard deviations of inspired carbon dioxide during speech and no speech for mean oxygen uptake ($V\dot{O}_2$) at each workload

### *4.2.3 Effects of gender*

A total of eight females volunteered for the pilot study. Half of the female participants (n=4) failed the TSI Portacount fit test. Therefore only four females were included in the analysis. It appeared females had lower $PICO_2$ for all conditions, but the final sample size was too small to accurately support this hypothesis. More research on females and their sensitivity to $CO_2$ re-breathing is an important issue that needs further analysis.

### *4.2.4 Effects of expired carbon dioxide*

Another problem that may contribute to $CO_2$ re-breathing is $PECO_2$. In Table 4.2 $PECO_2$ is observed to rise with exercise workload. However, $PECO_2$ appeared to be lower during speech. As well, $PECO_2$ appeared to vary between participants. For instance, Figure 4.4 and 4.5 is a series of tracings of two participants breathing flow curves as a function of time. One participant (Figure 4.4) $PECO_2$ was relatively low at 4.2% (no speech) and 4.1% (speech). The other participant (Figure 4.5) had significantly higher $PECO_2$ (above 7%). The participant with the higher $PECO_2$ appeared to have lower $f_R$ and maintained speech for longer.



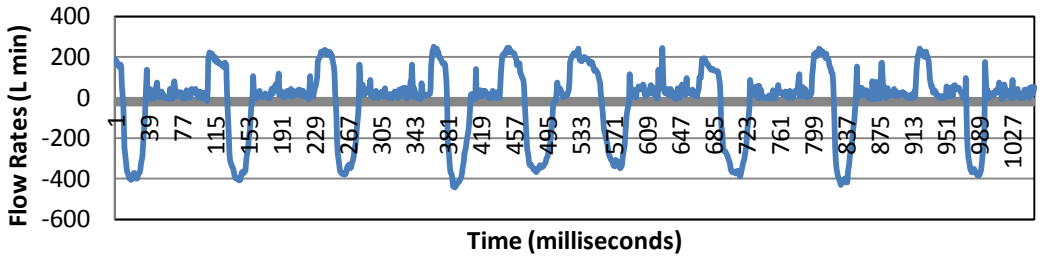



**Figure 4.4** Sample breathing flow curves during no speech (top) and speech (below) whose expired carbon dioxide was relatively low at 4.2%

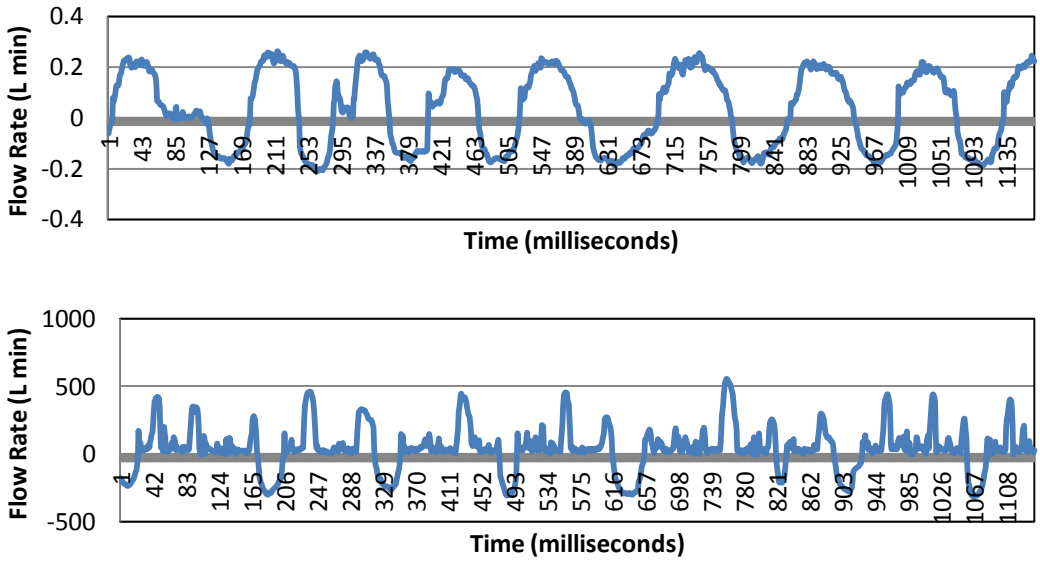



**Figure 4.5** Sample breathing flow curve no speech (top) and speech (below) whose expired carbon dioxide was above 7%

### *4.2.5 Dyspnoea*

Dyspnoea (MBS) scores during speech and no speech are shown in Table 4.2. The relationship between $PICO_2$ and dyspnoea was difficult to establish in this study. MBS peak scores arose during end exercise and speech periods for participants, yet end exercise generally had lower $PICO_2$ on average. Other confounding factors that may contribute to dyspnoea with this protocol include decreased inspiration time, $f_R$ and $V_T$ during speech.

### *4.2.6 Peak inspiratory air flow*

PIAF in this study was calculated as the mean of all breaths during 30 seconds of each measurement period and corrected to BTPS. The highest PIAF scores were seen during speech (Table 4.2). The maximum mean PIAF was 431.75 L $min^{-1}$ (SD=3.39) and occurred at 175 W during speech. Whereas the lowest mean PIAF was 61.25 L $min^{-1}$ (SD=10.91) occurred at rest and during no speech. PIAF was also affected by exercise workload and increased by 77% when PIAF was compared at rest (no speech) and at 175 W. It can be assumed higher flow rates affects $PICO_2$ by aiding in the removal of $PECO_2$ from the RPD.

### *4.2.7 Heart Rate*

Speech appeared to have an impact on HR. HR was on average 6% higher during speech than no speech. Yet, this difference decreased in magnitude with workload. As $PICO_2$ was generally higher during lighter workloads, this tends to support that $CO_2$ re-breathing increases HR.

## 4.3 Study Limitations

The pilot study allowed changes to the apparatus and procedures to be implemented before the field study was conducted. The main modifications to the methodology are summarised below.

### *4.3.1 Equipment modifications*

Prior to the pilot study the apparatus was observed to have high variability in $CO_2$ levels. Two compartments of water were used to collect samples of inhaled and exhaled air (Figure 4.6). It was detected that the water was absorbing $CO_2$ from the sampled air and was releasing this $CO_2$ over time, which resulted in artificially high

readings. The apparatus was subsequently modified so that inhaled and exhaled air was sampled from rubber balloons. This set up can be observed in Figure 4.7.


**Figure 4.6** Initial apparatus to collect separate gas samples of expired and inspired air using two compartments of water

**Figure 4.7** The modified apparatus to collect expired and inspired air samples using rubber balloon mechanism

In addition throughout the pilot study the $CO_2$ analyser exhibited a slow upward drift in readings. This was corrected by calibrating the apparatus immediately prior to testing. The need to calibrate the rig before each test was an essential aspect of the pilot procedure. It is noted that this limitation of the equipment may lead to some variability or overestimation of $CO_2$ re-breathing.

### *4.3.2 Procedural difficulties*

It is worth noting nearly one in four participants did not meet the preferred inclusion criteria of passing the TSI Portacount fit test (refer to Table 4.1). Despite few significant differences found in $PICO_2$ results for participants who passed or failed the TSI Portacount fit test it is recommended that this is upheld as inclusion criteria for the field study. This is because employees are required to pass fit tests before they don RPDs in the workplace. The disadvantage to this procedure is that it adds 10-15 minutes to the length of the assessment process and decreases the sample size for data analysis.

## 4.4 Summary

In summary, the practicability of performing the tests for the field study is high. The benefit of conducting the pilot study was it allowed us to identify and overcome possible errors that may limit data collection before moving onto the field study. The pilot study supported the hypothesis that $CO_2$ re-breathing increases during speech. Since increased $PICO_2$ necessitates increased $V_{E,}$ $f_R$, $PECO_2$, dyspnoea and limits exercise performance, speech may very well contribute to RPD discomfort and reduce wear time. RPDs that are designed to permit speech and communication should take these findings into consideration. Further analysis of $CO_2$ re-breathing in RPDs and its impact on workers who inevitably wear them for prolonged periods is warranted.

## THE FIELD STUDY

From the pilot study it was hypothesised that speech and low exercise workloads would contribute to $CO_2$ re-breathing in RPDs. A larger sample size was required in the field study so that the interaction of BSA, gender and age could be thoroughly investigated. The results of the field study are provided in the following sections.

### 4.5 Participants

A total of 46 participants (one female) trained in the use of RPDs, volunteered for the field study. Of this sample, 13% (n=6) did not meet the selection criteria for inclusion into the study, leaving a total of 40 participants. Five participants were excluded from participation at the level of the PAR-Q form and one due to equipment failure. All participants passed fit testing (>500 protection factor) with the large S.E.A full face mask.

The ages of the participants ranged from 19 to 58 years, with a mean age of 35 (SD=±9.5). The majority of these participants were non smokers (n=32) and 55% (n=22) reported that they were physically active or exercised on a regular basis.

State and trait anxiety scores were converted into percentile scores for a normal adult population. The mean was 28% for state (participants anxiety at the moment of testing) and 40% for trait (participants anxiety proneness). No participants were identified with severe or clinically severe levels of state or trait anxiety, which was an additional exclusion criterion. Table 4.4 provides information on the participants characteristics.

**Table 4.4** Characteristics of the field study participants

| | **Mean** | **Median** | **Minimum** | **Maximum** |
|---|---|---|---|---|
| **Age (years)** | 35 | 34 | 19 | 58 |
| **Weight (kg)** | 91.7 | 89.5 | 58 | 128 |

| | | | | |
|---|---|---|---|---|
| **Height (m)** | 1.79 | 1.77 | 1.67 | 1.92 |
| **BSA ($m^2$)** | 2.09 | 2.09 | 1.67 | 2.41 |
| **State anxiety score (%)** | 28 | 20 | 2 | 88 |
| **Trait anxiety score (%)** | 40 | 39 | 2 | 87 |
| **Gender** | 1 female, 39 males | | | |

**Kg, Kilogram, m, Metre, $m^2$, Metre Squared, BSA, Body Surface Area**

Testing was undertaken in an air conditioned room maintained at 24°C and 40% relative humidity. The duration that participants were able to complete the exercise assessment varied from 8-22 minutes. The sample varied in fitness, gender and BSA, therefore 22 participants (55%) were administered the high level exercise protocol and 18 completed the low level assessment. Within this, 12 participants (30%) did not reach 85% of their maximal HR. Reasons to stop the exercise test before target HR was reached included lower limb fatigue (n=6), end of exercise protocol (n=3), dyspnoea (n=2) and general fatigue (n=1). Post assessment, all participants reported speech contributed to dyspnoea while wearing the RPD. Unlike the pilot study no participants experienced high $PECO_2$ beyond 7% or described symptoms of headache, blurred vision or dizziness. This suggests trained users of RPDs may have decreased sensitivity to $CO_2$. Figure 4.8 is a flow chart of the study cohort.

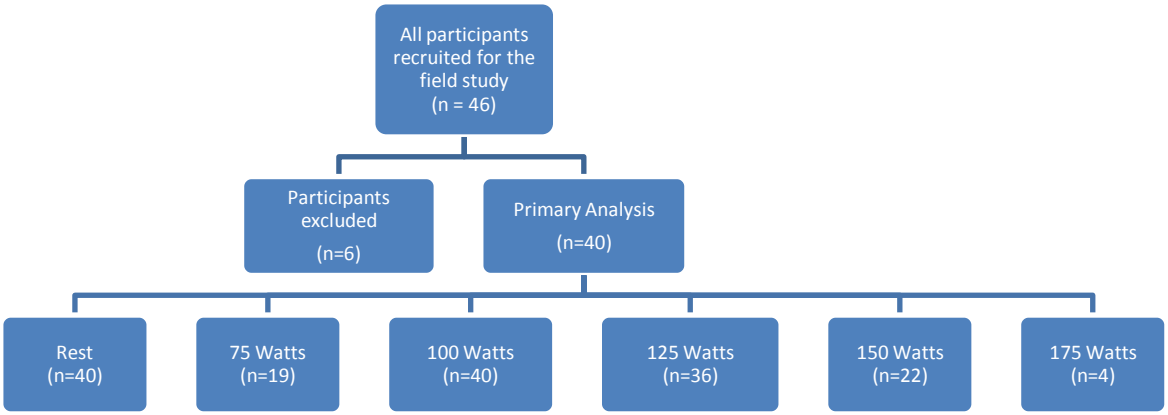



**Figure 4.8** Flowchart of field study participants

## 4.6 Results

The results of the field study for both breathing conditions (speech and no speech) are displayed in Table 4.5. Generally data for all 40 participants was reported on, but two data sets at rest and 100 W was disregarded due to inconsistency regarding speaking during a no speech stage. The mean (M) and standard deviations (SD) for all the parameters measured at rest and different workloads were compared. The recorded outcome parameters included percentage of inspired $CO_2$ ($PICO_2$), percentage of expired $CO_2$ ($PECO_2$), heart rate (HR), breathing frequency ($f_R$), peak inspiratory air flow (PIAF), dyspnoea (MBS) and oxygen uptake ($V\dot{O}_2$). The outcome measures were calculated across all six workloads (rest, 75 W, 100 W, 125 W, 150 W and 175 W) and the two breathing conditions (speech and no speech).

**Table 4.5** Effects of speech on respiratory parameters during rest and exercise wearing a full face respiratory protective device

| | *Rest* (n=40) | | | | *75 W (n=19)* | | | | *100 W (n=40)* | | | | *125 W (n=36)* | | | | *150 W (n=22)* | | | | *175 W (n=4)* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | | No Speech | | Speech | |
| | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD | M | SD |
| $PICO_2$ (%) | 1.52 | 0.38 | *2.10 | 0.47 | 1.20 | 0.21 | *1.50 | 0.36 | 1.16 | 0.26 | *1.57 | 0.36 | 1.05 | 0.20 | *1.46 | 0.37 | 0.96 | 0.19 | *1.36 | 0.32 | 1.01 | 0.27 | 1.43 | 0.17 |
| $PECO_2$ (%) | 3.87 | 0.38 | 3.82 | 0.42 | 4.82 | 0.47 | 4.70 | 0.56 | 4.80 | 0.54 | 4.60 | 0.46 | 4.79 | 0.44 | 4.56 | 0.49 | 4.63 | 0.46 | 4.44 | 0.67 | 4.74 | 0.31 | 4.56 | 0.23 |
| HR (beat $min^{-1)}$ | 82 | 12 | 84 | 14 | 112 | 15 | 116 | 16 | 121 | 13 | 125 | 16 | 134 | 14 | 137 | 14 | 144 | 10 | 146 | 10 | 150 | 9 | 157 | 9 |
| $f_R$ (breaths $min^{-1}$) | 17 | 5 | 13 | 4 | 21 | 5 | 18 | 4 | 22 | 6 | 19 | 5 | 25 | 5 | 21 | 5 | 26 | 6 | 24 | 5 | 26 | 4 | 26 | 4 |
| $\dot{V}O_2$ (mL-kg $min^{-1}$) | 7.0 | 0 | - | - | 18.8 | 1.51 | - | - | 21.6 | 2.18 | - | - | 25.3 | 2.75 | - | - | 28.7 | 3.32 | - | - | 33.2 | 4.01 | - | - |
| PIAF ** (L $min^{-1}$) | 80.50 | 15.89 | *125.75 | 30.77 | 150.00 | 15.01 | *225.00 | 28.87 | 172.75 | 20.47 | *247.25 | 27.18 | 201.50 | 20.02 | *268.75 | 25.75 | 232.25 | 30.84 | 305.25 | 35.52 | 227.75 | 31.79 | *323.50 | 46.42 |
| MBS (0-10) | 0 | - | 0.5 | - | 1 | - | 2.5 | - | 2 | - | 3 | - | 3 | - | 4 | - | 4 | - | 4.5 | - | 3 | - | 5 | - |

**M, Mean, SD, Standard Deviation, $PICO_2$, Percentage of Inspired Carbon Dioxide, $PECO_2$, Percentage of Expired Carbon Dioxide, HR, Heart Rate, $f_R$, Breathing Frequency, PIAF, Peak Inspiratory Air Flow , MBS, Modified Borg Dyspnoea Scale, BTPS, Body Temperature & Pressure Saturated.** *Statistical significance ($p$<0.05) from paired samples $t$-test.

**PIAF is in BTPS and rounded to the nearest 0.25

### *4.6.1 Effects of phonic respiration (speech)*

Speech significantly elevated the levels of $CO_2$ re-breathed inside the RPD. The mean level of $PICO_2$ during speech was (mean±SD) 2.1±0.47%, 1.5±0.36%, 1.6±0.36%, 1.5±0.37%, 1.4±0.32% and 1.4±0.17% for the period of Rest, 75 W, 100 W, 125 W, 150 W and 175 W respectively. In the same order the mean $PICO_2$ attained during no speech was 1.5±0.38%, 1.2±0.21%, 1.2±0.26%, 1.1±0.20%, 1.0±0.19% and 1.0±0.27% (refer to Table 4.6).

Multiple paired-samples *t* tests were conducted to compare $PICO_2$ that occurred in the two breathing conditions (no speech and speech) across all six exercise workloads (rest, 75 W, 100 W, 125 W, 150 W and 175 W) (alpha level was set to 0.05). Consistent with the pilot results, there was a significant difference in $PICO_2$ between periods of speech and no speech at rest ($t(38)=7.75$, $p=0.00$), 75 W ($t(18)=6.07$, $p=0.00$), 100 W ($t(35)=6.07$, $p=0.00$), 125 W ($t(33)=6.57$, $p=0.00$), and 150 W ($t(11)=4.90$, $p=0.00$). Although there was a weak relationship at 175 W, it did not achieve significance ($t(3)=2.93$, $p=0.06$) (refer to Figure 4.9).

**Table 4.6** Mean carbon dioxide inspired at rest and exercise for conditions of no speech and speech

| | *No Speech* | | *Speech* | | | |
|---|---|---|---|---|---|---|
| | M | SE | M | SE | t | df |
| Rest | 1.5 | 0.06 | 2.1* | 0.08 | 7.75 | 38 |
| 75 W | 1.2 | 0.03 | 1.5* | 0.06 | 6.07 | 18 |
| 100 W | 1.2 | 0.04 | 1.6* | 0.06 | 6.07 | 35 |
| 125 W | 1.1 | 0.03 | 1.5* | 0.06 | 6.57 | 33 |
| 150 W | 1.0 | 0.03 | 1.4* | 0.05 | 4.90 | 11 |
| 175 W | 1.0 | 0.04 | 1.4 | 0.03 | 2.93 | 3 |

**M, Mean, SE, Standard Error of the Mean. Note. *=Statistical significance (p≤0.05) from paired samples *t*-test.**

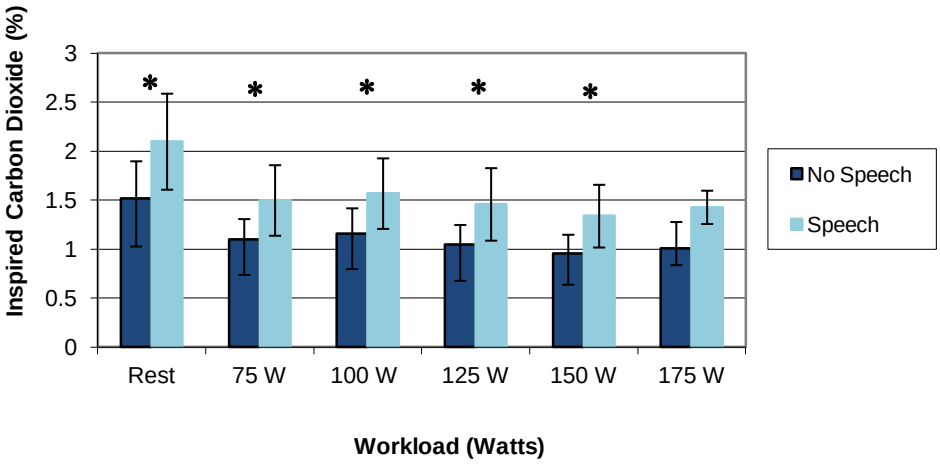



**Figure 4.9** Mean and standard deviations of inspired carbon dioxide during speech and no speech wearing a full face respiratory protective device. The asterisk represents significant differences at each workload ($p<0.05$).

Speech increased $PICO_2$ during rest and exercise. The highest percentage change for $PICO_2$, between speech and no speech occurred at 175 W. $PICO_2$ increased considerably by 42% during speech at 175 W (from 1.0% to 1.4% $PICO_2$). The highest mean $PICO_2$ occurred at lower workloads for both breathing conditions. On average, $PICO_2$ was 32% higher during speech at rest, than at end exercise for participants. Mean resting and end exercise values for $PICO_2$ are compared in Table 4.7.

**Table 4.7** Mean carbon dioxide inspired at rest and end exercise for speech and no speech

| | ***Rest*** | | ***End Exercise*** | |
|---|---|---|---|---|
| | No Speech | Speech | No Speech | Speech |
| $PICO_2$ (%) | 1.5 | 2.1 | 1.0 | 1.4 |
| SD | 0.38 | 0.54 | 0.16 | 0.37 |

**SD, Standard Deviation, $PICO_2$, Percentage of Inspired Carbon Dioxide**

Some participants $PICO_2$ exceeded 3% during speech at rest. For example, $PICO_2$ reached a maximum of 3.5% in one participant. Figures 4.10 to 4.12 shows

breathing flow data of three participants with 3% $PICO_2$ or greater. None of these participants reported symptoms connected to $CO_2$ re-breathing (nausea, headache or dizziness). In two of the three participants, speech caused a reduction in respiration by reducing $f_R$ by almost 20%. The third participant (Figure 4.12) had a $f_R$ of nine breaths per minute which was 50% lower than baseline.

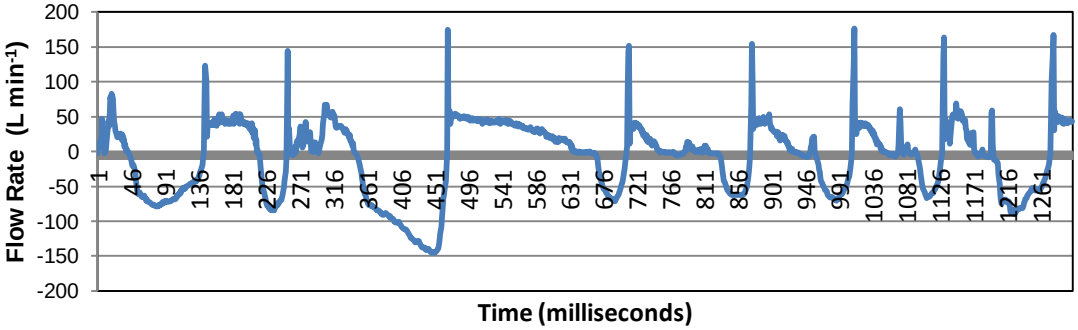



**Figure 4.10** Breathing flow data for one participant with inspired carbon dioxide as high as 3.0% during rest and speech

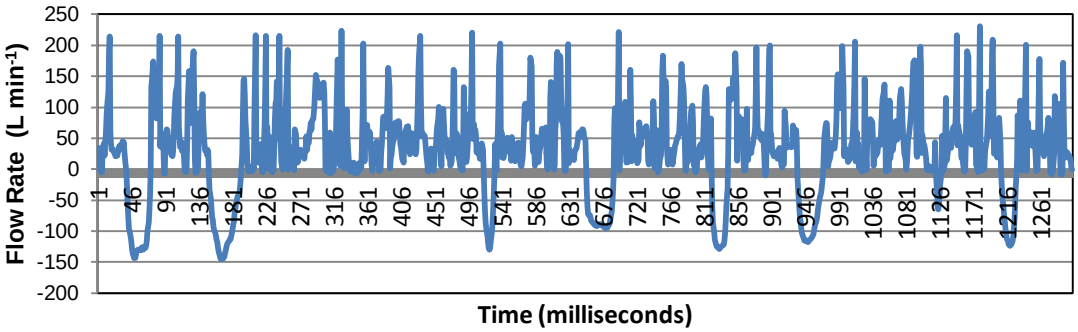



**Figure 4.11** Breathing flow data for one participant with inspired carbon dioxide as high as 3.1% during rest and speech

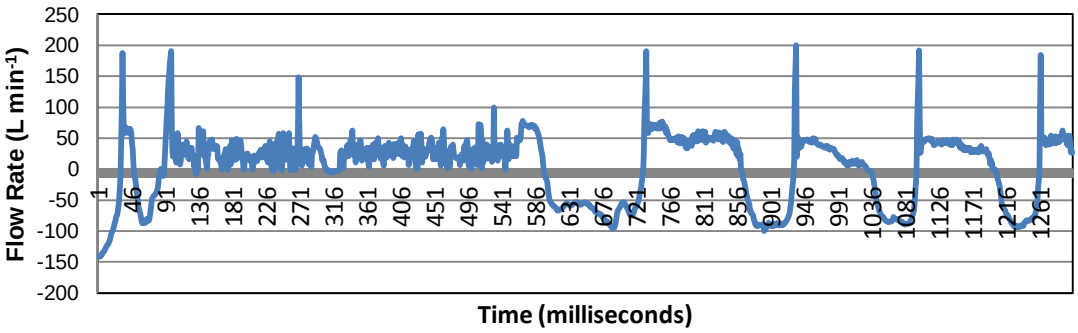



**Figure 4.12** Breathing flow data for one participant with inspired carbon dioxide as high as 3.5% during rest and speech

For two participants observed to have the lowest $PICO_2$ at rest and during speech (1.3%) their breathing patterns appeared to be inconsistent with others. One participant's $f_R$ was 25% higher during speech. The other participant's $f_R$ was observed not to change with or without speech (18 breaths per minute, 30% higher than the average).

In summary, $PICO_2$ levels during no speech and work was always below 2%. However, an elevation in $PICO_2$ above 2% occurred for several participants during speech at 75 W (n=2), 100 W (n=6) and 125 W (n=3). Therefore, the results of the field study support the findings from the pilot study that suggest $PICO_2$ is significantly elevated during periods of speech in RPDs.

### *4.6.2 Effects of oxygen uptake*

The field study also aimed to determine the impact of metabolic workload on $CO_2$ re-breathing. The mean $V\dot{O}_2$ values for rest and each exercise workload is displayed in Table 4.2. The highest mean $V\dot{O}_2$ was 33.15 ml kg $min^{-1}$ and gave rise to 1.0% (no speech) and 1.4% (speech) $PICO_2$. Additionally the minimum $PICO_2$ was 0.6% and was obtained at this work rate. The results obtained showed that higher $\dot{V}O_2$ levels resulted in the decline of $PICO_2$. Figure 4.13 shows a negative trend in $PICO_2$ with

increasing $V\dot{O}_2$ for both conditions. Hence it was hypothesised that increased $V\dot{O}_2$, may very well reduce $PICO_2$ in RPDs.

To evaluate this prediction, linear mixed model analysis was conducted to assess the effects of $\dot{V}O_2$ and the experimental conditions, speech and no speech, on $PICO_2$. There were five levels of $V\dot{O}_2$ corresponding to the following groups: rest (n=40), 75 W (n=19), 100 W (n=40), 125 W (n=36) and 150 W (n=22). Note that 175 W was not tested due to unsatisfactory sample size. Statistical significance was set at an alpha level of 0.05.

Without speech, the effect of $\dot{V}O_2$ on $PICO_2$ was significant, $F(1, 4)=19.8$, $p=0.00$. Similarly, interactions between speech and $\dot{V}O_2$ had significant effects on $PICO_2$, $F(1, 4)=25.7$, $p=0.00$. Post-hoc tests were conducted to examine all pairwise contrasts using the Bonferroni adjustment. Since this involved five pairwise contrasts for each workload (excluding 175 W due to small sample size) the critical alpha level to be used for these contrasts was 1/5 times 0.05, that is, a critical $\alpha$ of 0.2. Of the five contrasts without speech, level one (rest) differed significantly from all others and level 5 (150 W) differed significantly from level 1 (rest) and level 3 (100 W). However, level 2 (75 W) did not differ significantly from 3 (100 W) or 4 (125 W) ($p<0.05$). Similarly during speech, level one (rest) differed significantly from all others. Level 3 (100 W) did not differ from level 2 (75 W), level 4 (125 W) and level 5 (150 W). This reflects that $CO_2$ re-breathing is reduced significantly once a higher $\dot{V}O_2$ is obtained with exercise. However, the difference between $PICO_2$ against small increments in $V\dot{O}_2$ is less significant.

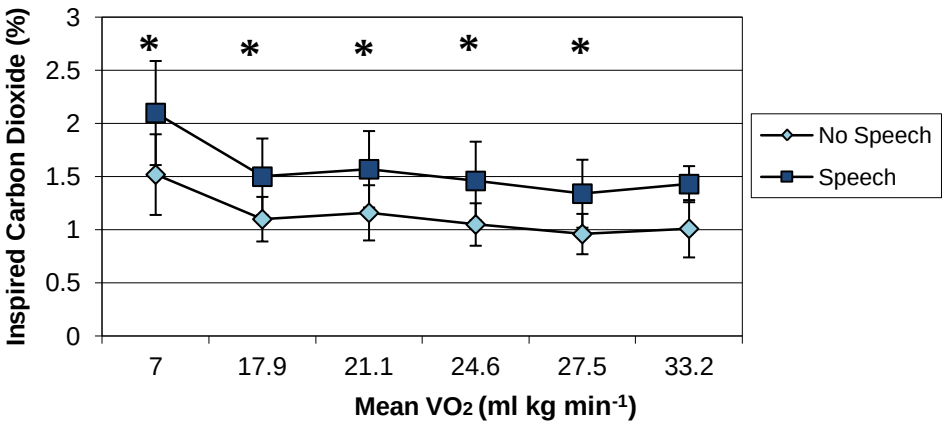



**Figure 4.13** Mean and standard deviations of inspired carbon dioxide for oxygen uptake ($V\dot{O}_2$) during both speech and no speech. The asterisk represents significant differences at each workload ($p<0.05$).

### *4.6.3 Body surface area*

Participants were categorised into groups based on their calculated BSA (small: BSA≤1.70 $m^2$; medium: 1.70 $m^2$<BSA≤1.90 $m^2$; large: BSA>1.90 $m^2$). The goal was to recruit a wide range of persons representing three body sizes (small, medium and large), however 35 participants (88%) fell into values for a person with a large BSA (>1.9 $m^2$). The mean BSA was 2.08 $m^2$ and only five participants (13%) had a BSA between 1.7 $m^2$ and 1.9 $m^2$ (medium body size). Therefore, analysis of BSA and $PICO_2$ were limited to these two categories.

An independent *t* test was conducted on $PICO_2$ values, with α at 0.05, to determine if BSA influenced the data. The mean $PICO_2$, PIAF, $V\dot{O}_2$ and for both medium and large BSA is displayed in Table 4.8.

Assumptions of normality and homogeneity of variance was met for both test conditions (no speech and speech) at rest. The *t* test results indicated that there was not a statistically significant difference in the $PICO_2$ levels between the medium BSA, no speech group (M=1.48, SD=0.31) and large, no speech group (M=1.52, SD=0.39) conditions $t(37)=0.25$, $p=0.80$. Similarly no significant differences were revealed for $PICO_2$ levels between the medium BSA, speech group (M=1.98,

SD=0.44) and large, speech group (M=2.12, SD=0.48) conditions $t(38)=0.58$, $p=0.72$.

At 75 W, a weak relationship between the medium BSA, no speech group (M=0.89, SD=0.01) and large BSA, no speech group (M=1.16, SD=0.19) was found however, it did not reach significance $t(15)=2.00$, $p=0.06$. There was a violation of the assumption of homogeneity of variance at 75 W (speech) so the *t* test for unequal variance was computed. The results indicated significant differences for $PICO_2$ levels between the medium BSA, speech group (M=1.18, SD=0.28) and large, speech group (M=1.58, SD=0.35) conditions $t(15)=4.32$, $p=0.00$.

Assumptions of normality and homogeneity of variance was met for both test conditions (no speech, speech) at 100 W. The *t* test results indicated that there was not a statistically significant difference in the $PICO_2$ levels between the medium BSA, no speech group (M=1.15, SD=0.27) and large, no speech group (M=1.16, SD=0.26) conditions $t(37)=0.13$, $p=0.90$. Similarly no significant differences were revealed for $PICO_2$ levels between the medium BSA, speech group (M=1.70, SD=0.60) and large, speech group (M=1.56, SD=0.34) conditions $t(34)=0.74$, $p=0.47$.

Again, assumptions of normality and homogeneity of variance was met for both test conditions (no speech and speech) at 125 W. The *t* test results indicated that there was not a statistically significant difference in the $PICO_2$ levels between the medium BSA, no speech group (M=1.04, SD=0.26) and large, no speech group (M=1.06, SD=0.19) conditions $t(34)=0.12$, $p=0.88$. Also, no significant differences were revealed for $PICO_2$ levels between the medium BSA, speech group (M=1.61, SD=0.58) and large, speech group (M=1.44, SD=0.34) conditions $t(32)=0.83$, $p=0.42$.

At 150 W assumptions of normality and homogeneity of variance was met for both test conditions (no speech, speech). The *t* test results indicated that there was not a statistically significant difference in the $PICO_2$ levels between the medium BSA, no speech group (M=0.89, SD=0.33) and large, no speech group (M=0.97, SD=0.18) conditions $t(20)=0.56$, $p=0.59$. Also, no significant differences were revealed for $PICO_2$ levels between the medium BSA, speech group (M=1.32, SD=0.36) and large, speech group (M=1.36, SD=0.33) conditions $t(10)=0.19$, $p=0.89$.

Lastly, at 175 W due to the small sample size tests for homogeneity of variance could not be carried out. Overall, these results suggest that BSA may not have an important affect on $PICO_2$ in RPDs. However, at some workloads there did appear to be a slight tendency for larger participants to have a greater level of $CO_2$ re-breathing. Future research will benefit from comparing $PICO_2$ in small to medium size wearers of RPDs.

**Table 4.8** Mean inspired carbon dioxide for medium (a) and large (b) BSA participants

**(a) Mean Carbon dioxide inspired at rest and exercise for speech and no speech tasks in medium BSA participants**

| *Stage* | *Power Output W* | *Oxygen Uptake* $V\dot{O}_2$ *ml kg min*$^{-1}$ | *PIAF No Speech L min*$^{-1}$ *(BTPS)* | *PIAF Speech L min*$^{-1}$ *(BTPS)* | *PICO*$_2$ *No Speech %* | *PICO*$_2$ *Speech %* |
|---|---|---|---|---|---|---|
| 1(n=4) | 0 | 7.0 | 61.13 | 99.25 | 1.5 | 2.0 |
| 2(n=3) | 75 | 21.0 | 135.40 | 248.5 | 0.9 | *1.2 |
| 3(n=4) | 100 | 25.0 | 139.80 | 227.75 | 1.2 | 1.7 |
| 4(n=4) | 125 | 29.5 | 166.88 | 248.75 | 1.0 | 1.6 |
| 5(n=2) | 150 | 34.3 | 200.85 | 306.0 | 0.9 | 1.3 |
| 6(n=1) | 175 | 38.2 | 190.30 | 292.0 | 1.0 | 1.6 |

**Percentage of Inspired Carbon Dioxide, PIAF, Peak Inspiratory Air Flow , W, Watts,$VO_1$, Oxygen Uptake, BTPS, Body Temperature & Pressure Saturated. *Statistical significance (p<0.05) from an independent *t* test**

**(b) Mean Carbon dioxide inspired at rest and exercise for speech and no speech tasks in large BSA participants**

| *Stage* | *Power Output W* | *Oxygen Uptake* $V\dot{O}_2$ *ml kg min*$^{-1}$ | *PIAF No Speech L min*$^{-1}$ *(BTPS)* | *PIAF Speech L min*$^{-1}$ *(BTPS)* | *PICO*$_2$ *No Speech %* | *PICO*$_2$ *Speech %* |
|---|---|---|---|---|---|---|
| 1(n=35) | 0 | 7 | 75.81 | 129.50 | 1.5 | 2.1 |
| 2(n=17) | 75 | 17.6 | 138.29 | 222.25 | 1.1 | *1.5 |
| 3(n=32) | 100 | 20.7 | 160.95 | 249.50 | 1.2 | 1.6 |
| 4(n=30) | 125 | 24.0 | 187.55 | 271.25 | 1.1 | 1.4 |
| 5(n=10) | 150 | 26.9 | 214.71 | 305.00 | 1.0 | 1.4 |
| 6(n=3) | 175 | 31.5 | 215.83 | 334.00 | 1.0 | 1.4 |

**Percentage of Inspired Carbon Dioxide, PIAF, Peak Inspiratory Air Flow , W, Watts,$VO_1$, Oxygen Uptake, BTPS, Body Temperature & Pressure Saturated. *Statistical significance (p<0.05) from an independent *t* test**

### *4.6.4 Effects of gender*

Only one female participant was recruited for the field study. Again, it appeared females had a lower $PICO_2$ for most conditions. However, a larger sample is required to accurately support this hypothesis. More research on females and their sensitivity to $CO_2$ re-breathing is an important issue that needs further analysis.

### *4.6.5 Effects of expired carbon dioxide*

Exhaled air was $CO_2$ rich and generally ranged from 3-5% in the data. Despite $PICO_2$ highest at rest and during speech, $PECO_2$ remained higher during periods of work and in the absence of speech (see Figure 4.14). The maximum mean $PECO_2$ was 4.82% and occurred at 75 W (no speech). The lowest mean $PECO_2$ was 3.82% and occurred at rest (speech).

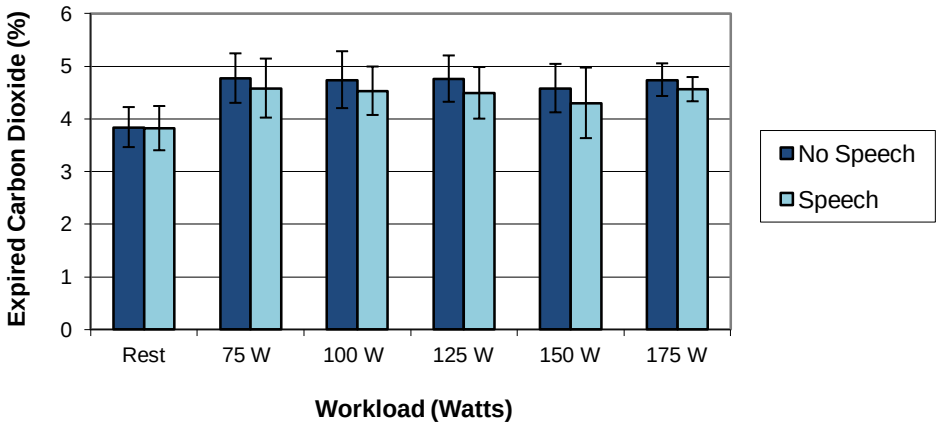



**Figure 4.14** Mean and standard deviations of expired carbon dioxide during exercise for speech and no speech

Overall, the two highest $PECO_2$ values was 5.8% and occurred at 75 W (speech) and 100 W (no speech). High $PECO_2$ did not correspond with symptoms of hypercapnia

(such as dyspnoea). Figure 4.15 and 4.16 reflects tracings of breathing flow curves for both these participants. Once more, higher $PECO_2$ appears to correlate with lower $f_R$ and larger $V_T$.

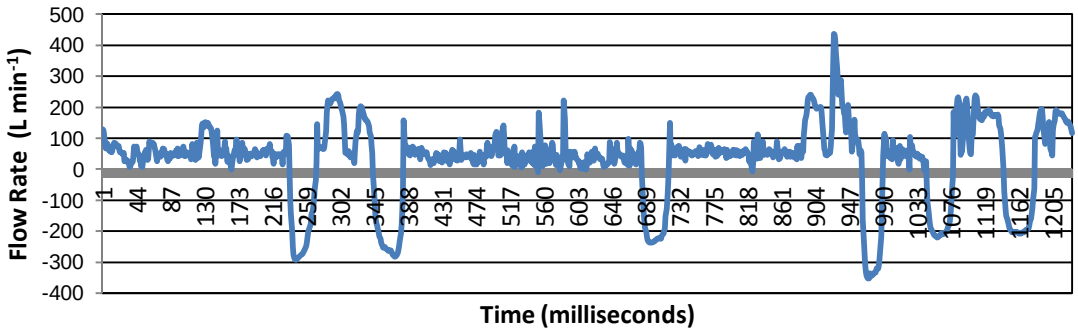



**Figure 4.15** Breathing flow data for one participant with expired carbon dioxide as high as 5.8% at 75 W (speech)

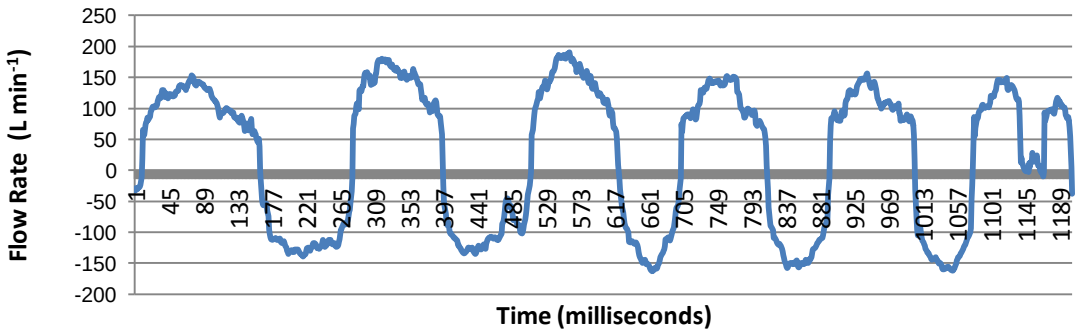



**Figure 4.16** Breathing flow data for one participant with expired carbon dioxide as high as 5.8% at 100 W (no speech)

### *4.6.6 Dyspnoea*

Dyspnoea (MBS) scores during speech and no speech are shown in Table 4.2. No dyspnoea was reported during rest. However, dyspnoea was observed to rise during both exercise and speech. $PECO_2$ may be linked to dyspnoea, as $PECO_2$ increased with exercise. However, $PECO_2$ appeared to be lower during speech, therefore, the link between $PCO_2$ and dyspnoea was difficult to establish in this study.

### *4.6.7 Peak inspiratory air flow*

PIAF in this study was calculated as the mean of all breaths during 30 seconds of each measurement period. The highest PIAF scores were seen during speech (Table 4.2). The maximum mean PIAF was 323.50 L $min^{-1}$ and occurred at 175 W during speech. Whereas the lowest mean PIAF was 80.50 L $min^{-1}$ occurred at rest and during no speech.

Multiple paired samples *t* tests were conducted to compare PIAF and the two breathing conditions (no speech and speech) across the six exercise workloads (rest, 75 W, 100 W, 125 W, 150 W and 175 W) (alpha level was set to 0.05). There was a significant difference in PIAF between periods of speech and no speech at rest ($t(39)=-2.85$, $p=0.01$), 75 W ($t(34)=-5.27$, $p=0.00$), 100 W ($t(39)=-4.14$, $p=0.00$), 125 W ($t(39)=-4.47$, $p=0.00$) and 175 W ($t(39)=-2.05$, $p=0.047$). Although there was a weak relationship at 150 W, it did not achieve significance ($t(39)=1.78$, $p=0.08$). These values are lower than those achieved in the pilot study signifying that trained wearers of RPDs may have a greater tolerance for performing work in RPDs. PIAF was also affected by exercise workload. For instance, PIAF increased by 77% from rest (no speech) to 175 W (no speech). Given the lowest mean $PICO_2$ readings occurring at 175 W, it is possible higher flow rates aid in the removal of $PECO_2$ in the RPD.

**Table 4.9** Mean peak inspiratory air flow at rest and exercise for conditions of no speech and speech

| | *No Speech* | | *Speech* | | | |
|---|---|---|---|---|---|---|
| | M | SE | M | SE | t | df |
| Rest | 80.50 | 2.51 | 125.75* | 4.87 | 2.85 | 39 |
| 75 W | 150.00 | 2.37 | 225.00* | 4.56 | 5.27 | 34 |
| 100 W | 172.75 | 3.24 | 247.25* | 4.30 | 4.14 | 39 |
| 125 W | 201.50 | 3.16 | 268.75* | 4.07 | 4.47 | 39 |
| 150 W | 232.25 | 4.88 | 305.25 | 5.62 | 2.05 | 39 |
| 175 W | 227.75 | 5.03 | 323.50* | 7.34 | 1.78 | 39 |

**M, Mean, SE, Standard Error of the Mean. Note. *=Statistical significance ($p \leq 0.05$) from paired samples *t*-test .**

### *4.6.8 Heart rate*

Speech appeared to influence HR. HR was on average 2.9% higher during speech than no speech. Hence during speech WOB appears to be increased in RPDs. Yet, this relationship appeared to decrease in importance as workload increased (175 W excluded). These differences were less than the pilot study results (down from 5.5%). Again, this indicates that trained users in RPDs have adapted to performing work in the device.

### *4.6.9 Breathing frequency*

At rest, speech decreased $f_R$ by 24%. There was a reduction in $f_R$ at every other workload except at 175 W, where $f_R$ during speech and no speech was comparable (refer to Figure 4.17). The maximum mean $f_R$ was 26 breaths·min$^{-1}$ at 175 W (speech and no speech). The minimum mean $f_R$ was 13 breaths min$^{-1}$ at rest (speech).

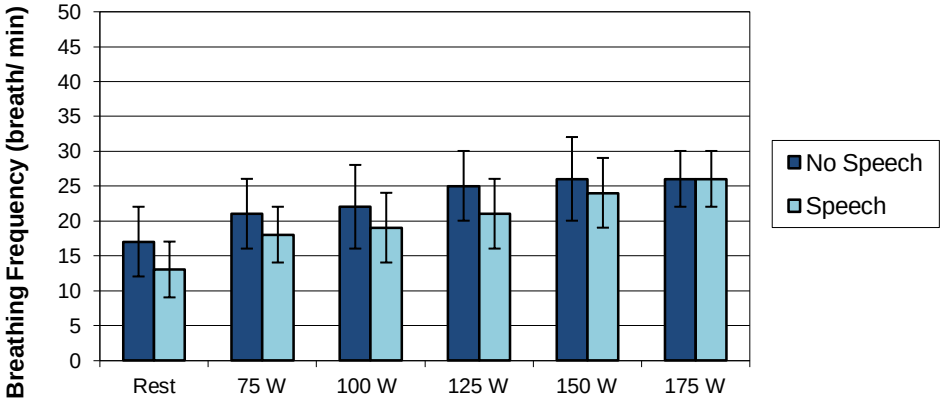



**Figure 4.17** Mean and standard deviations for breathing frequency during rest and exercise for speech and no speech

# 5 DISCUSSION AND CONCLUSION

## 5.1 Summary

Overall, the aim of this study was to evaluate the level of $CO_2$ re-breathing that occurs in RPDs. From the literature reviewed it was clear that a number of factors are already associated with $CO_2$ re-breathing in RPDs including, mask dead space, breathing resistance, work rate, RPD type and the size of person (ISO/TS16976-3: 2011). However, it was evident that little research has been conducted to evaluate the impact of speech on $CO_2$ re-breathing. Given that many occupations (for example, fire fighting, construction work and health care workers) require the use of RPDs as well as communication in the workplace this research provides more information in the use of RPDs in such situations.

Therefore, this study specifically looked at the impact of speech and various work rates on $CO_2$ re-breathing in RPDs. A protocol to test the level of $CO_2$ inspired during both speech and no speech was developed. Additionally, an apparatus was designed to collect both expired and inspired $CO_2$ samples and physiological parameters during a graded exercise test on a bicycle ergonometer. A pilot study provided an opportunity to test the assessment process with a group of volunteers before conducting the field study. Following this, a field based study was carried out to assess the levels of $CO_2$ re-breathing in workers trained in the use of RPDs.

From the results, it can be seen that $PICO_2$ in RPDs is elevated during speech. Additionally, mean $PICO_2$ appeared to reduce as exercise workload increased, to the point that there was minimal to no difference in $PICO_2$ at 175 W. A correlation with $V\dot{O}_2$ and reduced $PICO_2$ was also found for both breathing conditions (speech and no speech) at each exercise stage (except 175 W). Differences in $PICO_2$ between gender and BSA were not found. It was concluded that speech and low work rates contributed significantly to $CO_2$ re-breathing in RPDs.

The implication of this research is that $CO_2$ re-breathing in RPDs may be associated with wearer discomfort and may be linked with reduced wear time. The finding that $PICO_2$ is significantly elevated during speech is important as majority of

workers are required to communicate while wearing RPDs in the workplace. This knowledge will have an important impact on the use of RPDs.

## 5.2 Key Findings

Statistical analysis showed that both hypotheses were accepted. These key findings will be discussed and related to previous research in the following sections.

### *5.2.1 Phonic Respiration (Speech)*

Hypothesis one asked whether inspired $CO_2$ in RPDs will vary significant during speech. The answer is a qualified yes. These results confirm that speech interferes with respiration in RPDs by increasing $CO_2$ re-breathing. Results revealed speech can contribute to $CO_2$ surpassing current respirator design standards that specify inspired $CO_2$ should not exceed a maximum of 1% for more than one consecutive minute when testing RPDs (AS/NZS 1716: 2003). This specification is also applied in the Occupational Safety and Health Standards of OSHA: 1910.134 "Respiratory Protection" and European Standards: EN 13274-6: 2002 for respirator classification.

To our knowledge this is a physiological burden for RPDs that has not been highlighted in past research. However, the finding does align with the understanding that if an individual does not breathe correctly (for example, hypoventilates), hypercapnia will develop (Johnson et al. 2000, ISO/TS16976-3: 2011). This is the situation during speech. Speech tends to markedly decrease $V_E$, inspiration time and increase PIAF (Berndtsson 2004). Similar to others who have studied the effects of speech on respiration, the findings of this study also suggest that speech decreases $f_R$ (Doust and Patrick 1981, Baker et al. 2008). This also suggests speech produces a reduction alveolar respiration without a change in metabolic rate which tends to increase $CO_2$ concentrations in RPDs (ISO/TS 16976-3:2011).

Increased $PICO_2$ during speech was most likely the result of decreased positive pressure and ventilation in the mask that occurs with speech. Speech

decreases inspiration time and $f_R$ (Berndtsson 2004, Doust and Patrick 1981) which is likely to decrease the influx of fresh air into the mask during the inspiratory phase of breathing. This result over time may contribute to an accumulation of $CO_2$ in the blood and elevate $PECO_2$ and encumber breathing.

This current study demonstrates that periods of speech in RPDs cause an increase in $PICO_2$ well above the normal concentration found in atmospheric air (0.03%) (Williams 2010). $PICO_2$ was as high as 3% (100 times atmospheric concentrations) in some participants during periods of speech. In addition, almost one in three participants inspired $CO_2$ concentrations 2% or higher during periods of speech at rest and low work rates. Participants with the highest $PICO_2$ during speech appeared to be those participants more prone to hypoventilation. These $PICO_2$ values are at a level that has been shown to have an impact on humans. For example, a literature review by NIOSH (1976) indicates 1% inspired $CO_2$ is associated with respiratory stimulation such as increased $f_R$, alveolar $CO_2$ and $\dot{V}O_2$. A prolonged exposure of 2% may also cause headache and dyspnoea (Stromberg and Eklund 1996). Moreover, 3% $CO_2$ can increase $V_E$ by more than 35% (Takahashi et al. 2000).

The International Organization for Standardization (ISO) prepared a technical report on the effects of hypercapnia and the impact of $CO_2$ concentrations on respirator use (ISO/TC 16976-3.2: 2010). ISO (2010) specified that increased concentrations of $CO_2$ in the breathing space of a RPD may generate dyspnoea which causes the user to remove the device. A clear causal relationship between $PICO_2$ and dyspnoea has been documented in past studies (Maresh et al. 1997). However, this study could not make this link as speech, $PICO_2$ and increases in exercise workload contributed to feelings of dyspnoea. Also, it is unlikely that the wearer would experience significant discomfort as elevated $CO_2$ is only short-lived during speech. However, repeated $CO_2$ re-breathing (continuous speech) will lead to direct increases in blood $CO_2$ (McArdle, Katch and Katch 2001). In turn this will stimulate negative physiological responses and cause discomfort, thereby impacting the wear time of the device.

In summary, it appears little research has explored the impact of speech on $CO_2$ levels in RPDs. The findings of this study supported the initial hypothesis that speech has a significant effect on $CO_2$ re-breathing in RPDs. Given there are many

occupations that require workers to communicate and wear RPDs in the workplace, this research will have an important impact on the use of RPDs.

### *5.2.2 Oxygen Uptake (workload)*

There has also been concern that exercise compounds $CO_2$ re-breathing in RPDs due to increased metabolic production of $CO_2$ (Williams 2010, ISO/TS16976-3: 2011). During exercise there is a marked increase in $f_R$, $\dot{V}O_2$ and $PECO_2$ (McArdle, Katch and Katch 2001, Brooks, Fahey and Baldwin 2005). The concern is that in a semi closed or closed system, such as within a RPD, there is likely to be a build up of $CO_2$ (ISO/TS16976-3: 2011). If this extra $CO_2$ was re-breathed by the wearer this may very well lead to hyperventilation and dyspnoea and negatively impact work performance.

In the current study $PICO_2$ was shown to be inversely related to exercise and lower work rates increased $CO_2$ beyond recommended design limits (1%) (AS/NZS 1716: 2003). Therefore hypothesis two, which addressed whether $CO_2$ re-breathing would be influenced by $\dot{V}O_2$, is also accepted. This data suggests that the large full face S.E.A Pty Ltd Respirator became more efficient in the removal of dead space $CO_2$ at higher work rates. This is important as the metabolic production of $CO_2$ increases with exercise. These findings are consistent with other studies that found $PICO_2$ decreased with greater exercise efforts (Kloos and Lamonica 1966, Luria et al. 2004).

Factors that may influence these results include, flow rates during exercise tend to increase (Berndtsson 2004). In turn, this would assist in ventilating mask dead space and may explain decreased $CO_2$ re-breathing at higher workloads. Luria et al (2004) put forward that lower mask dead space during exercise may also lead to this. In addition, fewer words were able to be spoken when exercise was imposed. Therefore during high work rates and speech there is less interference in respiration than at lower work rates and speech.

These findings may explain the unusual results of previous studies (Craig et al. 1970 and Williams 2010) that demonstrated the greatest reduction in exercise capacity in wearers of RPDs occurred at lower work rates. In addition, a recent study by Roberge et al (2010) examined the physiological impact of N95 filtering face

piece respirators. Ten adults (seven women) conducted two 60 minute treadmill assessments at very low workloads walking at 2.74 km $hr^{-1}$ (1.7 miles $hr^{-1}$) and 4.02 km $hr^{-1}$ (2.5 miles $hr^{-1}$) while wearing the RPD. Data collected showed that dead-space $CO_2$ ranged from 2.5-3.5% $CO_2$ which is significantly above OSHA's ambient workplace standards. Roberge et al. (2010) concluded that even though the RPD did not impose any significant physiological burden on participants, $CO_2$ retention was a possibility due to elevated transcutaneous $CO_2$ (equivalent to arterial $CO_2$) levels. On a similar note, although no symptoms of $CO_2$ retention were recorded in this study, the increases in $CO_2$ during speech were sufficient enough to impact the wearer.

Previous studies have stated that $CO_2$ production is approximately 2.86 $ml.kg^{-1}.min^{-1}$ at rest yet at moderate to heavy exercise may exceed 50 $ml.kg^{-1}.min^{-1}$ (Williams 2010). Therefore, contrary to our study others have reported that mean $PICO_2$ was not always highest at rest (Warkander and Lundgren 1995).

A potential reason for this discrepancy is exercise intensities were only set at low to moderate workloads in this study. Therefore, the differences in $PICO_2$ at high or maximal $V\dot{O}_2$ cannot be compared and limits the interpretation of these results.

In summary, $CO_2$ re-breathing in RPDs was shown to decrease during increments in exercise workloads. The above finding has implications for individuals who are for the most part inactive and are required to wear RPDs in the workplace. There have been surprisingly few studies that have studied the relationship between $CO_2$ re-breathing and exercise workload in RPDs. Therefore further research on this is important.

## 5.3 Study Limitations

In this study it should be noted that there were a number of limitations. It was expected larger BSA participants would have a larger anatomical dead space and as a result more likely to retain $CO_2$ with each exhaled breath. In turn this would return $CO_2$ to the respiratory system with the next inhalation. However the current study consisted of predominantly large BSA participants. Therefore, future studies

of smaller BSA participants should be conducted to validate if BSA impacts $CO_2$ re-breathing in RPDs.

In addition, only one female participant was involved. A study on a larger scale that included equal numbers of males and females would allow for the physiological impact of $CO_2$ re-breathing in females to be compared.

As mentioned, only low to moderate exercise intensities were assessed in this study. Therefore, exercise tests of high intensity where blood lactate ($CO_2$ production) is not linear with $V\dot{O}_2$ and $PaCO_2$ increases dramatically, will require further analysis.

It is also important to note that one participant's data was ineligible due to technical problems with the equipment. A connection error between the DAQ board and the bicycle ergonometer occurred. However, this was a single anomaly and was resolved before further testing. See Figure 5.1 and 5.2 for an image of the apparatus and bicycle ergonmeter set up for the field study.

Also, for the purposes of the TSI Portacount fit test the air conditioning vents were obstructed during testing. This reduced room ventilation resulting in $CO_2$ build up in the room air as high as 0.1%. However, following completion of the fit test the room was aerated immediately before the exercise assessment process was undertaken. This step appeared to aid in returning $PCO_2$ to normal atmospheric concentrations (0.03-0.04%),

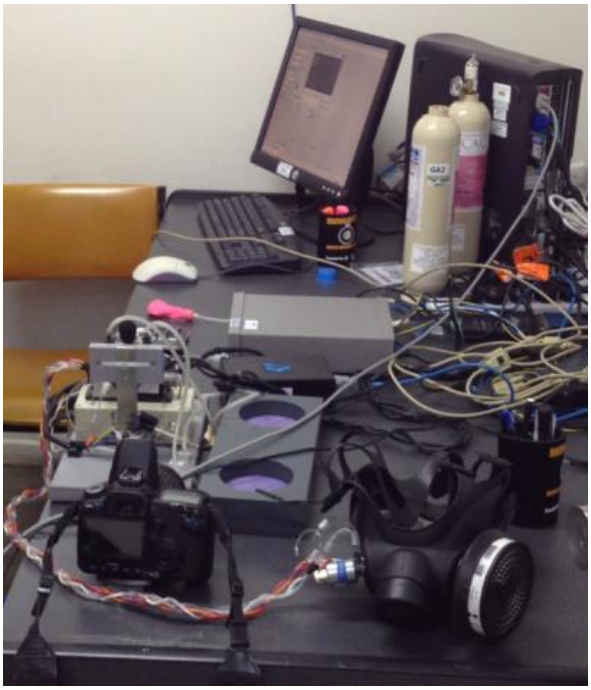


**Figure 5.1** The apparatus set-up

**Figure 5.2** Participant seated on the bicycle ergonometer

Another potential limitation in this research is that participants varied in the way they read each passage. Hoit and Lansing (2007) also agreed with these observations. For instance, some participants paused often, speaking fewer words. Other

participants paused occasionally, speaking more words during speech. Furthermore although participants were encouraged not to speak in the no speech stages of testing, a number of participants spoke briefly during this period. Lastly, some participants finished talking in advance of the measurement process being complete. According to Doust and Patrick (1981) respiration in the first 15 seconds after the cessation of speech is 114% of the mean value. This overshoot in respiration before analysis of $PICO_2$ was complete can be seen in Figure 5.3. These inconsistencies during testing will impact the results.

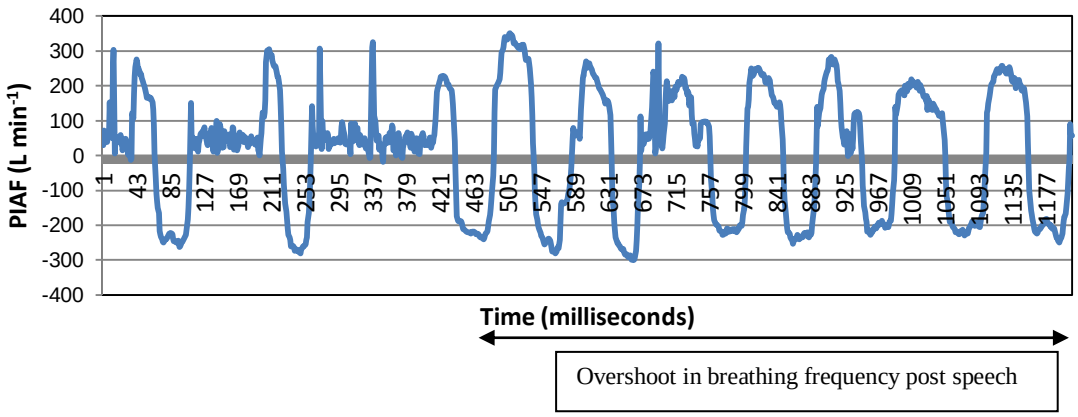



**Figure 5.3** Overshoot in respiration following a period of speech

## 5.4 Recommendations for Future Research

Recommendations for future research based on the findings of this study are as follows:

- Overall there was an underrepresentation of females and small to medium BSA participants. To confirm if gender and BSA has an impact on $CO_2$ re-breathing a further study needs to be carried out. It may be necessary to compare a small BSA or a predominantly female group to this data.
- This study compared $PICO_2$ during a graded exercise test on a bicycle ergonometer that was a maximum of 20 minutes in length. It would be ideal to measure $CO_2$ in RPDs during normal occupational

activities using portable $CO_2$ analysis equipment. This is due to the intermittent nature of occupational activities. In addition workers often wear RPDs for several hours rather than 20 minute periods. However, this mode of analysis is expensive and would require technology and equipment not readily available. Hence, this could be a future consideration for research investigating $CO_2$ re-breathing in RPDs.

- Lastly, this study mainly looked at $CO_2$ re-breathing during periods of low to moderate work rates. However, it is well know that $CO_2$ production dramatically increases during vigorous work rates group. Hence further research is still needed to assess the impact of $CO_2$ re-breathing at higher work rates.

## 5.5 Conclusion

In summary, this study established that there are significant increases in $CO_2$ re-breathing in RPDs during periods of phonic respiration (speech) and low work rates. It is worth noting that to our knowledge no previous investigations have evaluated the impact of speech on $PCO_2$ in RPDs. These results are particularly relevant to occupations where employees are required to wear RPDs and communicate in the workplace. Further research is still needed to assess the effects of gender and BSA on $CO_2$ re-breathing in RPDs. It is recommended that the findings in this study be considered in the future design and use of RPDs. In addition workers using RPDs should be aware of the physiological problems created by speech.

## REFERENCES


American College of Sports Medicine (ACSM) 2006, *ACSM's guidelines for exercise testing and prescription*, Lippincott Williams & Wilkins, London.

Arad, M, Heruti, R, Shaham, E, Atsmon, J and Epstein, Y 1992, "The effects of powered air supply to the respiratory protective device on respiration parameters during rest and exercise", *Chest*, vol.102, no.6, pp1800-1804.

Australian/New Zealand Standard (AS/NZS) 2003, *Respiratory protective devices*, AS/NZS 1716:2003, Standards Australia, Sydney.

Australian/New Zealand Standard (AS/NZS) 2009, *Selection, use and maintenance of respiratory protective equipment*, AS/NZS 1715: 2009, Standards Australia, Sydney.

Baker, S, Hipp, J & Alessio, H 2008, "Ventilation and speech characteristics during submaximal aerobic exercise", *Journal of Speech, Language and Hearing Research*, vol.51, pp1203-1214.

Bansal, S, Harber, P, Yun, D, Liu, D, Liu, Y, Wu, S, Ng, D & Santiago, S 2009, "Respirator physiological effects under simulated work conditions", *Journal of Occupational and Environmental Hygiene*, vol.6, pp221-227.

Berndtsson, G 2003, "A new simplified technique for measuring inspiratory flow characteristics", Draft paper for publication, p1-11.

Berndtsson, G 2004, "Peak inhalation air flow and minute volumes measured in a bicycle ergonometer test", *Journal of the International Society for Respiratory Protection*, vol.21, pp21-29.

Bishop, P, Lee, S, Conza, N, Clapp, L, Moore, A, Williams, W, Guilliams, M & Greenisen, M 1999, "Carbon dioxide accumulation, walking performance, and metabolic cost in the NASA launch and entry suit", *Aviation Space and Environmental Medicine*, vol.70, no.7, pp656-665.

Boron, W F & Boulpaep, E L 2003. *Medical physiology: A cellular and molecular approach.* Updated Edition. Pennsylvania: Elsevier Saunders.

Brooks, G, Fahey, T & Baldwin, K 2005, *Exercise Physiology: Human Bioenergetics and its Applications",* McGraw Hill, Boston, MA.

Butcher, S, Jones, R, Eves, N, Petersen, S 2006, "Work of breathing is increased during exercise with the self-contained breathing apparatus regulator", *Applied Physiology, Nutrition, and Metabolism*, vol.31, no.6, pp693-701.

Caretti, D, Scott, W, Johnson, A, Coyne, K & Koh, F 2001, "Work performance when breathing through different respirator exhalation resistances", *American Industrial Hygiene Association Journal*, vol.62, pp411-415.

Caretti, D, & Strickler, L 2003, Speech intelligibility during respirator wear: Influences of respirator speech diaphragm size and and background noise", *American Industrial Hygiene Association Journal*, vol.64, pp846-850.

Craig, F, Blevins, W & Cummings, E 1970, "Exhausting work limited by external resistance and inhalation of carbon dioxide", *Journal of Applied Physiology*, vol.29, no.6, pp847-851.

Crain, T. and Kazakov, D 2011. *Equipment description.* Held by Safety Equipment Australia (The S.E.A Group). Warriewood, NSW, Australia.

Doust, J H & Patrick J M 1981, "The limitation of exercise ventilation during speech. *Respiratory Physiology"*, vol.46, no.2, pp127-147.

Drummer, C, Friedel, V, Borger, A, Stormer, L, Wolter, S & Zittermann, A 1998, "Effects of elevated carbon dioxide environment on calcium metabolism in humans", *Aviation, Space and Industrial Medicine,* vol.69, no.3, pp291.

European Standards (EN) 2001, *Respiratory protective devices. Methods of test. Determination of carbon dioxide content of the inhalation air,* EN 13274-6:2001, SAI Global database.

Fletcher, S, Clark, M & Stanley, P 2006, "Carbon dioxide re-breathing with close fitting face respirator masks", *Anaesthesia,* vol.61, pp903-917.

Fothergill, D, Hedges, D & Morrison J 1991, "Effects of $CO_2$ and $N_2$ partial pressures on cognitive and psychomotor performance", *Undersea Biomedical Research,* vol.18, pp1-19, cited in Fletcher, S, Clark, M & Stanley, P 2006 "Carbon dioxide re-breathing with close fitting face respirator masks", *Anaesthesia,* vol.61, pp903-917.

Goodman, N & Curnow, J 1985, "The ventilatory response to carbon dioxide", *British Journal of Anaesthesia,* vol.57, pp311-318.

Harber, P, Tamomie, Bhattacharya, A & Barber, M 1982, "Physiologic effects of respirator dead space and resistance loading", *Journal of Occupational and Environmental Medicine,* vol.24, no.9, pp681-684.

Harber, P, Beck, J, Brown, C & Luo, J 1991, "Physiological and subjective effects of respirator mask type", *American Industrial Hygiene Association Journal,* vol.52, no.9, pp357-362.

Holmer, I, Kuklane, K & Gao, C 2007, "Minute volumes and inspiratory flow rates during exhaustive treadmill walking using respirators", *Annals of Occupational Hygiene,* pp1-9.

Hoit, J & Lansing, R 2007, "Speaking-related dyspnea in healthy adults", *Journal of Speech, Language and Hearing Research,* vol.50, no.2, pp361-374.

International Organization for Standardization (ISO) 2011, *Respiratory protective devices -Human factors. Part 3: Physiological responses and limitations of oxygen and limitations of carbon dioxide in the breathing environment,* ISO/TS 16976-3: 2011, ISO, SAI Global database.

International Organization for Standardization (ISO) 2007, *Respiratory protective devices- Human factors. Part 1: Metabolic rates and respiratory flow rates,* ISO/TS 16976-1:2007, ISO, SAI Global Database.

John 2003, "End tidal carbon dioxide monitoring", *Critical Care Nurse,* vol.23, no.4, pp83-88.

Johnson, A, Dooly, C & Dotson, C 1995, "Respirator mask effects on exercise metabolic measures", *American Industrial Hygiene Association Journal,* vol.56, no.5, pp467-467.

Johnson, A, Scott W, Lausted C, Coyne, K, Sahota, M & Johnson M 2000, "Effect of external dead volume on performance while wearing a respirator", *A Journal for the Science of Occupational and Environment Health and Safety,* vol.61, no.5, pp674-684.

Johnson, A, Mackey, K, Scott, W Koh, F 2005, "Exercise performance while wearing a tight-fitting powered air purifying respirator with limited flow", *Journal of occupational and environmental hygiene,* vol.2, no.7, pp368-373.

Jones, J 1991, "The physiological cost of wearing a disposable respirator", *American Industrial Hygiene Association Journal,* vol.52, no.6, pp219-225.

Kendrick, K, Smith, R, Baxi, S 2000, "Usefulness of the modified 0-10 Borg scale in assessing the degree of dyspnoea in patients with COPD and asthma", Journal *of Emergency Nursing*, vol.26, no.3,pp216-222.

Kloos, E & Lamonica, J 1966, *A machine-test method for measuring carbon dioxide in the inspired air of self-contained breathing apparatus,* U.S. Dept. of the Interior, Bureau of Mines. Washington, D.C.

Koh, F, Johnson, A, Scott, W, Phelps, S, Francis, E & Cattungal, S 2006, "The correlation between personality type and performance time while wearing a respirator", *Journal of Occupational and Environmental Hygiene,* vol.3, no.6, pp317-322.

Kyriazi, N 2011, "Performance comparison of breathing and metabolic simulators" *Journal of the International Society for Respiratory Protection*, vol.28, no.1, pp1-25.

Laird, I, Pack, R and Carr, D 1993, "A survey on the use and non-use of respiratory protective equipment in workplaces in a provincial New Zealand city", *The Annals of Occupational Hygiene,* vol.37, no.4, pp367-375.

Lofaso, F, Brochard, L, Touchard, D, Hang, T, Harf, A, Isabey, D 1995, "Evaluation of carbon dioxide re-breathing during pressure support ventilation with airway management system (BiPAP) devices", *Chest*, vol.108, no.3, pp772-778.

Louhevaara, V 1984, "Physiological effects associated with the use of respiratory protective devices. A review", *Scandinavian Journal of Work, Environment & Health*, vol.10, no.5, pp275-281.

Love, R, Muir, D, Sweetland, K, Bentley, R & Griffin, O 1979, "Tolerance and ventilatory response to inhaled $CO_2$ during exercise and with inspiratory resistive loading", *The Annals of Occupational Hygiene*, vol.22, pp43-52.

Luksch, A, Garhöfer, G, Imhof, A, Polak, K, Polska, E, Dorner, G. T, Anzenhofer, S, Wolzt, M & Schmetterer, L 2002, "Effect of inhalation of different mixtures of $O_2$ and $CO_2$ on retinal blood flow", *The British Journal of Ophthalmology*, vol.86, no.10, pp1143.

Luria, S, Givoni, S, Heled, Y & Tadmor, B 2004, "Evaluation of $CO_2$ accumulation in respiratory protective devices", *Military Medicine*, vol.169, no.2, pp121-124.

Mador, M & Tobin, M 1992, "The effect of inspiratory muscle fatigue on breathing pattern and ventilatory response to $CO_2$", *Journal Of Physiology*, vol.455, pp17-32.

Maresh, C, Armstrong, L, Kavouras, S, Allen, G, Casa, D, Whittlesey, M & LaGasse, K 1997, "Physiological and psychological effects associated with high carbon dioxide levels in healthy men", *Aviation Space and Environmental Medicine,* vol.68, no.1, pp41-45.

Margel, D., White, D & Pillar, G 2003, "Long-term intermittent exposure to high ambient $CO_2$ causes respiratory disturbances during sleep in submariners", *Chest*, vol.124, no.5, pp1716-1723.

Marieb, E & Hoehn K 2010 "*Human Anatomy and Physiology, Eighth edition"* New York, Pearson Education.

McArdle, L 1959, "Electrocardiographic studies during the inhalation of 30 per cent carbon dioxide in man", *British Journal of Anaesthesia,* vol.31, no.4, pp142-151.

McArdle, W, Katch, F & Katch V 2001, *Exercise Physiology: Energy, Nutrition, and Human Performance- Fifth Edition*, Lippincott Williams & Wilkins, USA.

Modified Borg Dyspnoea Scale (MBS), accessed 22/11/2011 from the Australian Lung Foundation, http://www.pulmonaryrehab.com.au

Mojoli, F, Lotti, G, Gerletti, M, Lucarini, C & Braschi, A 2008, "Carbon dioxide re-breathing during non-invasive ventilation delivered by helmet: a bench study", *Intensive Care Medicine*, vol.34, pp1454-1460.

National Institute for Occupational Safety and Health (NIOSH) 1976, *Breathing Resistance and Dead Space in Respiratory Protective Devices,* National Institute for Occupational Safety and Health (NIOSH), OHIO.

National Institute for Occupational Safety and Health (NIOSH) 2011, *NIOSH Pocket Guide to Chemical Hazards,* National Institute for Occupational Safety and Health (NIOSH), accessed 19/12/2011, http://www.cdc.gov/niosh/npg.html

National Institute for Occupational Safety and Health (NIOSH) 2011, accessed 3/10/2011, http://www.cdc.gov/niosh/topics/respirators.

Occupational Safety and Health Administration (OSHA) 2011, accessed 19/09/2011. http://www.osha.gov/SLTC/respiratoryprotection/index.html.

Physical Activity Readiness Questionnaire (PAR-Q) 2002, accessed 20/09/2011 from the Canadian Society for Exercise Physiology. http://www.csep.ca/forms.asp.

Parker, J, Peters, C & Barnett, T 1963 "Carbon dioxide and the work of breathing", *Journal of Clinical Investigation*, vol.42, no.8, pp1362-1372.

Rebar, J, Johnson, A, Russek-Cohen, E, Caretti, D & Scott, W 2004, "Effect of differing facial characteristics on breathing resistance inside a respirator mask", *Journal of Occupational and Environmental Hygiene,* vol.1, no.6, pp343-348.

Roberge, R J, Coca, A, Williams, J, Powell, J B & Palmiero, A J 2010, "Physiological impact of the N95 filtering facepiece respirator on healthcare workers", *Respiratory Care,* vol.55, no.5, pp569-577.

Safe Work Australia (2012), *Hazardous Substance Information System (HSIS). Carbon Dioxide,* Safe Work Australia 124-38-9, accessed 14/09/2012, http://hsis.safeworkaustralia.gov.au/HazardousSubstance

Sidney, D & Poon, C 1995, "Ventilatory responses to dead space and $CO_2$ breathing under inspiratory resistive load", *Journal of Applied Physiology,* vol.78, no.2, pp555-561.

Shykoff, B, E & Warkander, D, E 2011, "Physiologically acceptable resistance of an air purifying respirator*", Ergonomics,* vol.54, no.12, pp1186-1196.

Silverman, L, Lee, R, Lee, G, Drinker, K & Carpenter, T 1943, *Report on funadamental factors in the design of protective respiratory equipment: inspiratory air flow neasurements of human subjects with and without resistance,* Report no.5339, Office of Scientific Research and Development, United States War Research Agency, January 1943.

Silverman, L, Lee, G, Platkin, T, Sawyers, L, A & Yancey, A, R 1951, "Air flow measurements on human subjects with and without respiratory resistance at several work rates", *Archives of Industial Hygiene and Occupational Medicine,* vol.3, pp461-478.

Silverthorn, D 2004, *Human physiology: an integrated approach- third edition,* Pearson Benjamin Cummings, San Francisco, CA.

Sinkule, E & Turner, N 2004, "Inhaled carbon dioxide and oxygen concentrations during rest and exercise of three air –purifying hoods", *Medicine & Science in Sports & Exercise,*vol.36, no.5, pp245, abstract accessed 15/08/2011 from Ovid database.

Spielberger, C D, Gorsuch, R, L. and Lushene, R, E 1983, *The State-Trait Anxiety Inventory*. Mind Garden Inc.

Stromberg, T & Eklund J 1996, "A method for measuring the $CO_2$ dead space volume in facial visors and respiratory protective", *Ergonomics*, vol.39, no.9, pp1087-1087.

Suzuki, K, Ogawa, A & Matsumura, Y 2004, *Factors influencing carbon dioxide concentration increases of filtering respirators,* Speech at the ISRP Yokohama conference.

Szeinuk, J, Beckett, W, Clark, N & Hailoo, W 2000, "Medical evaluation for respirator use", *American Journal of Industrial Medicine,* vol.37, pp142-157.

Takahashi, M, Mano, Y, Shibayama, M & Yamami, N 2000, "Ventilatory response to carbon dioxide during moderate exercise", *Journal of Occupational Health,* vol.42, pp79-83.

TSI 2011, accessed 18/11/2012. http://www.tsi.com

Wanger, J 1996, *Pulmonary Function Testing: A Practical Approach, 2nd Edition,* Williams and Wilkins, USA.

Warkander, D, Norfleet, G, Nagasawa, K & Lundgren, C 1992, "Physiologically and subjectively acceptable breathing resistance in divers' breathing gear", *Undersea Biomedical Research,* vol.19, no.6, pp427-445.

Warkander, D & Lundgren, C 1995, "Dead space in the breathing apparatus; interaction with ventilation", *Ergonomics,* vol.38, no.9, pp1745-1758.

Williams, W J 2010. Physiological response to alterations in $O_2$ and $CO_2$: relevance to respiratory protective devices. *Journal of the International Society for Respiratory Protection,* vol.27, no.1, pp.27-51.

Yang, Y, Sun, C & Sun, M 1997 "The effect of moderately increased $CO_2$ concentration on perception of coherent motion", *Investigative Ophthalmology & Visual Science,* vol.38, no.4, pp1786-1786.

# APPENDIX A SUMMARY OF KEY INFORMATION OBTAINED FROM THE LITERATURE REVIEW

**Table 5.1** Literature review of carbon dioxide re-breathing in respiratory protective devices and the variables measured

| Reference | Year | Journal | N | RPD | Mode | Equipment | $PICO_2$ (%) Rest | $PICO_2$ (%) Work | Variables |
|---|---|---|---|---|---|---|---|---|---|
| Arad | 1992 | Chest | 10 | PAPR ± Blower | TM | Capnograph, Pressure Transducer | 1.3 ±0.7 | 1.0 ±0.3 | HR, $PIO_2$, $PICO_2$, $PEO_2$, $PECO_2$, $f_R$, PIAF, PEAF, Duty Cycle |
| Bishop | 1999 | Aviation Space and Environmental Medicine | 12 | LES with helmet visor | Walk | - | - | 4 | $PICO_2$, metabolic rate, $VO_2$ |
| Craig | 1970 | Journal of Applied Physiology | 12 | M9 protective mask | TM | Infrared, pneumotachometer, Strain gauge | - | 3.1-3.9* | MVV, HR, $V_T$, $f_R$,TI, TE, $VO_2$, $PICO_2$, $PO_2$,, $PECO_2$, PIAF, TI, TE, |
| Fletcher | 2006 | Anaesthia | 4 | Technol fluidshield PFR 95 | Pre and Post Procedure | Capnometer | - | - | $P_{ET}CO_2$, RPE |
| Johnson | 2000 | American Industrial Hygiene Association | 13 | Modified M17 air-purifying full face piece | TM | Mass spectrometer, pneumotachometer, pressure transducer | - | - | $VO_2$, HR, BP, RPE, BAC, TC, $f_R$, STAI, blood pH, lactate, $SpO_2$, $PCO_2$, |
| Harber | 1982 | Journ. Of Occup. Med. | 9 | Loads to simulate a RPD | B | Pneumotachometer, Spirometer, Pressure transducer, ECG | - | | $f_R$, TI, ET, TT, IE, IT, $V_E$, $V_T$, PP, PIAF, HR |
| Love | 1979 | Ann. Occup. Hyg. | 80 | Loads to simulate a self rescuer | TM | Katharometer, Pressure transducer, | 2,3, 4 & 5* | - | $VO_2$, $PICO_2$, $PECO_2$, $PACO_2$*, FEV1, FVC, MBC, $V_E$, Vl, $V_T$, DI, $f_R$, RQ |
| Mojoli | 2008 | Intensive Care Med | - | Head helmet | Rest | BMS, Flow meter (pneumotachometer) | 2.2±0.8 | - | $PICO_2$, PETCO, VE, VI |
| Roberge | 2010 | Respiratory Care | 10 | N95 FFR (2) | TM | Plethysmograph, $CO_2/O_2$ sensor model, Radiometer, Portacount | 2.0±0.3; 3.1±0.2** | 3.0±0.3; 3.2±0.5** | HR, $f_R$, $V_T$, $V_E$, $SpO_2$, $P_{ET}CO_2$, MBS, RPE |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Luria | 2004 | | 54 | ACBS & CETER | TM | Infrared | - | 2.3±0.46; 1.3±0.35 | $FICO_2$, HR |
| Sinkule | 2004 | Medicine & Science in Sports & Exercise | 7 | APEHR (A, B & C) | TM | - | - | - | $PICO_2$, $PIO_2$ |
| Stromberg | 1996 | Ergonomics | 8 | Welding visors (7) | B | Mass spectrometer, plethysmograph, pneumotachometer | 0.84± 0.35 | 0.96±0.23 | $PICO_2$,$P_{ET}CO_2$, Vd, $V_T$, Vi, HR, ECG |
| Takahashi | 2000 | J Occup Health | 12 | FFR | B | Gas analysers, pneumotachometer, pressure gage | 3% * | 3%* | $V_E$, $P_{ET}CO_2$ |
| Warkander | `1995 | Ergonomics | 5 | SCBA (3) | B | Mass spectrometer, Borg Scale, Validyne Pressure Transducer, Douglas bag, FM recorder, | 0.29±0.06; 0.73±0.11; 1.19±0.16 | 0.23±0.01; 0.61±0.09 0.90±0.15 | $V_E$. $P_{ET}CO_2$, $PCO_2$, $f_R$, $V_T$, $V_D$, $avCO_2$in, PmI, PmE, RPE |
| Warkander | 1992 | Undersea Biomedical Researh | 6 | SCBA | B (immersed) | Pressure transducer, mass spectrometer, diaphragmatic electromyogram | - | - | $P_{ET}CO_2$, $V_E$, $V_A$, $V_T$, $f_R$, MVV, FEV1, VC, ERV, $T_I/T_{TIOT}$, $VO_2$, RQ, WOB/V Pmin, Pmax, HR Dyspnoea |

** $CO_2$ was administered to subjects*

*** Mixed inspired/expired $CO_2$*

**Nomenclature:**

| | | | | | |
|---|---|---|---|---|---|
| **ACBS** | Armoured vehicle crewmember blower system | **LES** | Launch entry suit | **RPE** | Rating of perceived exertion |
| **APEHR** | Air purifying escape hood respirator | **MBC** | Maximum breathing capacity | **$spO_2$** | Blood oxygen saturation |
| **$avCO_2$, in** | Average $CO_2$ inspired | **MVV** | Max voluntary ventilation | **STAI** | Speilberger state trait anxiety inventory |
| **B** | Bike | **$PACO_2$** | Partial pressure of $CO_2$ in alveolar air | **TC** | Thermal comfort |
| **BAC** | Breathing apparatus comfort | **PAPR** | Powered air purifying respirator | **TI** | Inspiratory time |
| **BL** | Blood lactate | **$PECO_2$** | Partial pressure of $CO_2$ in expired air | **TE** | Expiratory time |
| **BMS** | Body and metabolic simulator | **$P_{ET}CO_2$** | End Tidal $PCO_2$ | **TT** | Total respiratory cycle time |
| **CCBA** | Closed circuit breathing apparatus | **PIAF** | Peak inspiratory, flow rate | **TLC** | Total lung capacity |
| **CETER** | Chemical team respirator | **PEAF** | Peak expiratory, flow rate | **TM** | Treadmill |
| **DI** | Dyspnoeic index = VE/MBC | **$PICO_2$** | Partial pressure of inspiratory $CO_2$ | **VE** | Expiratory minute volume |
| **$f_R$** | Breathing frequency | | | **VI** | Inspiratory minute volumes |
| **ECG** | Electrocardiogram | **$PIO_2$** | Partial Pressure of Inspired $O_2$ | **$VCO_2$** | $CO_2$ production per minute |
| **FEV1** | Forced expiratory volume in 1s | **Pm, in** | Inspiratory mask pressure | **Vd** | Dead Space |
| **FFR** | Filtering face piece respirator | **Pm, ex** | Expiratory mask pressure | **$VO_2$** | $O_2$ uptake per minute |
| **FVC** | Forced vital capacity | **PP** | Peak mouth pressure | **$V_T$** | Tidal volume, volume per breath |
| **HR** | Heart rate | **$P_{Cut}CO_2$** | Transcutaeous $CO_2$ | **VT** | Ventilatory threshold |
| **IE** | Inspiratory: Expiratory Time | **RQ** | Respiratory Quotient | | |

## APPENDIX B HREC APPROVAL

University of Wollongong

**INITIAL APPLICATION APPROVAL**
**In reply please quote: HE11/437**
Further Enquiries Phone: 4221 3386
DM:CJ

3 February 2012

Ms Carmen Smith
355 Arina Road
BARGO NSW 2574

Dear Ms Smith

Thank you for your email dated 1 February 2012 responding to the HREC review of the application detailed below. I am pleased to advise that the application has been **approved**.

| | |
|---|---|
| Ethics Number: | HE11/437 |
| Project Title: | THE CO2RE PROJECT: The impact of Carbon Dioxide Re-breathing in Respiratory Protective Devices (RPDs) |
| Name of Researchers: | Ms Carmen Smith, Mrs Jane Whitelaw, Dr Brian Davies |
| Approval Date: | 2 February 2012 |
| Expiry Date: | 1 February 2013 |

The University of Wollongong/ISLHD Health and Medical HREC is constituted and functions in accordance with the NHMRC *National Statement on Ethical Conduct in Human Research*. The HREC has reviewed the research proposal for compliance with the *National Statement* and approval of this project is conditional upon your continuing compliance with this document.

A condition of approval by the HREC is the submission of a progress report annually and a final report on completion of your project. _The progress report template is available at http://www.uow.edu.au/research/rso/ethics/UOW009385.html. This report must be completed, signed by the appropriate Head of School and returned to the Research Services Office prior to the expiry date.

As evidence of continuing compliance, the Human Research Ethics Committee also requires that researchers immediately report:

- proposed changes to the protocol including changes to investigators involved
- serious or unexpected adverse effects on participants
- unforseen events that might affect continued ethical acceptability of the project.

Research Services Office University of Wollongong NSW 2522 Australia
Telephone: +61 2 4221 3386 Facsimile: +61 2 4221 4338
research-services@uow.edu.au www.uow.edu.au/research

# APPENDIX C PARTICIPANT INFORMATION SHEETS

UNIVERSITY OF WOLLONGONG

**PARTICIPANT INFORMATION SHEET FOR THE PILOT STUDY**

**TITLE:** *The $CO_2$RE Project- The Impact of Carbon Dioxide ($CO_2$) Re-Breathing in Respiratory Protective Devices.*

**PURPOSE OF THE RESEARCH:**
**Measure** the level of **Carbon Dioxide** ($CO_2$) re-breathed (inhaled) in **Respiratory Protective Devices** (RPDs).
**Assess** the physical demands this places on the wearer, especially in relation to **breathing**.
**Use** this **information** to help manufacturers develop RPDs that are **safe** and more **comfortable** to use in the workplace.

**INVESTIGATORS:**


| Carmen Smith | Jane Whitelaw | A/Prof Brian Davies |
|---|---|---|
| (Principal investigator) | (Supervisor) | (Supervisor) |
| School of Health Sciences | School of Health Sciences | School of Health Sciences |
| cs847@uowmail.edu.au | jane_whitelaw@uow.edu.au | brian_davies@uow.edu.au |


**THE EXERCISE TEST:** If you choose to be included in the Pilot Project, you will be asked to participate in an exercise test on a bike wearing a RPD. Before the exercise test commences you will be screened to ensure there are no health risks associated with increasing your activity levels. Following this the researcher will take the time to fit you with an appropriate sized RPD (large or small). The exercise test will begin at low level and will be advanced in 5 minute stages by increasing pedal resistance. During the third minute of each stage you will be asked to read aloud from a prepared text. You will be asked to continue talking for one minute. Your heart rate, rating of breathlessness, breathing responses and level of inhaled $CO_2$ will be monitored continuously during the exercise test. We wish to stop the test after 17-21 minutes of exercise. However, we may stop the test at anytime due to fatigue or any symptoms you may experience. The appointment will require about 45 minutes of your time. It is important you know this project is completely voluntary. You have the right to request the test to be stopped at any stage, decline to answer specific questions and/or withdraw data from the study at any stage.

**POSSIBLE RISKS AND DISCOMFORTS:** There are certain discomforts associated with wearing a RPD. These include increased breathing discomfort, heat buildup, interference with vision and difficulty communicating. Also, it is important you

understand that there are a number of changes that may occur during exercise, such as irregularities in heart rate, abnormal blood pressure response and in extremely rare instances heart attack or death. Every effort will be made to minimise these risks by providing appropriate supervision during the test. In addition compensation will be provided to research participants if temporary or permanent injury occurs due to participation in the research.

**FUNDING AND BENEFITS TO BE EXPECTED:** The Principal Investigator (PI) is a Master Degree candidate in the School of Health Sciences at the University of Wollongong. PI Smith has been granted the Safety Equipment Australia (S.E.A) scholarship which amounts to a total sum of $35, 000. Your participation in The $CO_2$RE Project will play a significant role in the understanding of how the level of carbon dioxide in respirators influences the wearer. This will help manufacturers in the design of more comfortable RPDs and assist with improving respiratory protection in the workplace.

**CONFIDENTIALITY:** All information collected will be coded to provide confidentiality. The data will be stored in a locked file in a secure place or a password protected database when not I use by the University of Wollongong. Information gathered in this appointment will be used solely for statistical analysis, research articles and presentations. The only item that could identify participants would be the master copy of the booking sheet which will have the code for linking individuals to their raw data. Only the investigators named above will have access to the information. Under no circumstances is any personal or sensitive information disclosed. The responses you provide and the data collected will be deleted or shredded after a period of five years.

**ETHICS REVIEW AND COMPLAINTS:** This study has been reviewed by the Human Research Ethics Committee of the University of Wollongong. If you have any concerns regarding the way this research has been conducted, you can contact the UOW Ethics Officer on (02) 4221 4457. Should there be any adverse effects by participation all participants have access to compensation.

**ANY QUESTIONS:** If you have any questions about any of the procedures, please feel free to ask us, we will gladly answer them.

Thank you for your interest in The $CO_2$RE Project.

UNIVERSITY OF WOLLONGONG

**PARTICIPANT INFORMATION SHEET FOR THE FIELD STUDY**

**TITLE:** *The $CO_2$RE Project- The Impact of Carbon Dioxide ($CO_2$) Re-Breathing in Respiratory Protective Devices.*

**PURPOSE OF THE RESEARCH:**
**Measure** the level of **Carbon Dioxide** ($CO_2$) re-breathed (inhaled) in **Respiratory Protective Devices** (RPDs).
**Assess** the physical demands this places on the wearer, especially in relation to **breathing**.
**Use** this **information** to help manufacturers develop RPDs that are **safe** and more **comfortable** to use in the workplace.

**INVESTIGATORS:**


| Carmen Smith | Jane Whitelaw | A/Prof Brian Davies |
|---|---|---|
| (Principal Investigator) | (Supervisor) | (Supervisor) |
| School of Health Sciences | School of Health Sciences | School of Health Sciences |
| cs847@uowmail.edu.au | jane_whitelaw@uow.edu.au | brian_davies@uow.edu.au |


**THE EXERCISE TEST:** If you choose to be included in The $CO_2$RE Project, you will be asked to participate in an exercise test on a bike wearing a RPD. Before the exercise test commences you will be screened to ensure there are no health risks associated with increasing your activity levels. Following this the researcher will take the time to fit you with an appropriate sized RPD (large or small). The exercise test will begin at low level and will be advanced in 5 minute stages by increasing pedal resistance. During the third minute of each stage you will be asked to read aloud from a prepared text. You will be asked to continue talking for one minute. Your heart rate, rating of breathlessness, breathing responses and level of inhaled $CO_2$ will be monitored continuously during the exercise test. We wish to stop the test after 17-21 minutes of exercise. However, we may stop the test at anytime due to fatigue or any symptoms you may experience. The appointment will require about 45 minutes of your time. It is important you know this project is completely voluntary. You have the right to withdraw your consent to participate and/or data from the study at any stage.

**POSSIBLE RISKS AND DISCOMFORTS:** There are certain discomforts associated with wearing a RPD. These include increased breathing discomfort, heat buildup, interference with vision and difficulty communicating. Also, it is important you understand that there are a number of changes that may occur during exercise, such as irregularities in heart rate, abnormal blood pressure response and in extremely rare

instances heart attack or death. Every effort will be made to minimise these risks by providing appropriate supervision during the test. In addition compensation will be provided to research participants if temporary or permanent injury occurs due to participation in the research.

**FUNDING AND BENEFITS TO BE EXPECTED:** The Principal Investigator (PI) is a Master Degree candidate in the School of Health Sciences at the University of Wollongong (UOW). PI Smith has been granted the Safety Equipment Australia (S.E.A) scholarship which amounts to a total sum of $35, 000.. Your participation in The $CO_2$RE Project will contribute to our understanding of how the level of carbon dioxide in respirators influences the wearer. This information will help manufacturers to design more comfortable RPDs and assist with improving respiratory protection in the workplace.

**CONFIDENTIALITY:** All information collected will be coded to provide confidentiality. The data will be stored in a locked file in a secure place or a password protected database when not in use by the UOW. Information gathered in this appointment will be used solely for statistical analysis, research articles and presentations. The only item that could identify participants would be the master copy of the booking sheet which will have the code for linking individuals to their raw data. Only the investigators named above will have access to this information. Under no circumstances is any personal or sensitive information disclosed. The responses you provide and the data collected will be deleted or shredded after a period of five years.

**ETHICS REVIEW AND COMPLAINTS:** This study has been reviewed by the Human Research Ethics Committee of the UOW. If you have any concerns regarding the way this research has been conducted, you can contact the UOW Ethics Officer on (02) 4221 4457. Should there be any adverse effects by participation all participants have access to compensation.

**ANY QUESTIONS:** If you have any questions about any of the procedures, please feel free to ask us, we will gladly answer them.

Thank you for your interest in The $CO_2$RE Project.

## APPENDIX D INCLUSION AND EXCLUSION CRITERION

**INCLUSION CRITERIA**

- Clean shaven
- Prior experience with respirators or use them routinely on the job
- Pass Portacount test
- Men and women between the ages of 18 and 69 years
- Medical approval regarding use of respirators

**EXCLUSION CRITERIA**

- Contraindications to exercise listed on the PARQ form
- Pregnancy
- Inability to pass Portacount test (Field Study only)
- High blood pressure (over 144/94 mmHg)
- Unable to speak, read or write English
- State STAI Scores $90^{th}$ Percentile or above and/or history of problems with anxiety or claustrophobia
- Respiratory illness or reduced lung function

## APPENDIX E APPOINTMENT CONFIRMATION LETTER

UNIVERSITY OF WOLLONGONG

Dear

Thank you for signing up to participate in The $CO_2$RE Project. Your appointment time is:

**Date:** DAY MONTH YEAR
**Time:** APPOINTMENT TIME
**Place:** LOCATION OF ASSESSMENT
**With:** Carmen Smith

In preparation for the exercise assessment, you will need to aware of a few steps:

**On Assessment Day:**

- Do not exercise on the day of your appointment
- Do not consume any alcohol, caffeine, cigarettes/cigars or 'heavy' meals for 3 hours prior to your appointment
- Bring comfortable sporting clothes and running shoes (shorts and loose fitting top)
- Please be clean shaven and free of stubble
- It would be a good idea to complete:
  (1) PARQ form
  (2) Consent form

These documents make up an important part of the assessment.

**Attend Your Appointment**

Please arrive a little early and allow 45 minutes for the assessment
If you are running late or unable to keep this appointment please call us and let us know.

Please note all information collected will be held in the strictest of confidence.
We look forward to seeing you and thank you for your participation.

Sincerely,

Carmen Smith
Email: cs847@uowmail.edu.au

## APPENDIX F CONSENT FORM

**CONSENT FORM**

I have been given information sheet regarding the *Impact of Carbon Dioxide ($CO_2$) Re-Breathing in Respiratory Protective Devices"* and discussed the research project with *Carmen Smith* who is conducting this research as part of a *Masters of Science - Research* supervised by *Jane Whitelaw* in the *Department of School of Health Sciences* at the University of Wollongong.

I have read and understood this document in its entirety and had all my questions answered satisfactorily. I hereby consent to voluntarily participate in the test procedures I will perform with full knowledge of the risk and benefits involved.
I understand that my participation in this research is voluntary, I am free to refuse to participate and I am free to withdraw from the research at any time without penalty.

If I have any enquiries about the research, I can contact *Carmen Smith on*
***and/or*** *supervisor Jane Whitelaw on* ( Alternatively if I have any concerns or complaints regarding the way the research is or has been conducted, I can contact the Ethics Officer, Human Research Ethics Committee, Office of Research, University of Wollongong on 02 4221 4457.

By signing below I am indicating my consent to

- An **exercise test** on a bike wearing a respiratory protective device
- The **assessment** of the **physical demands** this places on my breathing responses
- The **use** of this **information** for improving the design and manufacture of respirators

I understand that the data collected from my participation will be used solely for statistical analysis, research articles and presentations and I consent for it to be used in that manner.

Participant Signature ..... Date ...../...../.....
Name (please print)
.....
Witness Signature ..... Date ...../...../.....
Name (please print)
.....

## APPENDIX G MODIFIED BORG SCALE OF DYSPNOEA

# Modified Borg Dyspnoea Scale

| | | |
|---|---|---|
| 0 | Nothing at all | |
| 0.5 | Very, very slight (just noticeable) | |
| 1 | Very slight | |
| 2 | Slight | |
| 3 | Moderate | Exercise Training Zone |
| 4 | Somewhat severe | |
| 5 | Severe | |
| 6 | | |
| 7 | Very severe | |
| 8 | | |
| 9 | Very, very severe (almost maximal) | |
| 10 | Maximal | |

Patient Instructions for Borg Dyspnoea Scale

**“**This is a scale that asks you to rate the difficulty of your breathing. It starts at number 0 where your breathing is causing you no difficulty at all and progresses through to number 10 where your breathing difficulty is maximal. How much difficulty is your breathing causing you right now?”

# APPENDIX H TERMINATION CRITERIA

**GENERAL INDICATIONS FOR STOPPING AN EXERCISE TEST IN LOW RISK ADULTS***

- Onset of angina and angina like symptoms
- Drop in systolic blood pressure of >10 mmHg from baseline blood pressure despite an increase in workload
- Excessive rise in blood pressure: systolic pressure > 250 mmHg or diastolic pressure > 115 mmHg
- Shortness of breath, wheezing, leg cramps, or claudication
- Signs of poor perfusion, light headiness, confusion, ataxia, pallor, cyanosis, nausea, or cold/clammy skin
- Failure of heart rate to increase with increased exercise intensity
- Noticeable change in heart rhythm
- Subject requests to stop
- Physical/verbal manifestations of severe fatigue, for example score 7 or above on the Modified Borg Dyspnoea Scale
- Failure of the testing equipment

Modified from ACSM (2006)

## APPENDIX I PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Physical Activity Readiness Questionnaire - PAR-Q (revised 2002)

# PAR-Q & YOU

**(A Questionnaire for People Aged 15 to 69)**

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

| YES | NO | | |
|---|---|---|---|
| ☐ | ☐ | 1. | **Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?** |
| ☐ | ☐ | 2. | **Do you feel pain in your chest when you do physical activity?** |
| ☐ | ☐ | 3. | **In the past month, have you had chest pain when you were not doing physical activity?** |
| ☐ | ☐ | 4. | **Do you lose your balance because of dizziness or do you ever lose consciousness?** |
| ☐ | ☐ | 5. | **Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?** |
| ☐ | ☐ | 6. | **Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?** |
| ☐ | ☐ | 7. | **Do you know of any other reason why you should not do physical activity?** |

## If you answered YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

## NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

**DELAY BECOMING MUCH MORE ACTIVE:**

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

**PLEASE NOTE:** If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

**No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.**

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____ DATE _____

SIGNATURE OF PARENT or GUARDIAN (for participants under the age of majority) _____ WITNESS _____

**Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.**

## APPENDIX J PRE-SCREENING QUESTIONNAIRE

**PRE SCREENING QUESTIONNAIRE**

| | | |
|---|---|---|
| SUBJECT No: | AGE: | DOB: |
| GENDER: M/F | PHONE: | E-MAIL: |
| EMERGENCY CONTACT: | | PHONE: |

| | | |
|---|---|---|
| **LUNGS** | | |
| DO YOU HAVE ASTHMA OR OTHER LUNG DISEASE? | YES | NO |
| DO YOU CURRENTLY SMOKE OR QUIT SMOKING WITHIN THE PREVIOUS 6 MONTHS? | YES | NO |
| **PSYCHOLOGICAL CONDITION** | | |
| HAVE YOU EVER HAD CLAUSTROPHBIA (FEAR OF CLOSED PLACES) OR PROBLEMS WITH ANXIETY? | YES | NO |
| **RESPIRATOR USE** | | |
| DO YOU HAVE EXPERIENCE WITH THE USE OF RESPIRATORS? | YES | NO |
| **AEROBIC EXERCISE** | | |
| ARE YOU INACTIVE? (I.E. YOU GET <30 MINUTES OF PHYSICAL ACTIVTY ON AT LEAST 3 DAYS PER WEEK? | YES | NO |
| **COMMENTS (IF YOU ANSWERED YES TO ANY OF THESE QUESTIONS OR WOULD LIKE TO ADD SOMETHING ABOUT LUNG CONCERNS, PLEASE LIST HERE.)** | | |
| | | |
| | | |

## APPENDIX K STATE TRAIT ANXIETY INVENTORY: FIVE SAMPLE ITEM AND PERMISSION LETTER

**SELF-EVALUATION QUESTIONNAIRE** STAI Form Y-1

**Please provide the following information:**

Name_____ Date_____ S_____

Age_____ Gender (*Circle*) **M** **F** T_____

**DIRECTIONS:**

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate number to the right of the statement to indicate how you feel *right* now, that is, *at this moment*. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

| | NOT AT ALL | SOMEWHAT | MODERATELY SO | VERY MUCH SO |
|---|---|---|---|---|
| 1. I feel calm | 1 | 2 | 3 | 4 |
| 2. I feel secure | 1 | 2 | 3 | 4 |
| 3. I am tense | 1 | 2 | 3 | 4 |
| 4. I feel strained | 1 | 2 | 3 | 4 |
| 5. I feel at ease | 1 | 2 | 3 | 4 |

License for Carmen Smith to reproduce/administer
up to a quantity of 50 within one year of December 14, 2011.

mind garden

www.mindgarden.com

To whom it may concern,

This letter is to grant permission for the above named person to use the following copyright material for his/her thesis or dissertation research.

Instrument: ***State-Trait Anxiety Inventory for Adults***

Authors: ***Charles D. Spielberger, in collaboration with R.L. Gorsuch, G.A. Jacobs, R. Lushene, and P.R. Vagg***

Copyright: ***1968, 1977 by Charles D. Spielberger***

Five sample items from this instrument may be reproduced for inclusion in a proposal, thesis, or dissertation.

The entire instrument may not be included or reproduced at any time in any other published material.

Sincerely,

Robert Most
Mind Garden, Inc.
www.mindgarden.com

## APPENDIX L THE RAINBOW PASSAGE

**THE RAINBOW PASSAGE**

"When the sunlight strikes raindrops in the air, they act like a prism and form a rainbow. The rainbow is a division of white light into many beautiful colours. These take the shape of a long round arch, with its path high above, and its two ends apparently beyond the horizon. There is, according to legend, a boiling pot of gold at one end. People look, but no one ever finds it. When a man looks for something beyond reach, his friends say he is looking for the pot of gold at the end of the rainbow."

## APPENDIX M PROMOTIONAL MATERIAL

# HARD TO BREATHE?

# WE NEED YOUR HELP!

## WE WANT TO GET TO THE CORE OF THE PROBLEM

University of Wollongong

The University of Wollongong is seeking volunteers to take part in The $CO_2$RE Project
We are researching how the level of carbon dioxide in respirators affects the wearer

**Please Volunteer!**

You will play an important role in helping to design safer and more comfortable respirators
It will only take about 30 minutes of your time

The Pilot Project will take place at the

**UOW during February 2012**

If you are interested or would like more information
Please contact Carmen Smith from UOW

0421 474 877 cs847@uowmail.com.au

# HARD TO BREATHE?

# WE NEED YOUR HELP!

## WE WANT TO GET TO THE CORE OF THE PROBLEM

University of Wollongong

The University of Wollongong is seeking volunteers to take part in The $CO_2$RE Project
We are researching how the level of carbon dioxide in respirators affects the wearer

**Please Volunteer!**

You will play an important role in helping to design safer and more comfortable respirators
It will only take about 30 minutes of your time

The $CO_2$RE Project will take place

**Monday, 16 April - Friday, 20 April 2012**

If you are interested or would like more information please contact

Carmen Smith from UOW
0421 474 877 cs847@uowmail.com.au

Supervisor Jane Whitelaw
02 4221 5232 jwhitelaw@uow.edu.au

## APPENDIX N RECRUITMENT SCRIPT

**DIALOGUE FOR RECRUITMENT DVD:**

"Breathing it is something you do all the time. However, a respirator can change the way we breathe normally. The University of Wollongong is currently recruiting participants for The $CO_2$RE Project. We are investigating if carbon dioxide re-breathing increases breathing effort in respirators during periods of work. If you are interested in participating please contact us for more information."

## APPENDIX O ASSESSMENT RECORD FORM

## 1. THE $CO_2$RE PROJECT: EXERCISE TEST RECORD CARD

**Date:** _____ **No:** ___ **TEMP:** ___ **HUMIDITY:** ___ **RPD: (CIRCLE): S/ L** **MHR (220 – AGE):** ___ **BEATS / MIN** **85% MHR:** ___**BEATS / MIN**

**HEIGHT:** ___**m** **WEIGHT:** ___ **KG** $A_{Du}$ = _____ $m^2$

- **Calibration Complete (Analyser & Pressure Transducer):**
- **Pre-screening materials complete:**
  - **PAR-Q**
  - **STAI**
  - **Consent**
  - **Questionnaire**

- **Blood Pressure:**
- **Fit Factor:**
- **Client details entered into Monark**
- **Rpm selected**
- **$CO_2$ Analyser connected**

| STAGE | TIME (min) | WATTS (W) | HR | FR | $ICO_2$ (%) | $ECO_2$ (%) | PIAF (l/s) | $VO_2$ (l/min) | MBS (0-10) |
|---|---|---|---|---|---|---|---|---|---|
| Rest | 0 | 0 | | | | | | | |
| SPEECH | 0 | 0 | | | | | | | |
| Pre Test | 0 | 50 | | | | | | | |
| 1 | 2 | 75 | | | | | | | |
| SPEECH | 5 | 75 | | | | | | | |
| 2 | 7 | 100 | | | | | | | |
| SPEECH | 10 | 100 | | | | | | | |
| 3 | 12 | 125 | | | | | | | |
| SPEECH | 15 | 125 | | | | | | | |
| 4 | 17 | 150 | | | | | | | |
| SPEECH | 20 | 150 | | | | | | | |
| Cool Down | 22 | 50 | | | | | | | |

COMMENTS: _____

## 2. THE $CO_2$RE PROJECT: EXERCISE TEST RECORD CARD

**Date:** _____ **No:** ___ **TEMP:** ___ **HUMIDITY:** ___ **RPD: (CIRCLE):** S/ L **MHR (220 – AGE):** ___ **BEATS / MIN** **85% MHR:** ___**BEATS / MIN**

**HEIGHT:** ___**m** **WEIGHT:** ___ **KG** $A_{Du}$ = _____ $m^2$

- Calibration Complete (Analyser & Pressure Transducer):
- Pre-screening materials complete:
  - PAR-Q
  - STAI
  - Consent
  - Questionnaire
- Blood Pressure:
- Fit Factor:
- Client details entered into Monark
- Rpm selected
- $CO_2$ Analyser connected

| STAGE | TIME (min) | WATTS (W) | HR | FR | $ICO_2$ (%) | $ECO_2$ (%) | PIAF (l/s) | $VO_2$ (l/min) | MBS (0-10) |
|---|---|---|---|---|---|---|---|---|---|
| Rest | 0 | 0 | | | | | | | |
| SPEECH | 0 | 0 | | | | | | | |
| Pre Test | 0 | 50 | | | | | | | |
| 1 | 2 | 100 | | | | | | | |
| SPEECH | 5 | 100 | | | | | | | |
| 2 | 7 | 125 | | | | | | | |
| SPEECH | 10 | 125 | | | | | | | |
| 3 | 12 | 150 | | | | | | | |
| SPEECH | 15 | 150 | | | | | | | |
| 4 | 17 | 175 | | | | | | | |
| SPEECH | 20 | 175 | | | | | | | |
| Cool Down | 22 | 50 | | | | | | | |

COMMENTS: _____