ABSTRACT

Title of Thesis: MODEL OF EXERCISE PERFORMANCE
WHILE WEARING A RESPIRATORY
PROTECTIVE MASK

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Respiratory protective masks were introduced more than 80 years ago. However, improvements can still be made. A model that predicts the effects of a respirator on a person would allow respirator design to proceed more rapidly. Such a model would be an important design tool that would provide valuable information.

A previously designed model, Coyne’s (2001) model, does not predict performance time, oxygen consumption and minute ventilation well when exercise intensity is above the anaerobic threshold. Coyne’s study aimed at exercise during steady state, and thus no transient effects were included in the study. The goals of this research were to: 1) extend Coyne’s (2001) model of the pulmonary effects while wearing a respirator to severe exercise conditions(exercise at an intensity above the anaerobic threshold); 2) modify the model to include transient effects; and 3) correctly predict exercise performance time with and without a respirator mask.

This model emphasized respiratory responses and incorporated mathematical descriptions of experimental results obtained from exercising humans. Prediction equations for tidal volume, anaerobic threshold, minute volume, respiratory work, and performance time were included, as well as dynamic changes in each. This model can help to design future respirators, aid workers wearing respirators, and regulate occupational health and safety.

In general, the current model can predict performance time when subjects exercise both with and without masks. Using work rate to predict performance time is better than using oxygen deficits. The current model was fitted for 30% and 80% VO_2max of experimental data from the Human Performance Laboratory (University of Maryland, College Park). The results showed predicted values were reasonable and closer to the experimental data. Results of physiological values and performance times showed that the model structure was valid and that the model was capable of making rational predictions of the average effects of respirator wear on the pulmonary system during physical activity.

MODEL OF EXERCISE PERFORMANCE WHILE WEARING A RESPIRATORY PROTECTIVE MASK

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A0, A1, A2, A3 = oxygen consumption amplitudes (L/min)
AT = anaerobic threshold (L/min)
B_{02} = baseline oxygen consumption or oxygen consumption without doing exercise (L/min)
Cadence = how many revolutions in a minute. (Rev/min)
EE_{02}= end exercise oxygen consumption (L/min)
G, g = acceleration due to gravity (m/s$^{2)}$
h_{step}= height of the step (m)
Load =additional weight (kg)
$m_{t\,=}$ total mass (kg)
n_{step} = number of steps
OD = oxygen deficit (L/min)
OD_2 = oxygen deficit reach to steady state when wearing respirators
R_{exh} = exhalation resistance (cmH_2O/L/s)
R_{inh} = inhalation resistance (cmH_2O/L/s)
RPD = respiratory period (sec)
RR = respiratory rate (breaths/sec)
TD1, TD2, TD3 =time delay (s)
T_{exh} = exhalation time (s)
T_{inh} = inhalation time (s)
t_{wd} = performance time form the current model (s)
v = velocity (m/s)
VE = minute ventilation (L/s)
VE_{calc} = calculate minute ventilation from the current model (L/s)
VE_{coyne} = minute ventilation from Coyne's model (L/s)
VE_{meas}= experimental data of minute ventilation (L/s)
$V_{min}(t)$ = transient minute ventilation
$\dot{V}_{02}$ = Oxygen consumption (L/min)
$\dot{V}_{02}adj$ = adjust VO2 which consider the additional weight of respirators
$\dot{V}_{02calc}$ = calculate oxygen consumption from the current model (L/min)
$\dot{V}_{02coyne}$ = oxygen consumption from Coyne's model (L/min)
$\dot{V}_{02max\,=}$ maximum oxygen consumption (L/min)

$\dot{V}_{o2meas}$= experimental data of oxygen consumption (L/min)
VT = tidal volume (L)
VT(t) = transient tidal volume (L)
WR_{ext} = External work rate (W)
WR_{phys} = Physical work rate (W)
η = muscular efficiency
$\tau 1$, $\tau 2$, $\tau 3$ = time constant (s)

Chapter 1: Introduction

A model that predicts the effects of a respirator on a person's performance would allow respirator design to proceed more rapidly. Such a model would be an important design tool that would provide valuable information. However, due to the variability of human response to exercise, work, and respirator wear, the proposed model includes many assumptions that limit the expected accuracy of the predictions.

A previous model (Coyne, 2001) predicted the oxygen consumption, minute ventilation, and tidal volume well for a limited number of exercising subjects while wearing and not wearing a respiratory protective mask. However, it was mentioned that for three subjects wearing respirators and exercising at 80-85% of maximal oxygen consumption (which is usually above the anaerobic threshold), the errors in the model were greater than those below 70% of maximal oxygen consumption. This implied that the model could have problems in correctly predicting the outputs during heavy exercise intensity. The previous model assumed steady state exercise. However, most exercise parameters incorporate transient effects and thus transient factors were discussed in the current model.

The objectives of this research were to 1) extend Coyne's (2001) model of the pulmonary effects while wearing a respirator to heavy intensity exercise conditions; 2) modify the model to include transient effects; and 3) correctly predict exercise performance time while wearing and not wearing a respiratory protective mask.

The first step in accomplishing these objectives was to find better equations for the model. Coyne used statistical analysis to find the best fit empirical equations. Most of the equations were obtained from linear regression of experimental data. However, when exercise intensity is above the anaerobic threshold, VE (minute ventilation) no longer exhibits a linear increase and therefore cannot be fully described by a linear equation. Therefore, it can be assumed that the errors are greater in Coyne's model at 80-85% of oxygen consumption, which is above the anaerobic threshold. In the current study, all equations from Coyne's model were checked and it was previously demonstrated that the equations for the low exercise intensity predicted values well and only had small errors. Other equations in Coyne's model, which related to heavy exercise intensity, had to be adjusted.

Exercise above the anaerobic (lactate) threshold usually means severe exercise. It has been well documented that the nature of $\dot{V}_{02}$ response to exercise is a function of exercise intensity (Gaesser and Poole, 1996 ; Whipp, 1987). If exercise intensity is moderate, $\dot{V}_{02}$ will eventually reach steady state (Coyne, 2001). However, when exercise intensity is above an individual's anaerobic threshold, $\dot{V}_{02}$ kinetics become more complex.

Exercise $\dot{V}_{02}$ kinetics have three phases in moderate exercise. Phase 1 represents the first 15 to 25 seconds of exercise, which rapidly increases $\dot{V}_{02}$. This increase in $\dot{V}_{02}$ is mainly attributed to the increase in cardiac output and pulmonary blood flow. In phase 2, the influence of muscle metabolic change on $\dot{V}_{02}$ is reflected, which increases exponentially toward a steady-state level. A linear dynamic relationship between $\dot{V}_{02}$ and work rate can be seen in phase 2. In phase 3, $\dot{V}_{02}$ reaches steady-state (Gaesser and Poole, 1996). However, when exercise intensity is very heavy, there is a slow component in phase 3. The slow component affects the time to reach steady state. Figure 1 showed these phases.

Based on $\dot{V}_{02}$ kinetics, Coyne's model needed to be adjusted in order to be accurate at heavy intensity work rates. Previous studies (Dwyer and Bybee, 1983; Rusko et al., 1980; Thorland et al., 1980; and Weltman and Katch, 1979) showed a relationship between anaerobic threshold (AT) and maximal oxygen consumption. The relationship was determined to be (Thorland et al., 1980):

$$AT= 0.8624\dot{V}_{02\max} -7.1585 \tag{1}$$

where $\dot{V}_{02\max}$ was the maximum oxygen uptake [L/min]. This equation was shown to overpredict the anaerobic threshold for Caretti et al. (2001) and underpredict in a study by Powers et al. (1984). It seems likely that the anaerobic threshold may have depended on more than just the $\dot{V}_{02\max}$, therefore multiple regression equations should be evaluated.

In the previous model, Coyne used oxygen deficit to predict performance time. It was shown that respiratory work affects the oxygen deficit and oxygen deficit is associated with performance time. However, this method was too general to predict the performance time and needs to be adjusted. Also, oxygen consumption does not jump immediately increase to steady state level. Tidal volume and minute ventilation change gradually to steady state as well. The equations for these transient effects were added into the current model.

Other factors like vision, thermal effects, and emotional effects were not discussed in the proposed model. Since this model focused on heavy exercise intensity and transient conditions, these factors were assumed to have very small effects on the current model. In future studies, these factors should be added into the model.

This study extended the model of Coyne to predict performance time well during heavy exercise intensity and added transient effects. Thus, this model was made to estimate physiological factors more correctly.

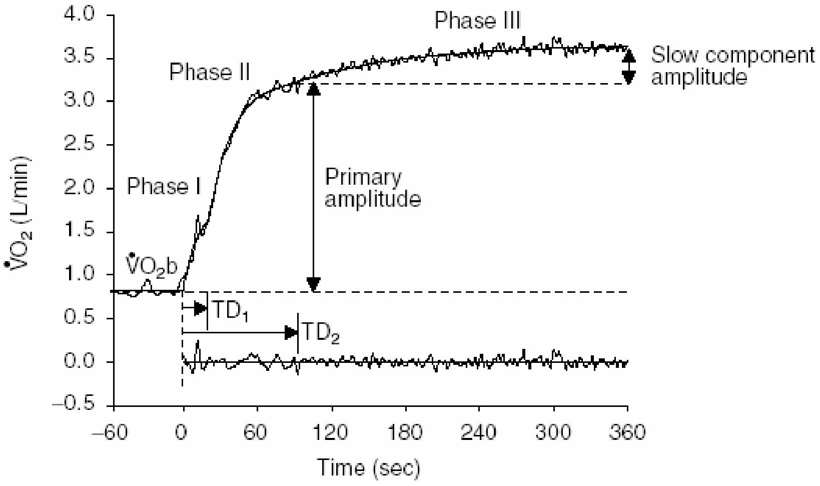


Figure 1. Three phases of oxygen consumption (Bearden and Moffatt, 2000)

Chapter 2: Objectives

1) Extend Coyne's model (2001) of the pulmonary effects while wearing a respirator,

2) Modify the model to include transient effects, and

3) Correctly predict exercise performance time with and without a respirator mask.

Chapter 3: Literature Review

3.1 Coyne's Model

The basis for the model proposed in this thesis was Coyne's (2001) model. Therefore, the structure and equations of the previous model must be discussed first. Figure 2 shows a flowchart of the previous model's structure. Table 1 presents all of the equations used in the model. The aim of Coyne's model was to predict the effects of a respiratory protective mask on a person during physical activity.

In the model, the inputs and outputs (Table 2) were selected first and then the relationship was identified later. The outputs of the model were oxygen consumption, minute ventilation, tidal volume, oxygen deficit, performance time, respiratory rate, inhalation and exhalation times, and respiratory work. The output parameters were found to be affected by the external work rate, subject characteristics, respirator characteristics, and respiratory system characteristics. Coyne defined subject characteristics as age, height, weight, and maximal oxygen consumption. Respirator characteristics included inhalation and exhalation resistances, mass, and dead volume. Respiratory system characteristics included additional dead volume and resistance. These input factors were plugged into software developed by Coyne. This section details each factor in the previous model (Coyne, 2001).

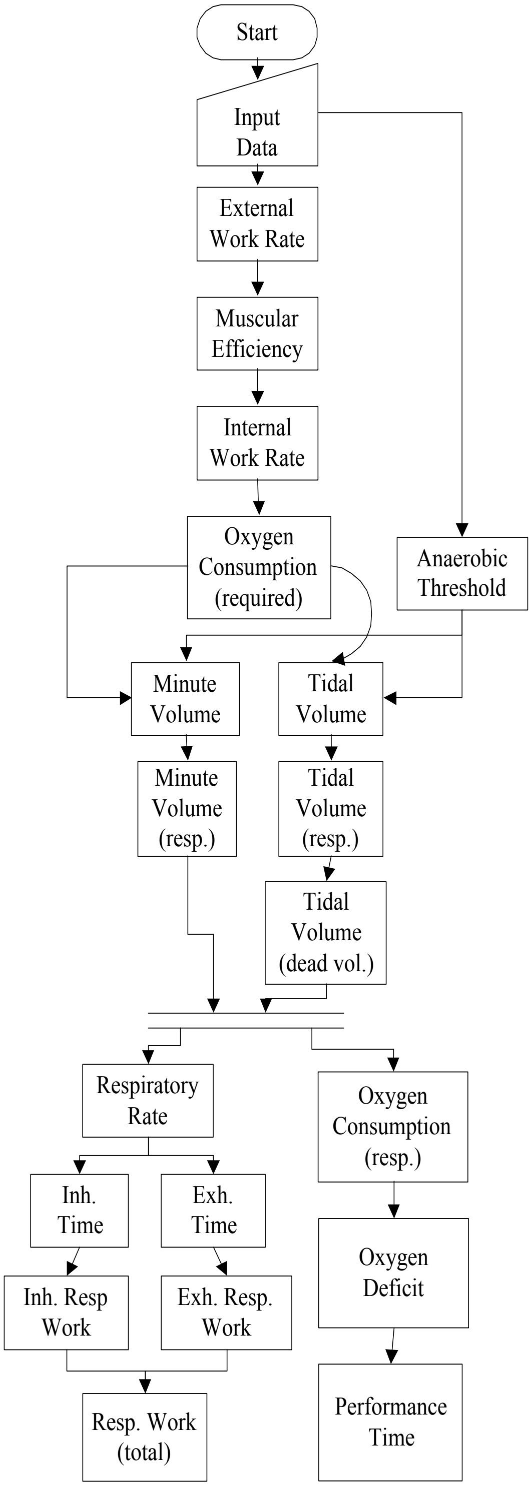


Figure 2 Structure of Coyne's model (Coyne, 2001)

Table 1. Summary of the equations used in Coyne's model.

External Work Rate

$$WR_{ext} = \frac{\text{cadence} \cdot \text{load} \cdot \dfrac{\text{distance}}{\text{revolution}} \cdot g}{60}$$

$$WR_{ext} = \text{h}_{\text{step}} \cdot \text{mass} \cdot \text{n}_{\text{step}} \cdot \text{g}$$

$$WR_{\text{ext}} = \text{m}_{\text{t}} \cdot g \cdot \text{v} \cdot \frac{\text{G}}{100}$$

Efficiency as a Function of Work Rate

$$\eta = \frac{WR_{ext}}{200} \qquad 0 \le WR_{ext} < 20.1$$

$$\eta = 0.1003 + 0.0006(WR_{ext} - 20.1) \qquad 20.1 \le WR_{ext} < 159.3$$

$$\eta = 0.183 + 0.0002(WR_{ext} - 159.3) \qquad 159.3 \le WR_{ext} < 240$$

$$\eta = 0.2 \qquad 240 \le WR_{ext}$$

Physiological Work Rate

$$\text{WR}_{\text{phys}} = \frac{\text{WR}_{\text{ext}}}{\eta}$$

Oxygen Consumption as a Function of Physiological Work Rate

$$\text{V}_{\text{O2}} = 0.002952\text{WR}_{\text{phys}}$$

Anaerobic Threshold as a Function of Maximal Oxygen Consumption

$$\text{AT} = 0.8624\text{V}_{\text{O2max}} - 7.1585$$

Minute Ventilation as a Function of Oxygen Consumption

$$\%V_{E\max} = 0.0095 \cdot \%V^2_{O2\max} - 0.133 \cdot \%V_{O2\max} + 17.153$$

$$V_{Emax} = 20.01V_{O2max} + 27.855$$

Tidal Volume as a Function of Oxygen Consumption

$$\%V_{Tmax} = 0.9987 \cdot \%V_{O2max} - 1.6809$$

$$V_{Tmax} = 0.3864 \cdot V_{O2max} + 0.6416$$

Change in Minute Ventilation with Resistance

25-30% V_{O2max}: $V_E = 0.3705 - 0.0037R_{inh} - 0.02236R_{exh}$

35-40% V_{O2max}: $V_E = 0.4754 - 0.0018R_{inh} - 0.0206R_{exh}$

45-50% V_{O2max}: $V_E = 0.6088 - 0.0065R_{inh} - 0.0469R_{exh}$

65-70% V_{O2max}: $V_E = 0.9718 - 0.0156R_{inh} - 0.0846R_{exh}$

80-85% V_{O2max}: $V_E = 1.3979 - 0.0454R_{inh} - 0.0967R_{exh}$

Change in Tidal Volume with Resistance

25-30% V_{O2max}: $V_T = 0.5023 + 0.0059R_{inh} + 0.1046R_{exh}$

35-40% V_{O2max}: $V_T = 0.6271 + 0.0092R_{inh} + 0.2080R_{exh}$

45-50% V_{O2max}: $V_T = 0.9698 - 0.0091R_{inh} + 0.0890R_{exh}$

65-70% V_{O2max}: $V_T = 1.4525 - 0.0027R_{inh} - 0.0024R_{exh}$

80-85% V_{O2max}: $V_T = 1.7955 - 0.0162R_{inh} + 0.0746R_{exh}$

Change in Minute Ventilation with Dead Volume

$$\Delta V_E = 0.170432V_D - 0.00681 - \frac{(\%V_{O2max} - 0.15)}{0.15} \cdot \left(\frac{1.8}{60}\right)$$

Change in Tidal Volume with Dead Volume

$$\Delta V_T = 0.1950 + 0.2517V_D - \frac{0.4256\%V_{O2max}}{100}$$

Oxygen Consumption as a Function of Resistance and Dead Volume

$$\mathrm{V_{O2}} = 0.0340\mathrm{V_E} + 0.4322$$

Performance Time

$$\text{Perf time} = \left(\frac{4.03}{\mathrm{O_2}\ \text{deficit rate}}\right)$$

Respiratory Rate

$$\mathrm{RR} = \frac{\mathrm{V_{E,adjusted}}}{\mathrm{V_{T,adjusted}}}$$

Respiratory Period

$$\mathrm{RPD} = \frac{1}{\mathrm{RR}}$$

Exhalation Time as a Function of Respiratory Period

$$\mathrm{T_{exh}} = 0.6176\mathrm{RPD} - 0.2145$$

Table 2. Inputs and Outputs of Coyne's model

Input	● Subject characteristics ➢ Age, height, weight, $\dot{V}O_2$max ● Respiratory system characteristics ➢ Additional dead volume, resistance ● Respirator characteristics ➢ In/exhalation resistance, mass, dead volume
Output	● Oxygen consumption ● Minute ventilation, ● Tidal volume, ● Oxygen deficit, ● Performance time, ● Respiratory rate ● Inhalation and exhalation times, ● Respiratory work.

3.1.1 External Work Rate

Equations for determining the external work rate for treadmill running, cycling, and walking were selected for the model.

3.1.2 Efficiency as a Function of External Work Rate

Based on the equations developed by Johnson (1992) for positive work rates, Coyne showed that those equations did not fit well. Instead data from previous studies (Webb et al., 1988); Nagle et al., 1990; and Hambraeus et al., 1994) were used to plot and create a new linear regression equation.

Data from Nagle et al. (1990) were also used to assess the equation for negative efficiency.

3.1.3 Physiological Work Rate

The physiological work rate in Coyne's model was calculated from the external work rate and efficiency.

3.1.4 Oxygen Consumption

Data about oxygen consumption and respiratory exchange ratio were obtained from Johnson (1976). Lusk's (1928) equation was used to calculate physiological work rate. Oxygen consumption was plotted versus physiological work rate and a linear regression was performed.

3.1.5 Anaerobic Threshold

The following studies were used for calibration in Coyne's model: Balsom (1988), Bradley (1982), Claiborne (1984), Dwyer and Bybee (1983), Gray (1981), Jones (1984), Robbins (1982), Weltman and Katch (1979), Weltman et al. (1978), and Johnson et al. (1999).

The two linear regression equations and two multiple regression equations with the correlation coefficients were selected for statistical analysis. Based on the statistical analysis, one equation was selected. Data from Caretti et al. (2001) and Powers et al. (1984) were used to validate the selected equation.

3.1.6 Minute Ventilation as a Function of Oxygen Consumption

A plot of minute ventilation versus oxygen consumption was obtained for eight subjects from Coyne's study and the data below the anaerobic threshold was fit to a linear relationship while an exponential curve was fit to the data above the anaerobic threshold.

3.1.7 Tidal Volume as a Function of Oxygen Consumption

The data from the eight subjects were pooled and plotted. Linear, quadratic, exponential, and power models were fit to the data and plotted. Based on the statistics, the linear model was selected by Coyne.

3.1.8 Effects of Resistance on Minute Ventilation and Tidal Volume

The data of average minute ventilation and average tidal volume from the eight subjects were obtained. Multiple regression equations were obtained regressing average minute ventilation on inhalation and exhalation resistance.

3.1.9 Changes in Minute Ventilation and Tidal Volume with Dead Space

Minute ventilation and tidal volume data were obtained for rest and light exercise (Stannard and Russ, 1948) and severe exercise (Johnson et al., 2000). Linear regression equations were fit to the resting and light exercise data. Plots of the data and the regression lines were obtained. However, none were shown for severe exercise.

3.1.10 Oxygen Consumption as a Function of Minute Ventilation

A regression equation was used to fit oxygen consumption and minute ventilation data obtained from the eight subjects in the study.

3.1.11 Oxygen Consumption as a Function of Tidal Volume

Oxygen consumption and tidal volume data were obtained from Coyne's study. The data were plotted and a regression equation was fit to the data.

3.1.12 Actual Oxygen Consumption

Actual oxygen consumption was determined using the equation for oxygen consumption as a function of minute ventilation.

3.1.13 Oxygen Deficit

The oxygen deficit was found as the difference between required and actual oxygen consumption.

3.1.14 Performance Time

Performance time was found by dividing an estimate of the maximal oxygen deficit by the actual oxygen deficit.

3.1.15 Respiratory Rate and Respiratory Period

The respiratory rate was found by dividing the adjusted minute ventilation by the adjusted tidal volume. The respiratory period was determined from the inverse of the respiratory rate.

3.1.16 Exhalation Time as a Function of Respiratory Period

Data from the inhalation/exhalation study (Johnson et al., 2001) were used for the analysis. Subjects in Coyne's study exercised while wearing an air purifying respiratory protective mask at 80-85% of $\dot{V}_{02\max}$ until voluntary termination. A plot of exhalation time versus respiratory rate was obtained. A linear regression was obtained.

3.1.17 Breathing Waveform Based on Work Rate

Coyne estimated work rates at which the transitions between waveforms occurred.

3.1.18 Respiratory Work Rate

Respiratory work rate equations were obtained from Johnson (1993). Inhalation and exhalation work rates were determined separately. The work of inhalation and exhalation was determined by multiplying the work rate by the corresponding time (inhalation or exhalation). The total respiratory work was found by adding the inhalation and exhalation work. Total respiratory work rate was calculated by dividing total respiratory work by the respiratory period.

3.2 Physiological Change and Lactate Formation

3.2.1 Lactate Formation

During light to moderate levels of exercise, the body can get sufficient oxygen. However, with severe exercise, energy demands exceed oxygen supply or utilization rate. In order to get enough energy from another source, anaerobic glycolysis is necessary to produce energy. In anaerobic glycolysis, $NADH_2$ releases pairs of excess non-oxidized hydrogen, which combine temporarily with pyruvate ($C_3H_4O_3$) to form lactate. This reversible reaction is shown in Figure 3.

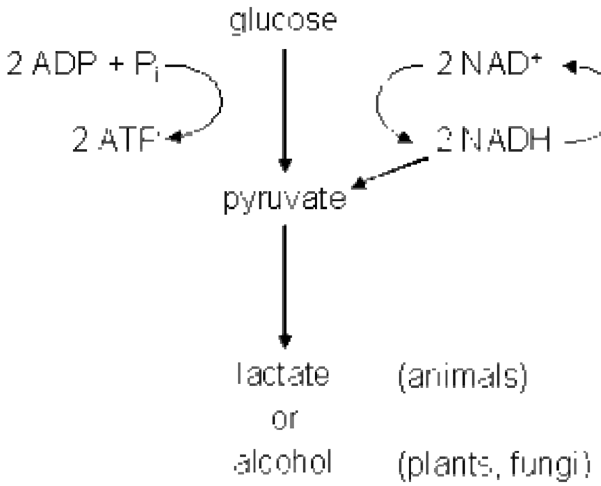


Figure 3. Chemical schematic of lactate formation (William et al., 2000).

When lactate forms within muscle, it diffuses rapidly into the blood for buffering and rapid removal from the site of energy metabolism. This allows glycolysis to continue supplying additional anaerobic energy for ATP re-synthesis. Lactate levels in blood and muscle continue to increase and ATP regeneration cannot keep up with the rate of utilization. Thus, the body feels fatigue and decreases exercise performance time. When the body can get enough oxygen again during lower intensity or recovery, NAD+ will again bind hydrogen molecules from lactate and oxidize lactate to form ATP. Thus, work can continue to be performed.

3.2.2 Blood Lactate Threshold

During light and moderate exercise, aerobic metabolism adequately meets energy demands. Non-active tissues rapidly oxidize any lactate formed. Even as oxygen consumption increases, the blood lactate still remains stable. When exercise intensity is high enough for a buildup of lactate, also known as the lactate threshold, aerobic exercise performance can be predicted (Ahmaidi et al., 1996). Furthermore, at a specific exercise intensity, the rate of lactate production and transport into blood exceeds the rate of removal from blood. This is also known as the lactate threshold. Blood lactate starts to increase exponentially at about 50-55% of $\dot{V}_{02\max}$ for an untrained person (Barstow, 1994). The usual explanation for increased amounts of lactate during heavy exercise is tissue hypoxia. Anaerobic glycolysis gives partial energy when tissue lacks oxygen. Therefore, lactate builds up. Svedahl (2003) defined the lactate threshold as the exercise intensity that is associated with a substantial increase in blood lactate during an incremental exercise test. Figure 4 shows the amount of lactate in untrained persons. Above the lactate threshold, the value of lactate increases faster than below the lactate threshold. Usually, a trained person has more capacity to accumulate lactate in the body. This may be because a trained person has better muscle efficiency and more energy stored in muscle. The lactate threshold occurs at a higher oxygen consumption level in a trained versus untrained person.

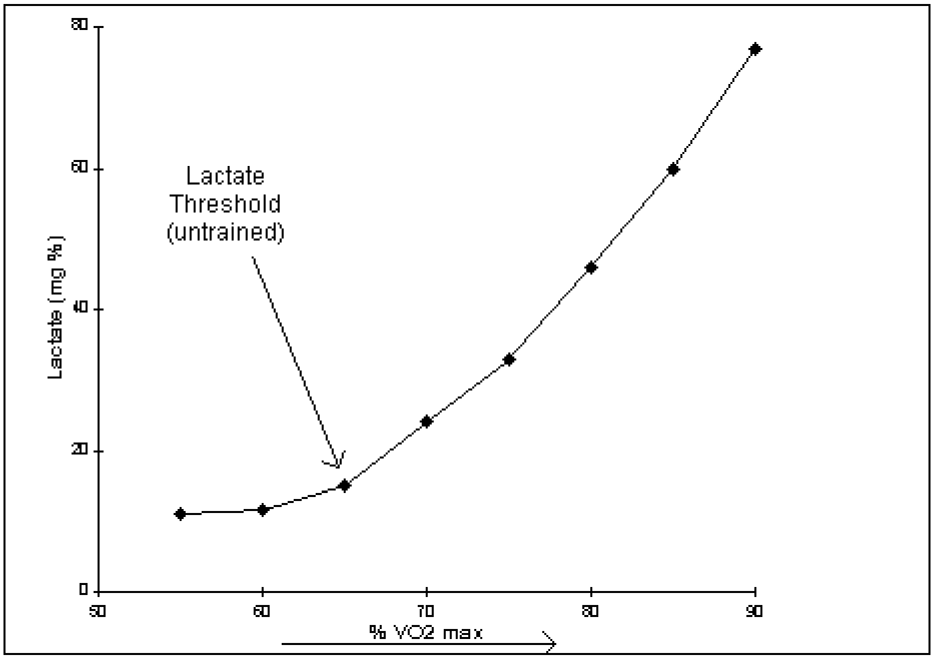


Figure 4. Blood lactate levels in an untrained person as a function of oxygen consumption (William et al., 2000).

3.2.3 Anaerobic Threshold (AnT) Affects Physiology Factors

During heavy exercise, lactate formation gives an added demand on pulmonary ventilation, which causes hyperventilation. This results from buffering lactate to carbonic acid. In the lung, carbonic acid splits into its water and carbon dioxide components. This non-metabolic carbon dioxide provides an added stimulation to ventilation (William et al., 2000). The following is this reaction:

$$HLa + NaHCO_3 \rightarrow NaLa + H_2CO_3 \rightarrow H_2O + CO_2 \qquad (2)$$

As exercise $\dot{V}_{02}$ increases, minute ventilation takes a sharp upswing. The point at which pulmonary ventilation increases disproportionately with oxygen consumption during graded exercise has been termed the ventilation threshold. It is about at the same time that blood lactate begins to accumulate. Therefore, the ventilation threshold can be used to indicate the lactate threshold from the minute ventilation response during exercise. Figure 5 shows these relationships.

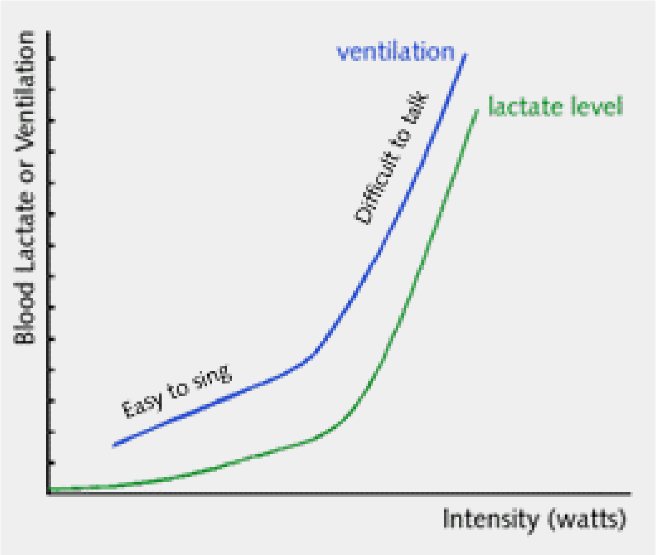


Figure 5. Minute ventilation and blood lactate levels versus exercise intensity before and after their respective thresholds (William et al., 2000).

3.2.4 VO_2 Slow Component

Above the lactate threshold, prolonged steady-state exercise produces a secondary rise in oxygen consumption, the oxygen slow component. The slow component of $\dot{V}_{02}$ reflects an inadequate O_2 supply in active muscle and an additional energetic requirement with exercise above the lactate threshold (Xu and Rhodes, 1999). This slow component delays the attainment of steady-state $\dot{V}_{02}$ for low exercise intensities and drives the $\dot{V}_{02}$ to the maximum level for heavy exercise intensities.

Some research has shown that the slow component of $\dot{V}_{02}$ is closely linked to the blood lactate levels. It takes almost the same amount of time to increase the slow component of $\dot{V}_{02}$ and lactate (Poole et al., 1988; Xu and Rhodes, 1999). This implies that these two factors are highly correlated. Because the slow component affects the lactate level, it may also affect exercise performance.

3.3 Oxygen Consumption and Exercise Model

3.3.1 Background

Hughson and Morrissey (1982) demonstrated that the $\dot{V}_{02}$ kinetics in the transition from rest to exercise at 40% of AT was faster than the $\dot{V}_{02}$ kinetics during the transition from 40 to 80% of AT. If $\dot{V}_{02}$ kinetics had behaved as a linear system, the time constant of the response would have been unchanged whether or not the workload was increased from the same baseline. This implies that other factors are involved in the control of $\dot{V}_{02}$ dynamic response at the onset of exercise.

When exercise is performed in the heavy intensity domain, the sustained elevation of blood lactate and the delayed development of the slow $\dot{V}_{02}$ component make the oxygen consumption dynamic model more complex. The following developed models included transient effects and the slow component of oxygen consumption. Each of them has limitations and different test procedures.

3.3.2 Bearden and Moffatt's Model

The purpose of Bearden and Moffatt's (2000) study was to test their model for the calculation of the O_2 deficit above the lactate threshold that included separate deficit phases corresponding to the biphasic $\dot{V}_{02}$ kinetics, and to test the implications of the traditional O_2 deficit model for severe exercise being equivalent to the deficit calculated using the steady-state (Bearden and Moffatt, 2000).

Data was obtained from each work rate transition for each subject by nonlinear regression with minimization of the sum of squared residuals. The first 25 seconds were always removed from the analysis to ensure that the early venous return component did not influence the results.

The data of eight minutes of cycling during severe and very severe exercise intensity were fit with three models. Model 1 was a single monoexponential function with time delay:

$$\dot{V}_{02}(t) = \mathrm{B}\,\dot{V}_{02} + \mathrm{A1}\,[1 - exp\,((t\text{-TD1})/\tau_1)] \qquad (3)$$

Model 2 was a double monoexponential function with common time delay:

$$\dot{V}_{02}(t) = \mathrm{B}\,\dot{V}_{02} + \mathrm{A1}\,[1 - exp\,((t\text{-TD1})/\tau_1)] + \mathrm{A2}\,[1 - exp\,((t\text{-TD2})/\tau_2)] \qquad (4)$$

where TD1 = TD2.

Model 3 was a double monoexponential function with independent time delays:

$$\dot{V}_{02}(t) = \mathrm{B}\,\dot{V}_{02} + \mathrm{A1}\,[1 - \exp\,((t\text{-TD1})/\tau_1)] + \mathrm{A2}\,[1 - \exp\,((t\text{-TD2})/\tau_2] \qquad (5)$$

where TD1 <TD2; $\dot{V}_{02}(t)$ is the $\dot{V}_{02}$ at any time t; B $\dot{V}_{02}$ is the baseline $\dot{V}_{02}$; A1 and A2 are $\dot{V}_{02}$ amplitudes for the fast and slow components, respectively; TD1 and TD2 are time delays for the fast and slow components, respectively; and τ_1 and τ_2 are time constants for the fast and slow components after their time delays, respectively. For Equation 4, the statistical model was constrained with a conditional term that forced the

slow component $\{A2\ [1 - \exp(t\text{-}TD2/\ \tau_2)]\}$ to be included only when t => TD2. Table 3. showed these values of parameters.

The study showed that Model 2 fit the data significantly better than model 1 ($P < 0.001$). Additionally, Model 3 fit the data significantly better than Model 2 ($P = 0.017$). Model 2 was constrained by the second time delay (TD2), whereas Model 3 was free to fit the data without this constraint. It was also mentioned that Model 3 could result in equal time delays if this was the optimal solution as defined by the nonlinear regression goal of minimizing the sum of the squared residuals. Figure 6 shows the exponential Model 3 fit of a transition for cycling from unloaded to above lactic acid threshold (LAT) during eight minutes of severe exercise.

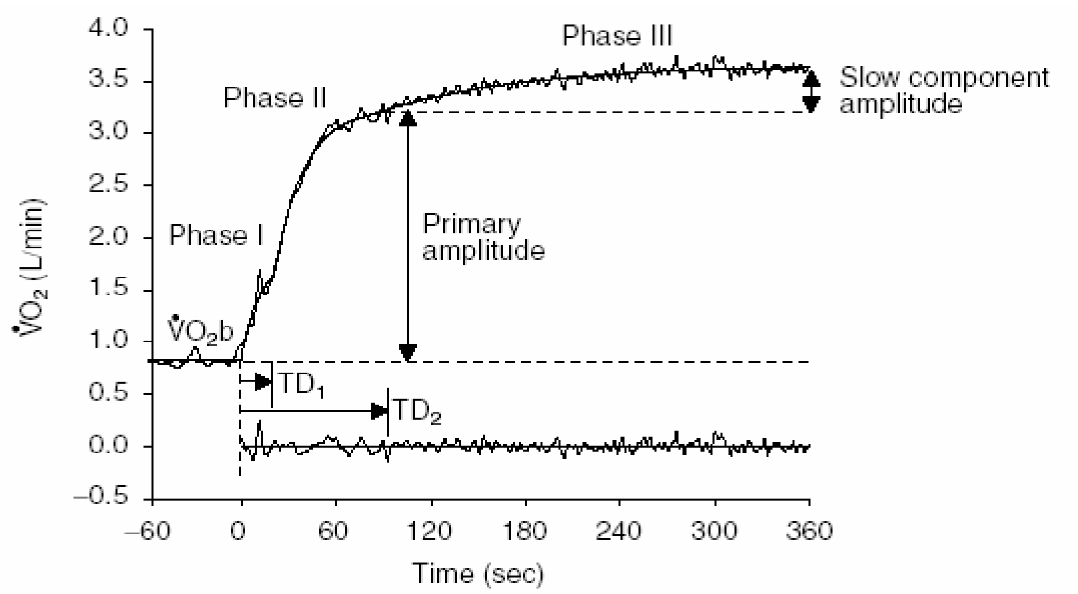


Figure 6. Bearden and Moffatt's model (2000) showed exponential Model 3 fit for a transition from unloaded cycling to above the lactate threshold (LAT) during eight minutes of severe exercise. TD1 and TD2 are the time delays for onset of fast and slow components, respectively.

Total O_2 deficit (OD_{Trad}) was calculated as the difference between the O_2 that would have been consumed if a steady state had been attained immediately at the onset of exercise and the oxygen consumed during the exercise period (definite integral of Equation 4):

$$OD_{Trad} = t\,(B\dot{V}_{02} + A1 + A2) - \int (Eq.\ 4)\,dt \tag{6}$$

The data showed that calculating the O_2 deficit in the traditional manner was not valid for above-lactate threshold since at that level, $\dot{V}_{02}$ was composed of two phases, including one that did not begin until 2–3 min after the onset of the work rate transition.

OD_{New} was similar to the sum of two calculated deficits for work rate as it increased above the lactate threshold. There was a separate deficit for the fast and slow components of Model 3. This calculation was made mathematically by subtracting a volume equal to TD2 *A2 from the traditional calculation (Figure 6).

$$OD_{New} = OD_{Trad} - (A2 * TD2) \tag{7}$$

Since this study separates the slow and the fast components, it probably can predict oxygen deficit better.

Table 3. Summary of Bearden model parameters (Bearden and Moffatt, 2000).

	$B\dot{V}o_2$, liters	A_1, liters	TD_1, s	τ_1, s	A_2, liters	TD_2, s	τ_2, s
				Model 1			
VH8	0.81 ± 0.11	1.83 ± 0.42	7.60 ± 9.76	58.81 ± 23.35			
H8	0.82 ± 0.12	1.53 ± 0.43	13.44 ± 7.11	41.37 ± 11.64			
				Model 2			
VH8	0.81 ± 0.11	1.36 ± 0.34	22.68 ± 3.68	20.11 ± 6.28	1.05 ± 0.43	22.68 ± 3.68	808.85 ± 760.85
H8	0.82 ± 0.12	1.20 ± 0.29	22.81 ± 2.93	19.35 ± 3.23	0.62 ± 0.25	22.81 ± 2.93	598.32 ± 791.94
				Model 3			
VH8	0.81 ± 0.11	1.53 ± 0.34	22.73 ± 3.59	22.11 ± 3.29	0.54 ± 0.18	135.76 ± 43.91	296.30 ± 122.49
H8	0.82 ± 0.12	1.37 ± 0.38	23.16 ± 4.41	21.08 ± 5.14	0.25 ± 0.11	163.06 ± 41.17	120.03 ± 42.36
				3-min Bout			
VH3	0.81 ± 0.15	1.66 ± 0.37	21.83 ± 7.00	25.68 ± 6.66			
H3	0.81 ± 0.10	1.45 ± 0.41	18.36 ± 5.92	29.83 ± 6.07			

3.3.2 Fujihara Control Model

Fujihara et al. (1973) performed a series of impulse and ramp work rate experiments on subjects doing the cycling test. This model was able to describe respiratory transient responses. This transient function has a time response to an impulse work load and to a step input work load. Furthermore, this model provides the function that describes the rapid and slower ventilatory responses. This model gave the correct description of the response of the respiratory system to abrupt changes in the ventilatory demand and is described in Laplace transform:

$$\Delta VE(s) = \{AE \exp(-stD1)/(1+s\tau 1)\}+\{B\exp(-stD2)/[(1+s\tau 2)(1+\tau 3)]\} \qquad (8)$$

where $\Delta VE(s)$= change in minute ventilation, m^3/sec; A,B= constant; tD1,tD2= time delays; $\tau 1$, $\tau 2$, $\tau 3$= time constant and s= complex Laplace transform parameter.

3.3.3 Carter's Model

This study aimed to examine oxygen consumption kinetics during running and cycling. Through mathematical modeling, the breath-by-breath gas exchange responses to moderate and severe exercise were determined. $\dot{V}_{02}$ responses were fit with either a two-phase (below lactate threshold) or three-phase (above lactate threshold) exponential model. The parameters of the $\dot{V}_{02}$ kinetic response were similar for the two exercise modes; however, the $\dot{V}_{02}$ slow component was significantly ($P< 0.05$) greater for cycling than for running at 50% and 75% lactate threshold.

In this study, nonlinear regression techniques were used to fit $\dot{V}_{02}$ data after the onset of exercise with an exponential function. The mathematical model consisted of two (moderate exercise) or three (severe exercise) exponential terms, each representing one phase of the response:

$$\dot{V}_{02}(t)=\dot{V}_{02}(b)+\underset{\text{(Phase 1)}}{A0(1-e^{\wedge}(-t/\tau_0)}+\underset{\text{(Phase 2)}}{A1(1-e^{\wedge}(-t-TD1)/\tau_1)}+\underset{\text{(Phase 3)}}{A2(1-e^{\wedge}(-t-TD2)/\tau_2)} \tag{9}$$

where Phase 1 is the cardiodynamic component; Phase 2 is the primary respiratory component, Phase 3 is the slow component; $\dot{V}_{02}(b)$ is the resting baseline average value; *A*0, *A*1, and *A*2 are the asymptotic amplitudes for the exponential terms; τ_0, τ_1, and τ_2 are the time constants; and TD1 and TD2 are the time delays. Table 4 showed these values of parameters.

Figure 7 shows one subject at four different exercise intensities. Despite different absolute $\dot{V}_{02}$ for the two types of exercise, the transient responses were similar, except that a larger slow component was seen in cycling.

Table 4. Summary of parameters estimates for the model of Carter (Carter, 2000).

	80% LT		25%Δ		50%Δ		75%Δ	
	Run	Cycle	Run	Cycle	Run	Cycle	Run	Cycle
BL V_{O_2}, ml/min	388 ± 39	439 ± 24	422 ± 28.4	447 ± 11	411 ± 32.4	442 ± 11.2	413 ± 75	470 ± 22
A_0', ml/min	720 ± 96	384 ± 69*	930 ± 68	619 ± 62*	1,064 ± 172	656 ± 101*	1,181 ± 151	861 ± 154*
TD, s	25.5 ± 4.1	23.0 ± 3.0	22.6 ± 1.9	22.3 ± 2.9	16.6 ± 1.6	21.2 ± 1.7	17.9 ± 1.4	21.8 ± 1.5
A_1', ml/min	1,570 ± 177	858 ± 142*	2,347 ± 230	1,522 ± 219*	2,559 ± 276	1,773 ± 231*	2,736 ± 326	2,110 ± 267*
τ_1, s	15.0 ± 2.0	18.0 ± 4.0	19.4 ± 3.0	21.6 ± 2.2	20.1 ± 2.0	22.4 ± 3.4	15.9 ± 2.2	22.6 ± 5.4
TD_2, s			120.1 ± 12.9	131.3 ± 8.8	111.6 ± 9.9	116.8 ± 16.3	105.2 ± 8.9	119 ± 14.9
A_2', ml/min			73.5 ± 20.9	102 ± 9.8	204.8 ± 31.9	334 ± 68.9†	301.5 ± 58.3	430 ± 60†
τ_2, s			207.6 ± 22.4	232.5 ± 14.5	234.3 ± 23.3	229.5 ± 20.9	256.9 ± 24.2	254.7 ± 21.1
Relative A_2', % EE $\dot{V}_{O_2}$			3.2 ± 1.1	6.6 ± 0.5	7.3 ± 0.5	15.3 ± 1.4†	9.6 ± 1.2	16.9 ± 0.8†
EE $\dot{V}_{O_2}$, ml/min			2,420 ± 232	1,624 ± 228*	2,764 ± 306	2,107 ± 290*	3,037 ± 367	2,540 ± 322*

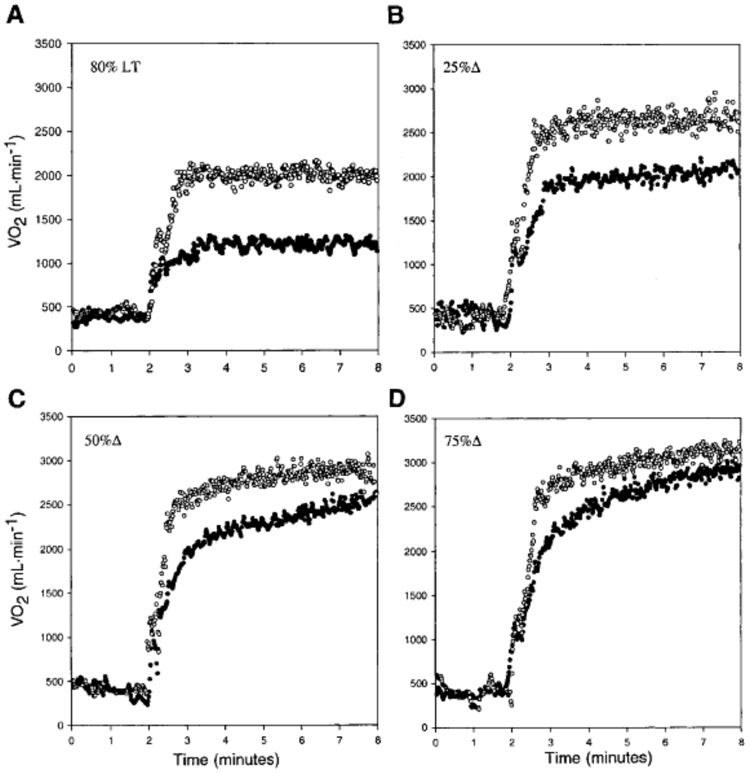


Figure 7. Transient responses for four different exercise intensities during two different types of exercise (white: running; black: cycling) for the same subject.

3.3.4 Model of Oxygen Consumption at Onset and End of Exercise

Cleuziou et al. (2003) found inconsistencies with dynamic asymmetry between the onset and recovery transient responses in oxygen consumption. The purpose of this study was to examine $\dot{V}_{02}$ transients during moderate and severe intensity cycling exercise. Single or double exponential models were used to characterize the $\dot{V}_{02}$ kinetics at exercise onset as a function of time by using a nonlinear fitting procedure. The single exponential on-transient model for moderate intensity exercise was determined by a similar equation in the previous section:

$$\dot{V}_{02}(t) = A1\ [1-\exp(-(t-TD1)\ /\tau\ 1)]\ U1 \qquad (10)$$

The double exponential transient model for severe exercise is shown by:

$$\dot{V}_{02}(t) = A1\ [1-\exp(-(t-TD1)/\tau\ 1)]\ U1 + A2\ [1-\exp\ (-(t-TD2)/\tau\ 2)]\ U2 \qquad (11)$$

where A1 is the unloaded cycling baseline. A2 represents the asymptotic value for the slow component magnitude. τ 1 and τ 2 are the time constants. TD1 and TD2 are the independent time delays components. U1=0, when t<TD1and U1=1 when t>= TD1; U2=0 when t<TD2; and U2=1 when t>=TD2. Table 5 showed the values of these parameters.

The single exponential transient model for the entire recovery period was shown to be (Paterson and Whipp, 1991):

$$\dot{V}_{02}(t) = EEVO_2 - A1\ [1-e\hat{}\ (-(t-TD1)/\tau_1)]\ U1 \qquad (12)$$

The double exponential transient model for the entire recovery period with the two terms beginning after independent time delays was (Scheuermann et al., 1998):

$$\dot{V}_{02}(t) = EEVO_2 - A1\ [1-e\hat{}\ (-(t-TD1)/\tau_1)]\ U1 - A2\ [1-e\hat{}\ (-(t-TD2)/\tau_2)]\ U2 \qquad (13)$$

The double exponential transient model for the entire recovery period with both fast and slow components was(Carter et al., 2000):

$$\dot{V}_{02}(t) = EE\dot{V}_{02} - A1\ [1-e\hat{}\ (-(t-TD1)/\tau\ 1)]\ U1 - A2\ [1-e\hat{}\ (-(t-TD1)/\tau\ 2)]\ U1 \qquad (14)$$

where EE$\dot{V}_{02}$ is the end-exercise $\dot{V}_{02}$, A1 is the difference between EE$\dot{V}_{02}$ and the steady-state exercise.

Two models (Eqs. 10 and 11) were shown to significantly ($p<0.05$) fit the experimental data and to characterize the kinetics of $\dot{V}_{02}$ response at the onset of the transient phase during moderate and severe exercise intensities. For the off-transient model, Eq. 12 fits the data better than the other models. When compared with heavy exercise, the lower values of $\tau 1$ were obtained for the off-transient model during moderate exercise when compared with severe exercise. A1 for severe exercise was significantly higher than for moderate exercise in both transient models. Figure 8 showed a comparison between two different work rates. The on and off-transient responses also showed dynamic asymmetry for severe exercise intensity.

The research demonstrated that a dynamic asymmetry of the fundamental component was observed between $\dot{V}_{02}$ on- and off-transients of severe cycling in subjects. Here, on-transients defined the intensity from low to heavy; off-transients defined intensity from heavy to low. For severe exercise intensity, the slow component was present during both exercise and recovery with similar magnitude and time course.

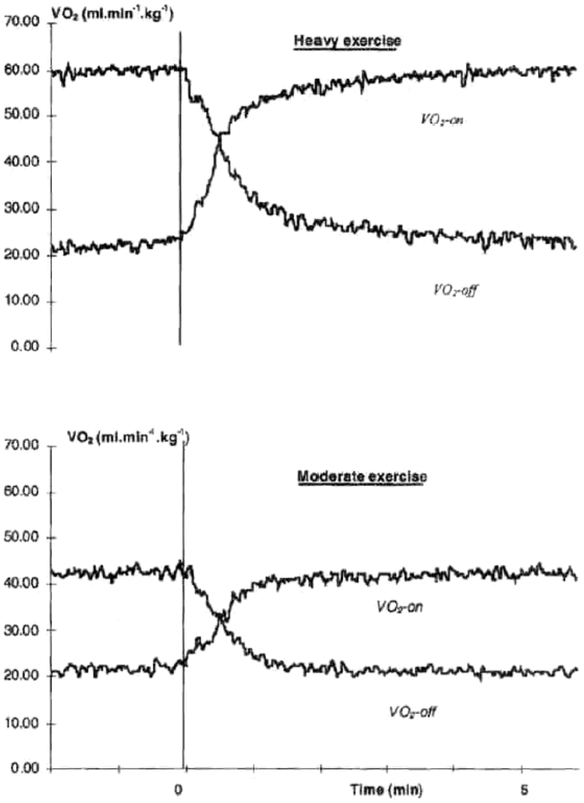
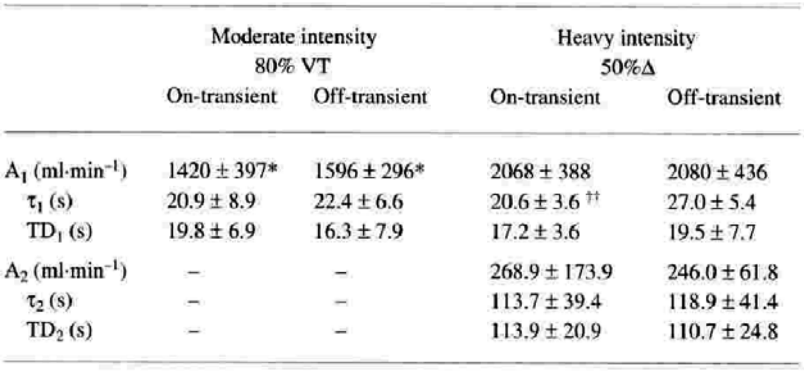


Figure 8. On- and off-transient responses of $\dot{V}_{02}$ during exercise above the lactate threshold (upper panel) and below the lactate threshold (lower panel) (Cleuziou, et al., 2003).

Table 5. Summary of parameters estimates for the model of Cleuziou

(Cleuziou, et al., 2003).



	Moderate intensity 80% VT		Heavy intensity 50%Δ	
	On-transient	Off-transient	On-transient	Off-transient
A_1 (ml·min⁻¹)	1420 ± 397*	1596 ± 296*	2068 ± 388	2080 ± 436
τ_1 (s)	20.9 ± 8.9	22.4 ± 6.6	20.6 ± 3.6 ††	27.0 ± 5.4
TD_1 (s)	19.8 ± 6.9	16.3 ± 7.9	17.2 ± 3.6	19.5 ± 7.7
A_2 (ml·min⁻¹)	–	–	268.9 ± 173.9	246.0 ± 61.8
τ_2 (s)	–	–	113.7 ± 39.4	118.9 ± 41.4
TD_2 (s)	–	–	113.9 ± 20.9	110.7 ± 24.8

3.3.6 Hill Model for $\dot{V}_{02}$ Kinetics During Severe Exercise Intensity

The purpose of this study was to investigate the effect of exercise mode on the characteristics of the oxygen uptake response to exercise within the severe intensity domain. In this study, maximal $\dot{V}_{02}$ values were found to be more severe in running than in cycling, and these values were reached faster in running than in cycling (Hill, 2003). This study demonstrated that the time constant of the primary phase of the $\dot{V}_{02}$ response was faster in running than in cycling at the equivalent intensities in the severe domain. Second, it demonstrated that the amplitude of the primary phase was greater in running than in cycling since the faster, larger primary phase contributed to faster attainment of $\dot{V}_{02\max}$ in running than in cycling. Third, the amplitude of the slow component was shown to be smaller in running than in cycling.

The following model was used in Hill's study:

$\dot{V}_{02}(t) =$ A0 baseline $\dot{V}_{02}$
+A1 (1-e^-t/ τ_1) Phase1 cardiodynamic component
+A2 (1-e- (t-TD2)/ τ_2) Phase 2 primary respiratory component
+A3 (1-e- (t-TD3)/ τ_3) Phase 3 slow respiratory component (15)

where A1, A2, and A3 are the asymptotic amplitudes for the three exponential terms; τ_1, τ_2, and τ_3 are the time constants; and TD2 and TD3 are the time delays. (Table 6 showed the values of these parameters).

The Phase 1 term was terminated at the onset of Phase 2 and was assigned the value for that time (A'1); also the end of phase 2 was assigned as (A'2) and the end of phase 3 was assigned (A'3). The following were the models mentioned in the study:

$$A'1 = A1\ (1\text{-}e\hat{\ }\text{-}TD2/\ \tau_1) \tag{16}$$

$$A'2 = A2\ (1\text{-}e\hat{\ }\text{-}(TD3\text{-}TD2)/\ \tau_2) \tag{17}$$

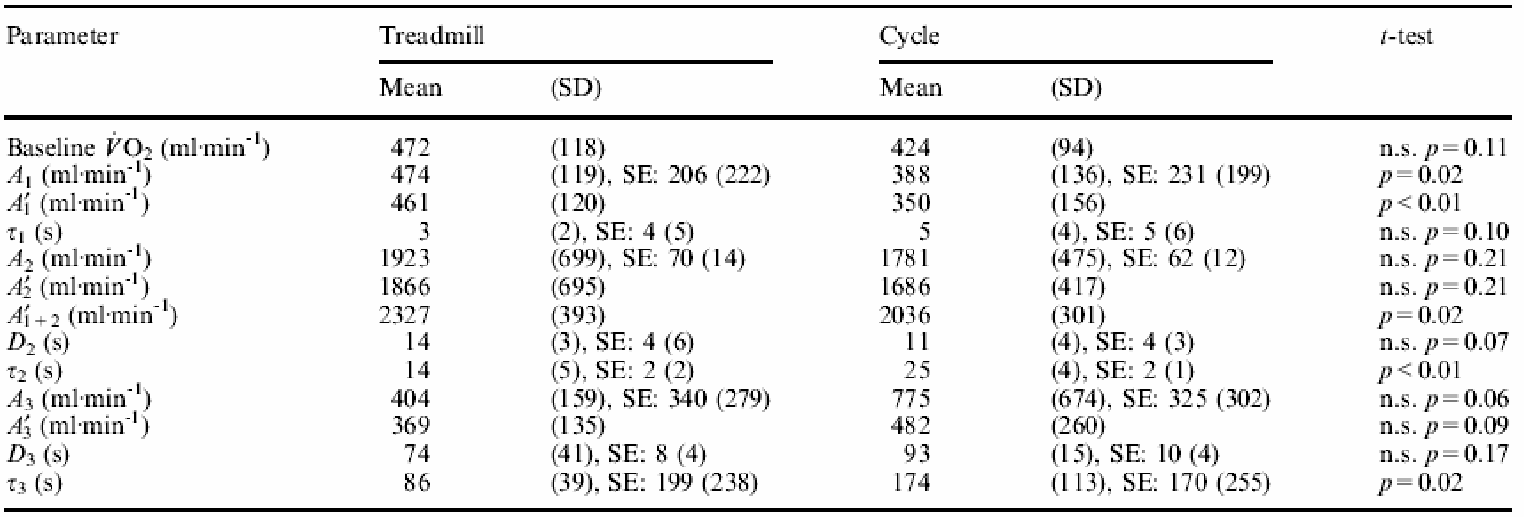
$$A'3 = A3\ (1\text{-}e\hat{\ }\text{-}(\text{time to fatigue-}TD3)/\ \tau_3\ ) \tag{18}$$

According to the A'1, A'2, and A'3, the overall time constant of the response in each test was determined using a simple mono-exponential equation with no delay.

$$\dot{V}O_2\,(t)= A0 + (\ A_{total}\ (1\text{-}\exp(\text{-}t/t_{total})) \tag{19}$$

The $\dot{V}O_2$ responses were fit to a three-phase exponential model. The time constant of the primary phase was faster in treadmill tests than in cycle ergometer tests and the amplitude of the primary phase (phase 2) was greater in running than in cycling when it was expressed in absolute terms. Therefore, it was concluded that exercise modality affected the characteristics of the $\dot{V}_{02}$ response at equivalent intensities in the severe intensity domain.

Table 6. Summary of parameters estimates for the model of Hill (Hill, 2003)



Parameter	Treadmill		Cycle		*t*-test
	Mean	(SD)	Mean	(SD)	
Baseline $\dot{V}O_2$ (ml·min^{-1})	472	(118)	424	(94)	n.s. $p = 0.11$
A_1 (ml·min^{-1})	474	(119), SE: 206 (222)	388	(136), SE: 231 (199)	$p = 0.02$
A'_1 (ml·min^{-1})	461	(120)	350	(156)	$p < 0.01$
τ_1 (s)	3	(2), SE: 4 (5)	5	(4), SE: 5 (6)	n.s. $p = 0.10$
A_2 (ml·min^{-1})	1923	(699), SE: 70 (14)	1781	(475), SE: 62 (12)	n.s. $p = 0.21$
A'_2 (ml·min^{-1})	1866	(695)	1686	(417)	n.s. $p = 0.21$
A'_{1+2} (ml·min^{-1})	2327	(393)	2036	(301)	$p = 0.02$
D_2 (s)	14	(3), SE: 4 (6)	11	(4), SE: 4 (3)	n.s. $p = 0.07$
τ_2 (s)	14	(5), SE: 2 (2)	25	(4), SE: 2 (1)	$p < 0.01$
A_3 (ml·min^{-1})	404	(159), SE: 340 (279)	775	(674), SE: 325 (302)	n.s. $p = 0.06$
A'_3 (ml·min^{-1})	369	(135)	482	(260)	n.s. $p = 0.09$
D_3 (s)	74	(41), SE: 8 (4)	93	(15), SE: 10 (4)	n.s. $p = 0.17$
τ_3 (s)	86	(39), SE: 199 (238)	174	(113), SE: 170 (255)	$p = 0.02$

Table 7. Summary of models discussed in Chapter 3

Model	Equations
Bearden and Moffatt's Model	● VO$_2$ (t) = B VO$_2$ + A1 [1- $e$xp ((t-TD1)/τ1)] ● VO$_2$ (t) = B VO$_2$ + A1 [1 – *exp* ((t-TD1)/ τ 1)] + A2 [1 – *exp* ((t-TD2)/τ 2)] ● VO$_2$ (t) = B VO$_2$ + A1 [1 – exp ((t-TD1)/ τ 1)] + A2 [1- exp ((t-TD2)/ τ 2] ● OD$_{Trad}$ = t (BVO$_2$ VO$_2$ + A1 + A2) - ∫ (*Eq. 4)* dt ● OD$_{New}$ = OD$_{Trad}$ - (A2 * TD2)
Fujihara et al. transient response	● ΔVE(s) = {AE exp(-stD1)/(1+sτ1)}+{Bexp(-stD2)/[(1+sτ2)(1+τ3)]}
Carter's Model	● VO2 (t)=VO2(b)+A0(1-e^(-t/τ0)+A1(1-e^(-t-TD1)/τ1)+A2(1-e^(-t- TD2)/ τ 2)
Cleuziou et al. Model of Oxygen Consumption at Onset and End of Exercise	● VO$_2$ (t) = A1 [1-e^ (-(t-TD1) /τ 1)] U1 ● VO$_2$ (t) = A1 [1-e^ (-(t-TD1)/τ 1)] U1+ A2 [1-e^ (-(t-TD2)/τ 2)] U2 ● VO$_2$ (t) =EEVO$_2$- A1 [1-e^ (-(t-TD1)/τ 1)] U1 ● VO$_2$ (t) = EEVO$_2$ - A1 [1-e^ (-(t-TD1)/τ 1)] U1- A2 [1-e^ (-(t-TD2)/τ 2)] U2 ● VO$_2$ (t) = EEVO$_2$ - A1 [1-e^ (-(t-TD1)/τ 1)] U1- A2 [1-e^ (-(t-TD1)/τ 2)] U1
Hill Model for VO2 Kinetics During Severe Exercise Intensity	● VO2(t) = A0+A1 (1-e^-t/ τ 1) +(1-e- (t-TD2)/ τ 2) +A3 (1-e- (t-TD3)/ τ3) ● A'1 = A1 (1-e^-TD2/ τ 1) ● A'2 = A2 (1-e^-(TD3-TD2)/ τ 2) ● A'3 = A3 (1-e^-(time to fatigue-TD3)/ VO2 3) ● VO2(t)= A0 + (A$_{total}$ (1-e^-t/t$_{total}$)

Chapter 4: Procedures

4.1 Background

Coyne used linear regression methods to form the equations. However, some physiological parameters do not show a simple linear relationship and require more complex equations. For example, when exercise intensity is heavy or severe, oxygen consumption increases faster than for moderate exercise. A simple linear equation cannot fully describe transient effects from moderate intensities to severe intensities. Therefore, it was necessary to first find better equations from other studies and adjust Coyne's model. Some of the new equations were based on theory and therefore gave a better foundation. Finally, the current model was compared to Coyne's model and experimental data.

4.2 Structure of the model

4.2.1 Modifications to Structure of Coyne's Model

In Coyne's model, when exercise intensity was heavy or severe, the output results had higher percentage errors than when exercise intensity was light. This was because the model did not include transient equations and did not add the slow component of oxygen consumption. This implied that the model structure needed to be revaluated. Based on the flowchart of Coyne's model (Figure 2), there were some structures that needed to be adjusted.

First, Coyne's model could not predict performance time very well; therefore, the flowchart of performance, oxygen deficit, and oxygen consumption needed to be adjusted. The most fundamental concept defining the limits of physical performance was the relation between intensity and duration of the performance. Therefore, work rate was an important factor for the current model. A possible way of predicting performance time was to use work rate and oxygen consumption.

Second, in Coyne's flowchart, the anaerobic threshold was directly linked to tidal volume. Above the anaerobic threshold, tidal and minute volumes would change. However, the anaerobic threshold was shown to be related to oxygen consumption (Dwyer and Bybee, 1983; Rusko et al., 1980; Thorland et al., 1980; Weltman and Katch, 1979). Thus, Coyne's flowchart that related tidal volume to the anaerobic threshold needed to be adjusted.

Third, the respiratory rate would be affected by the extra carbon dioxide from heavy intensity exercise, which is usually anaerobic exercise. The extra carbon dioxide would stimulate the respiratory system to get more oxygen. Thus, the respiratory system would increase the respiratory rate in order to get more oxygen. When there is not enough oxygen, skeletal and respiratory muscles do not work properly; therefore, performance time would decrease. According to this theory, respiratory rate is a possible function of performance time. The portions of Coyne's flowchart regarding respiratory rate and performance time also needed to be adjusted.

4.2.2 Flowchart for the present model

The flowchart for the present model is presented in Figure 9. First, equations for determining the external work rate for various activities were selected. Second, the equations developed by Johnson (1992) for muscular efficiency were used. Coyne's new equation for muscular efficiency was judgment based on very limited data points. For example, for heavy exercise intensity, there was only one data point in Coyne's equation; therefore, in the current model, Johnson's equation was used. Third, the physiological work rate was calculated from the external work rate and efficiency. Next, oxygen consumption was plotted versus physiological work rate and a linear regression was performed. Fifth, based on the Kamon's (1972) equation, oxygen consumption was used to predict performance time. Sixth, Hill's (2001) model was chosen to predict transient oxygen consumption. Seventh, oxygen deficit was calculated by performance time and oxygen consumption (Convertino et al., 1984).

Also, minute ventilation and tidal volume were functions of oxygen consumption. Both of them affected the respiratory rate. Respiratory work rate equations were obtained from Johnson (1993). Additional resistances were functions of minute ventilation.

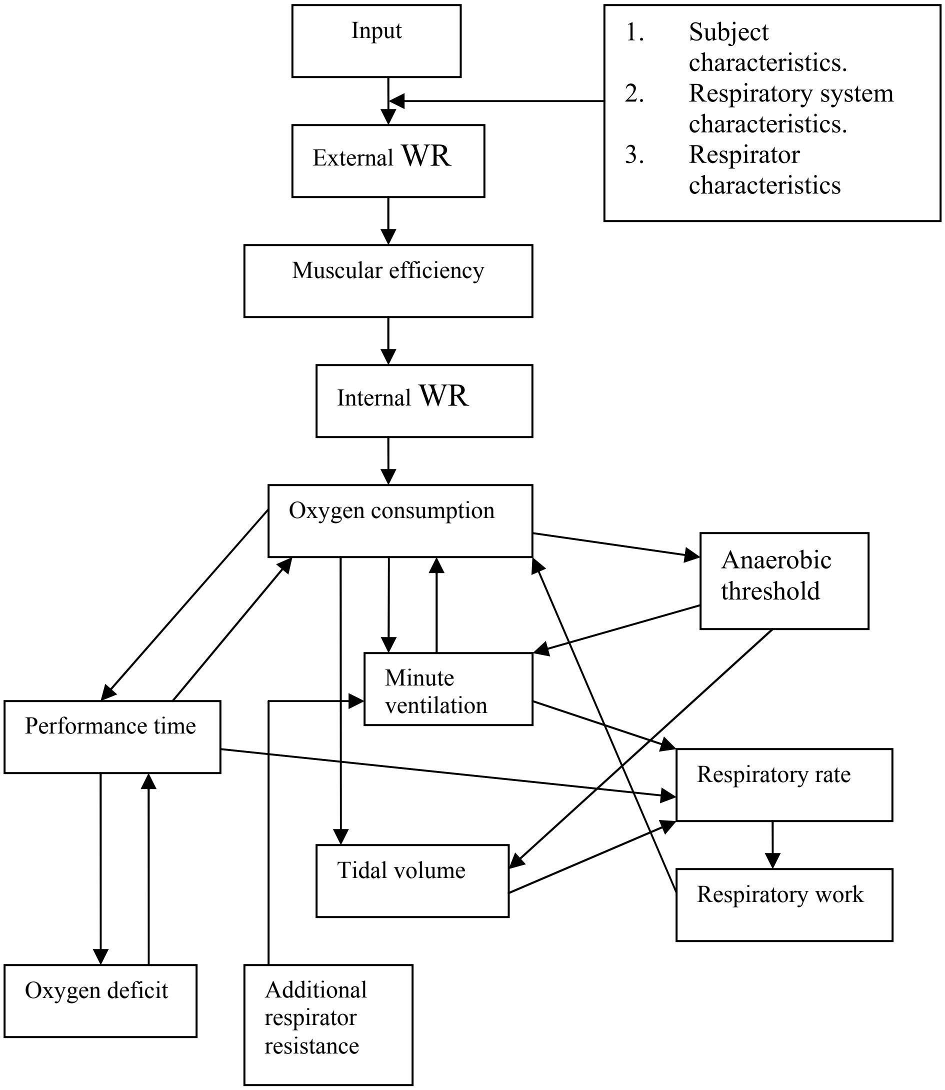


Figure 9. Flow chart of model

4.2.3 Performance Time

Because transient effects were not included in Coyne's model, no direct predictions of performance time for respirator wearers were made. Some studies have shown that the accumulated oxygen deficit is a possible method for the estimation of anaerobic capacity (Paterson and Whipp, 1991; Wasserman et al., 1973; Barstow, 1994; Koppo et al., 2002). Coyne stated that Bearden and Moffatt (2000) found the maximum oxygen deficit for work above the anaerobic threshold was 4.03 L. Therefore, to predict the performance time, an equation consisting of the maximum oxygen deficit divided by the actual oxygen deficit was used in Coyne's model (Coyne, 2001):

$$\text{Perf time} = \left(\frac{4.03}{\text{O}_2 \text{ deficit rate}} \right) \tag{20}$$

where Perf time was performance time in min.

This equation was shown to be a very rough estimate of performance time. Coyne used this equation to provide an estimate of performance time so that different respirators could be compared. Due to current debates over the oxygen deficit concept, this equation was changed in the current study.

Due to different activities and different subjects, it is very difficult to correctly predict performance time. Performance time is related not only to work rate but also to many other factors such as thermal stress, vision, and muscle types. In the current model, work rate and oxygen consumption were assumed to be the most important factors for the performance time. The other factors were assumed to stay constant with performance time.

Based on this assumption, the relationship between work rate and performance time, or the interaction between oxygen consumption and performance time were discussed. Generally, intense exercise can be performed for a short time. Moreover, when a subject wears a respiratory mask, an additional work load is added to the subject. People performing at the same work rate who wear respirators usually have shorter performance times than people without respirators. Based on these concepts, performance time could be a function of work rate or oxygen consumption and of whether the subject's wearing a respirator or not.

4.4.2 Calculate for Performance Time in Present Model

Performance time was calculated by the following steps in the current model:

Step 1: Work Rate vs. Steady-State $\dot{V}_{02}$

The characteristics of oxygen consumption kinetics change with exercise intensity. When exercise is performed at a given work rate, $\dot{V}_{02}$ increases exponentially to a steady-state level. Neither the slope of the increase in $\dot{V}_{02}$ with respect to work rate nor the time constant of $\dot{V}_{02}$ responses has been found to be a function of work rate (Coyne, 2001). This indicates a linear dynamic relationship between work rate and steady-state $\dot{V}_{02}$:

$$\dot{V}_{02} = 0.002952\ \mathrm{WR}_{phys} \tag{21}$$

Step 2: Put steady-state $\dot{V}O_2$ into performance time equation

In the current model, the Kamon (1972) equation was used to predict the performance time. This equation had the following limitation: When subjects reached 100% of their oxygen consumption, the equation showed that the performance time was 180 seconds. Under this condition, the equation assumed that exercise intensities (100%

of subjects' oxygen consumption) were totally anaerobic and subjects could perform at least 180 seconds.

$$t_{wd} = 7200\,(\dot{V}_{02\max}/\dot{V}_{02}) - 7020 \qquad (22)$$

Step 3: Using predicted performance time to calculate transient oxygen consumption

From the oxygen consumption models discussed in Chapter 3, the Hill (2003) model was chosen. Other models had some limitations, such as different exercise test methods, exercise intensities, and measurement methods. Therefore, the other models were not as appropriate for the current model during severe exercise intensity. The following are the transient oxygen consumption equation from Hill's model:

$$\begin{aligned}
\dot{V}_{02}\,(t_{wd}) = {} & A0 && \text{baseline } \dot{V}_{02} \\
& + A1\,(1\text{-}e\text{\textasciicircum}\text{-}t_{wd}/\,\tau_{1}) && \text{Phase1 cardiodynamic component} \\
& + A2\,(1\text{-}e\text{-}\,(t_{wd}\text{-}TD2)/\,\tau_{2}) && \text{Phase 2 primary respiratory component} \\
& + A3\,(1\text{-}e\text{-}\,(t_{wd}\text{-}TD3)/\,\tau_{3}) && \text{Phase 3 slow respiratory component} \qquad (14)
\end{aligned}$$

where $\tau 1 = 3$, $\tau 2 = 14$, $\tau = 86$, $TD1 = 14$, $TD2 = 86$, $A1 = 474$, $A2 = 1866$, and $A3 = 404$ (for treadmill).

Step 4: Using transient oxygen consumption and performance time to calculate oxygen deficit

From Convertino et al. (1984), the oxygen deficit can be calculated:

$$OD = \dot{V}_{02}\,(t_{wd})^{*}\, t_{wd} - \dot{V}_{02}\,(t_{wd})\,[t_{wd} + \tau_{02} \exp\,(t_{wd}/\tau_{02})] \qquad (23)$$

where t_{wd} is performance time without masks.

Step 5: Calculate the performance time when wearing respirator

According to Johnson (1993), when subjects wore respirators, the data showed that most of the subjects hypoventilated because of the resistance of the masks. Therefore, the resistance factors were added into the current model. Coyne (2001) found the relationship between steady-state minute ventilation and additional respiratory resistance (Coyne, 2001):

$$25\text{-}30\%\ \dot{V}_{o2\max}:\quad V_E = 0.3705 - 0.0037R_{inh} - 0.02236R_{exh} \tag{24}$$

$$35\text{-}40\%\ \dot{V}_{o2\max}:\quad V_E = 0.4754 - 0.0018R_{inh} - 0.0206R_{exh} \tag{25}$$

$$45\text{-}50\%\ \dot{V}_{o2\max}:\quad V_E = 0.6088 - 0.0065R_{inh} - 0.0469R_{exh} \tag{26}$$

$$65\text{-}70\%\ \dot{V}_{o2\max}:\quad V_E = 0.9718 - 0.0156R_{inh} - 0.0846R_{exh} \tag{27}$$

$$80\text{-}85\%\ \dot{V}_{o2\max}:\quad V_E = 1.3979 - 0.0454R_{inh} - 0.0967R_{exh} \tag{28}$$

The minute ventilation transient equation was as follows (Astrand and Rodahl, 1970):

$$\dot{V}_E(t) = 22.340(\dot{V}_{O2}(t) + 2.557642*10\text{^}{-4}) \quad \text{(below ventilation threshold)}$$

$$=22.340(\dot{V}_{O2}(t)+2.557642*10\text{^}{-4})-1.09593*10\text{^}{-4}+3.196486*10\text{^}{-9}/$$

$$(5.5*10\text{^}{-5}-\dot{V}_{O2}(t)) \qquad \text{(above ventilation threshold)} \tag{29}$$

assuming the transient and steady-state minute ventilation equations were equal. Therefore, $\dot{V}_{o2}(t)$ could be calculated from equation. (29). Based on the Karmon performance equation (22), performance time (with mask or with additional resistance) could also be calculated.

4.4.3 Transient Effects

Following the onset of exercise, $\dot{V}_{02}$ could not increase immediately to the steady-state value, even for moderate exercise intensity (Johnson 1991). During the period of transition, the energy demand had to be met partially from other sources. Coyne's equations did not include these transient factors. For example, the $\dot{V}_{02\text{max}}$ transition from 0-30% must differ from 30-70%. This indicated that the transition was a very important factor in the current study.

In the current model, transient effects were added. Minute ventilation and tidal volume equations that related to oxygen consumption were changed. Furthermore, factors that were related to the performance time equation were also changed. The following equations demonstrate these changes:

M***inute volume (Astrand and Rodahl, 1970):***

$\dot{V}_E(t) = 22.340(\dot{V}_{02}(t)+2.557642*10\text{^}{-4})$ (below ventilation threshold)

$$= \dot{V}_E(t) - 1.09593*10\text{^}{-4} + 3.196486*10\text{^}{-9}/(5.5*10\text{^}{-5} - \dot{V}_{02}(t)) \quad (29)$$

(above ventilation threshold)

Respiratory rate (Martin and Weil, 1979):

$$RR(t) = \dot{V}_E(t)/VT \quad (30)$$

Tidal volume (Martin and Weil, 1979):

$$VT(t) = 1.8457*10\hat{\ }-4 + 61.1667\,\dot{V}_{02}(t) \qquad (31)$$

4.4.4 Computer Program

The model was implemented in Visual Basic 6.0, with default values (Table 8) for all inputs parameters. Thus, users could start the program without entering any values. Based on Coyne's model and available information from the Human Performance Laboratory (University of Maryland, College Park), the U.S. Army M17 and M40 masks were selected to be included as respirators in the current model. The default condition was no respirator. Furthermore, this model allowed the user to enter values for respirator inhalation and exhalation resistances, dead volume, and mass. Also, the user could choose to enter a work rate, select a treadmill speed and grade, select bike ergometer values, or select stepping values.

Table 8. Input (the default values) and output in the current model

Input	**<u>Subject characteristics</u>** ● Age, height, weight, $\dot{V}_{02}$max **<u>Respiratory system characteristics</u>** ● Additional dead volume, resistance **<u>Respirator characteristics</u>** ● In/exhalation resistance, mass, dead volume
Output	● Performance time, ● Steady-state oxygen consumption, ● Steady-state tidal volume, ● Oxygen deficit, ● Steady-state minute ventilation

Chapter 5: Results and Discussion

5.1 Transient factors

The current model included transient equations; therefore, a comparison between the current model and Coyne's model was needed. The experimental data from the Human Performance Laboratory (University of Maryland, College Park) were used in these comparisons. (IRB no.03-0285 and no. 01385)

5.1.1 The comparison between Coyne's model, experimental data and the current model.

Coyne (2001) tested eight subjects who exercised at four different intensity levels; 95, 147, 193 and 240W. (without wearing respirators). All subjects achieved exercise intensities of 95 and 147W (Levels 1 and 2 respectively). Only six completed 193W (Level 3). Only four subjects finished the whole test (240W, Level 4). Table 9 shows the steady-state data. The average steady-state measured oxygen consumption for each stage was 1.94L/min (Level 1), 2.46L/min (Level 2), 2.98L/min (Level 3) and 3.54L/min (Level 4).

Table 9. Experimental data for four exercise intensities. (Coyne 2001)

Subject ID	$\dot{V}_{02}$ (L/min)	$\dot{V}_E$ (L/min)	VT(L)	
1	1.8	54.26	1.26	
2	1.81	37.5	0.6	
23	1.83	49.54	1.21	
145	1.83	42.81	0.81	Level 1
173	2.16	44.09	1.42	95W
214	1.87	36.29	1.13	
221	2.19	35.06	0.95	
231	2.01	41.08	0.84	

Mean	1.9375	42.57875	1.0275	
SD	0.160957	6.669417	0.273378	
Subject ID	$\dot{V}_{02}$	$\dot{V}_{E}$	VT	
1	2.43	55.94	1.36	Level2
2	2.5	67.26	1.46	147W
23	2.06	59.36	1.65	
145	2.59	69.83	1.55	
173	2.5	53.84	1.86	
214	2.66	52.95	2.21	
221	2.41	39.81	1	
231	2.52	57.1	0.98	
Mean	2.45875	57.01125	1.50875	
SD	0.180114	9.246334	0.413985	
Subject ID	$\dot{V}_{02}$	$\dot{V}_{E}$	VT	
1	3.05	64.54	1.65	Level3
145	2.89	79.25	1.76	193W
173	3.01	84.39	2.34	
214	3.1	56.06	2.8	
221	2.95	46.95	1.47	
231	2.92	62.71	1.28	
Mean	2.986667	65.65	1.883333	
SD	0.080664	14.05476	0.575036	
Subject ID	$\dot{V}_{02}$	$\dot{V}_{E}$	VT	
1	3.57	89.85	1.76	Level4
214	3.6	71.48	2.75	240W
221	3.55	78.38	2.12	
224	3.45	76.25	1.11	
Mean	3.5425	78.99	1.935	
SD	0.065	7.793574	0.685493	

The four work rates (95W, 147W, 193W, and 240W) were input into the current model and the simulation was run. The results of the current model gave the outputs of calculated steady-state oxygen consumption, minute ventilation, and tidal volume. Using the same work rate inputs, Coyne's model was also run as a simulation and was compared to the current model. Table 10 shows these comparisons.

Table 10. Model simulated similar oxygen consumption during each level of exercise intensity

Work Rate	$\dot{V}_{02}$ meas	$\dot{V}_{02}$ calc	$\dot{V}_{02}$ (Coyne)	VT meas	VT calc	VT (Coyne)	$\dot{V}_E$ meas	$\dot{V}_E$ calc	$\dot{V}_E$ (Coyne)
95	1.94	1.93	1.94	1.03	1.05	1.3	42.58	40.4	51.76
147	2.46	2.46	2.36	1.51	1.58	1.61	57.01	56	71.84
193	2.99	2.99	2.77	1.88	1.87	1.898	65.65	75.1	96.32
240	3.54	3.54	3.2	1.94	2.02	2.208	78.99	88.8	126.6

The results showed in the same work rate, the current model's steady-state oxygen consumption data were very close to the experimental data (Figure 10). The range of the difference between the current and experimental data was from 4.8% to -3.48%. Standard deviation of experimental data showed the oxygen consumption of the current model and the experimental data was the same. As demonstrated in Figure 11, Coyne's model deviated more from the experimental data (0% to -9.34%) than the current model and under-predicted oxygen consumption for levels 3 and 4 of exercise intensity.

From these results, the current model demonstrated that it can predict average steady-state oxygen consumption well. The difference ranged from 0.86% to -1.1%. However, all data points were in the range of standard deviation. According to this comparison, the current model predicted oxygen consumption with less error than Coyne's model for all levels of exercise intensity especially for level 3 and 4.

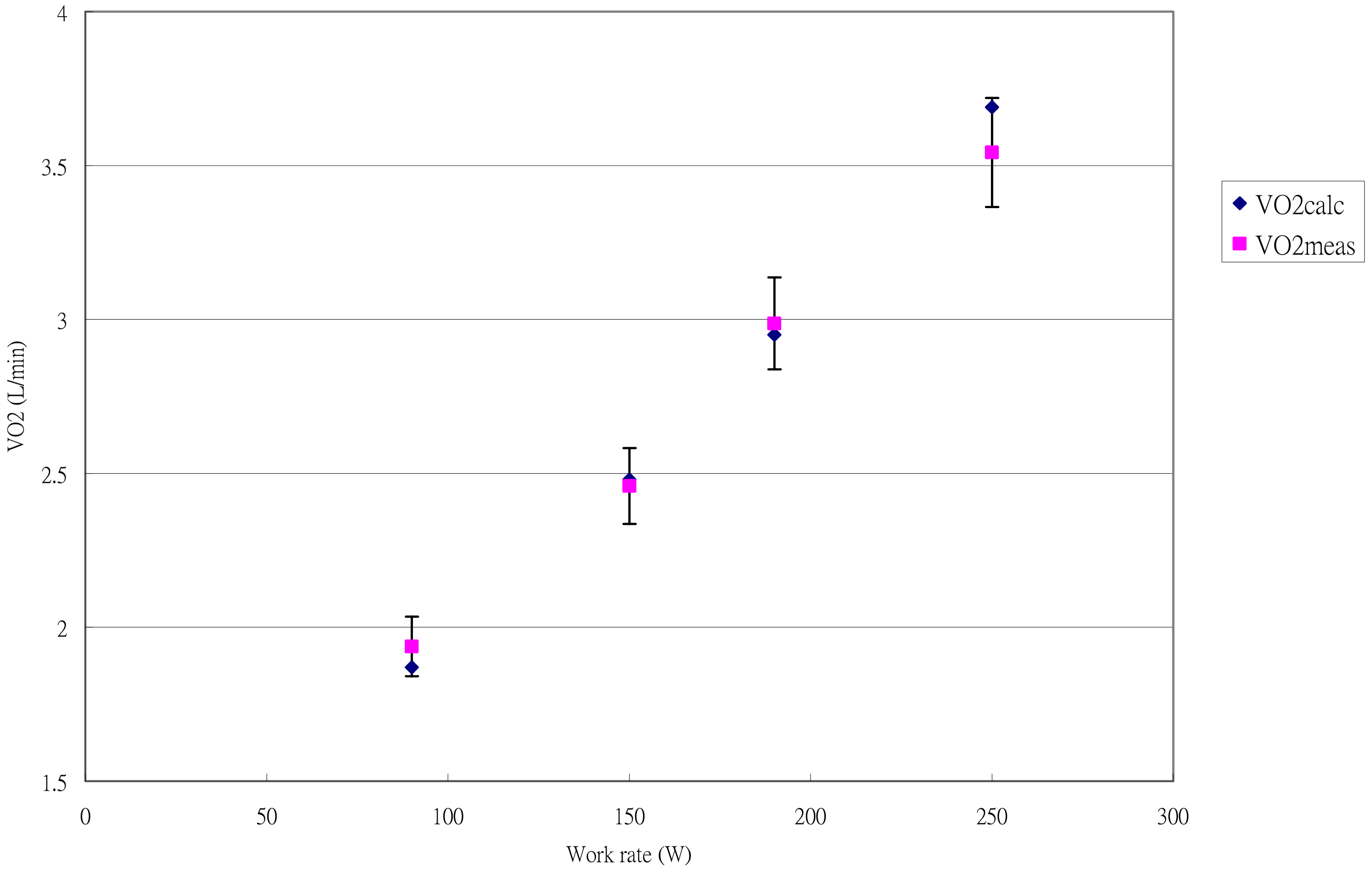


Figure 10 Comparisons of oxygen consumption between experimental data and the current model (without masks)

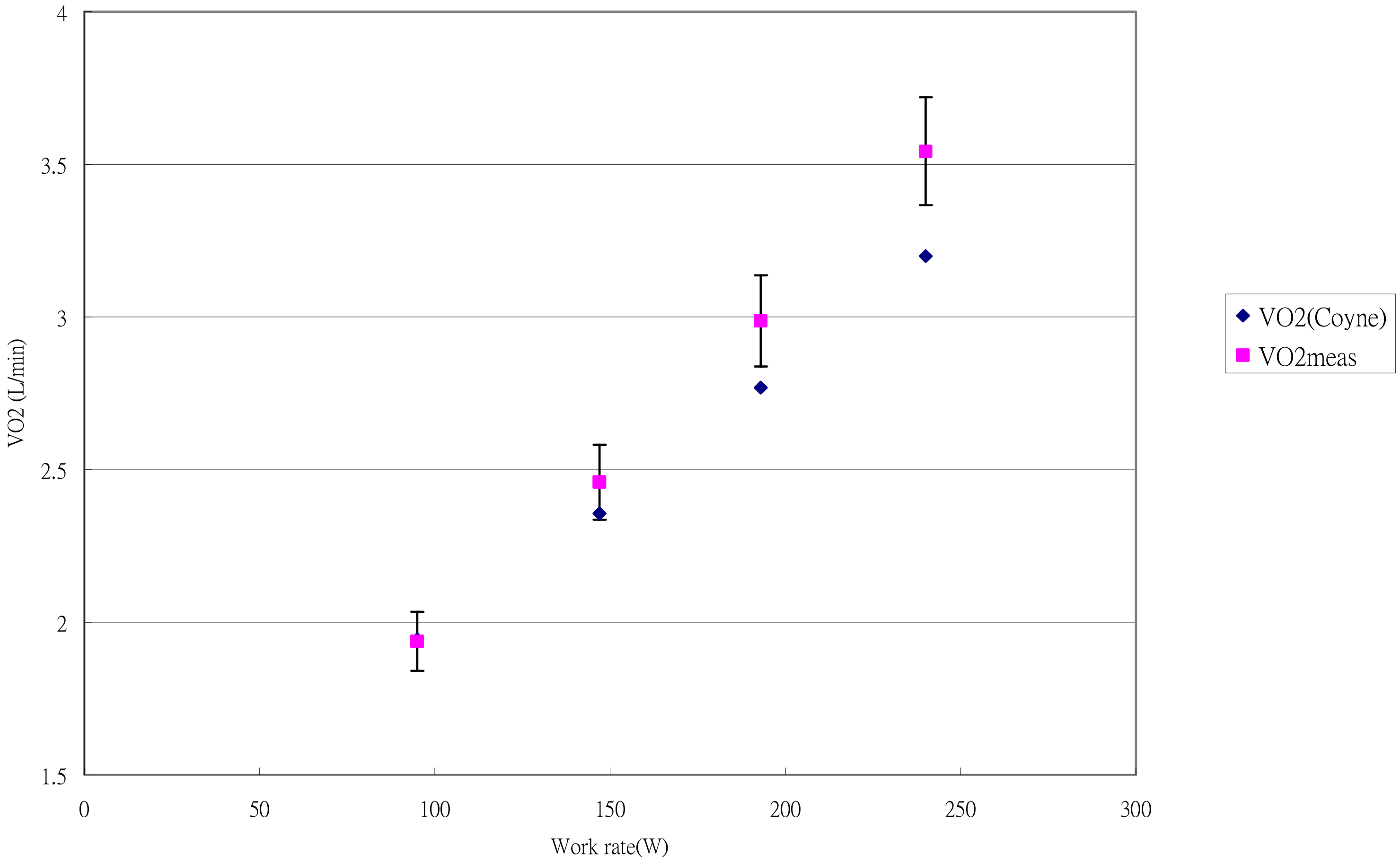


Figure 11 Comparison of oxygen consumption between the experimental data and Coyne's model (without masks)

5.1.2 Comparisons of steady-state tidal volume and minute ventilation

Data points shown in Table 10 were used in this comparison. Figures 12 and 13 showed comparisons between calculated and measured tidal volume and minute ventilation. Coyne's simulated data were also included in these figures. The results showed that the current model over-predicted the steady-state tidal volume during Levels 1, 2, and 4. Level 3 had the best predicted value. However,, the standard deviation of the experimental data showed there was no different between experimental data and the data in the current model. Compared to the current model, Coyne's model over-predicted the steady-state tidal volume for level 1 and 4 of exercise intensity and deviated from the experimental data more than the current model.

For steady-state minute ventilation, the current model under-predicted during Levels 1 and 2 but over-predicted during Levels 3 and 4. However, the standard deviation of the experimental data showed that there was no different between the experimental data and data of level 1 and 2. This indicated that the transient equation that was put into the current model made less accurate predictions at heavy exercise intensity. However, the current model predicted better than Coyne's model. Coyne's model over-predicted minute ventilation for every level of exercise intensity. Overall, the current model had better predictions than Coyne's model for steady-state. Results verified that the current model could well predict these interactions. Although there were still a few errors, the convex trend of the prediction was successful.

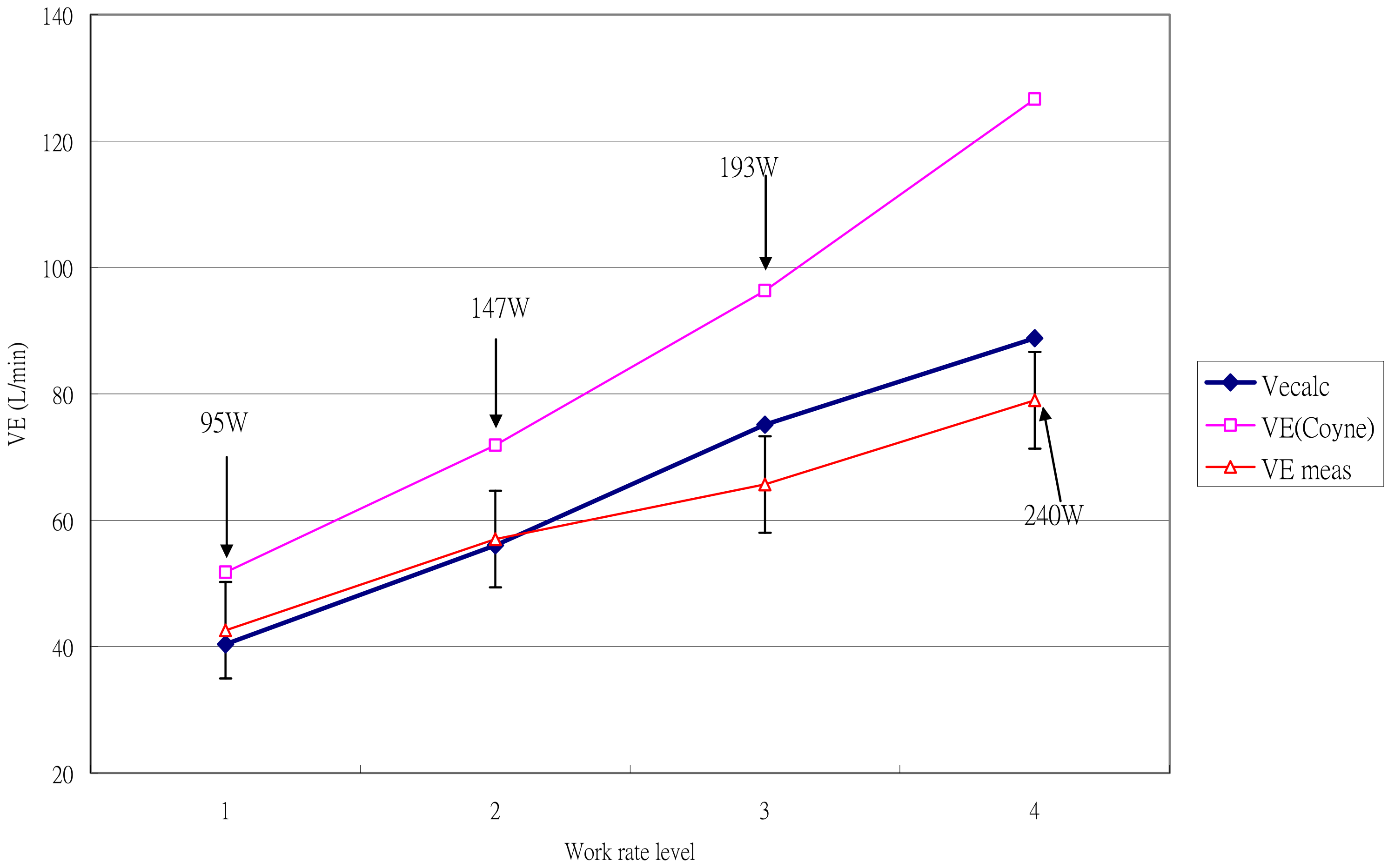


Figure 12 Comparison of steady-state minute ventilation between present model, Coyne, and measured

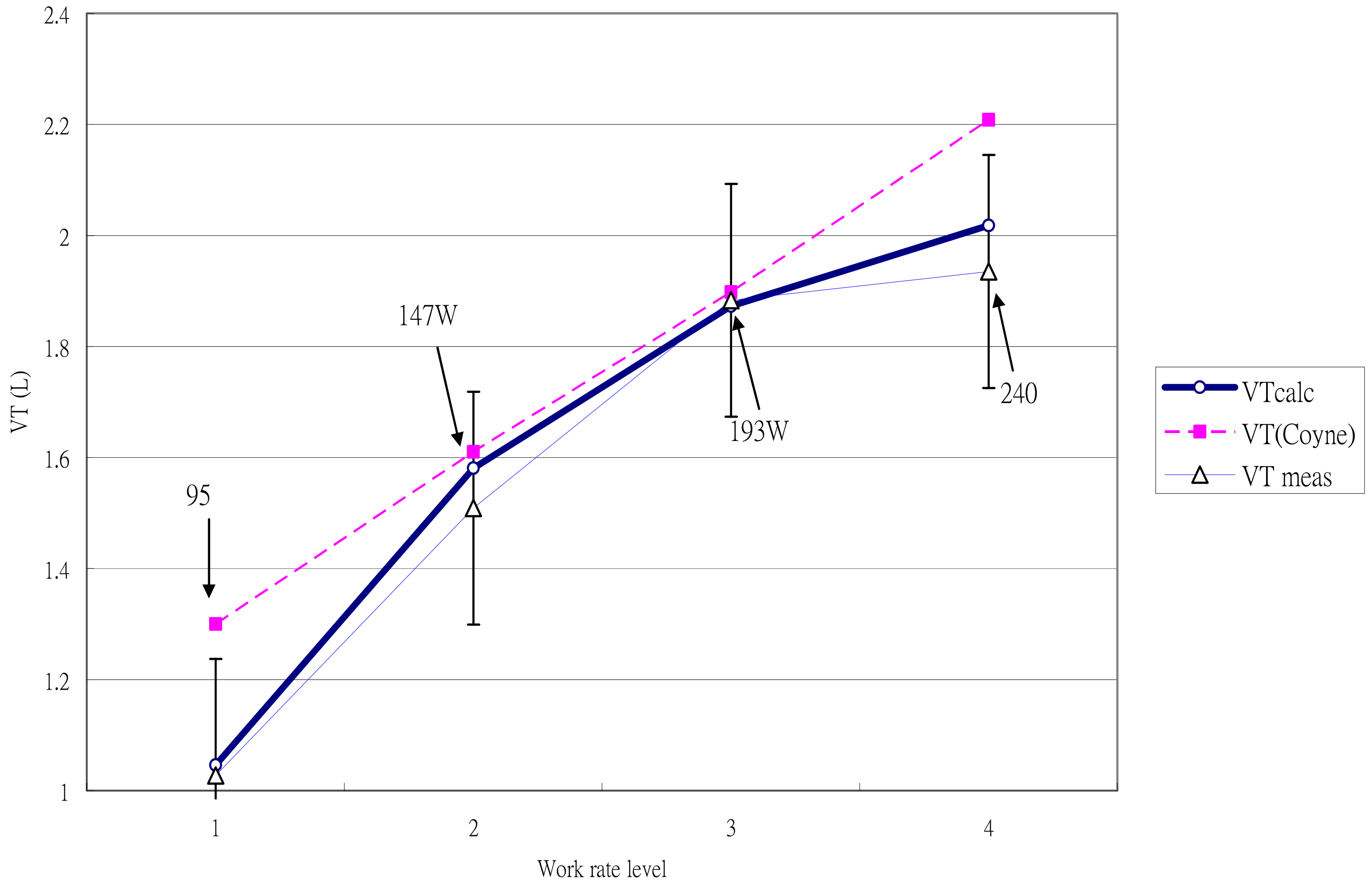


Figure13 Comparison of steady-state tidal volume between present model, Coyne, and measured data

5.1.3 Transient oxygen consumption compared to experimental data

The transient oxygen consumption equation was added in the current model to better fit the experimental data. In this section, the experimental data was obtained from Coyne (2001), who tested subjects exercising (without masks) continuously on a treadmill without rest from 0% to 80% $\dot{V}_{02\max}$. There were five stages (30%, 40%, 50% 70%, and 80%$\dot{V}_{02\max}$) in this study. The current model used these experimental data for five subjects' average steady-state oxygen consumption to identify each level's oxygen consumption transient factors. Thus, oxygen consumption values were calculated by the transient equation and plotted. The average of $\dot{V}_{02\max}$ within these subjects was 3.47L/min. Therefore, the model value of $\dot{V}_{02\max}$ was set at 3.5L/min. The $\dot{V}_{02}$ values for each level were calculated based on each level's %$\dot{V}_{02\max}$,. Figure 14 shows the oxygen consumption curve based on the transient oxygen consumption equation. After making this transient oxygen consumption curve, other experimental data from the Human Performance Laboratory (University of Maryland, College Park) were added to verify. Two different studies data points (30% and 80%$\dot{V}_{02\max}$) were plotted into the model. Figure 15 and 16 showed these data points. The results showed the current model slightly under predicted at 30%$\dot{V}_{02\max}$ but gave better predictions for 80%$\dot{V}_{02\max}$. In general, in these two ranges of %$\dot{V}_{02\max}$, the current model made good predictions and very close to the experimental data.

No other data points were found in the literature for 40% to 70% $\dot{V}_{o_2}$max; therefore, the transient between 40% and 70%$\dot{V}_{o_2}$max ranges could not be verified. The current model did not have enough data to make any conclusion between these %$\dot{V}_{o_2}$max ranges.

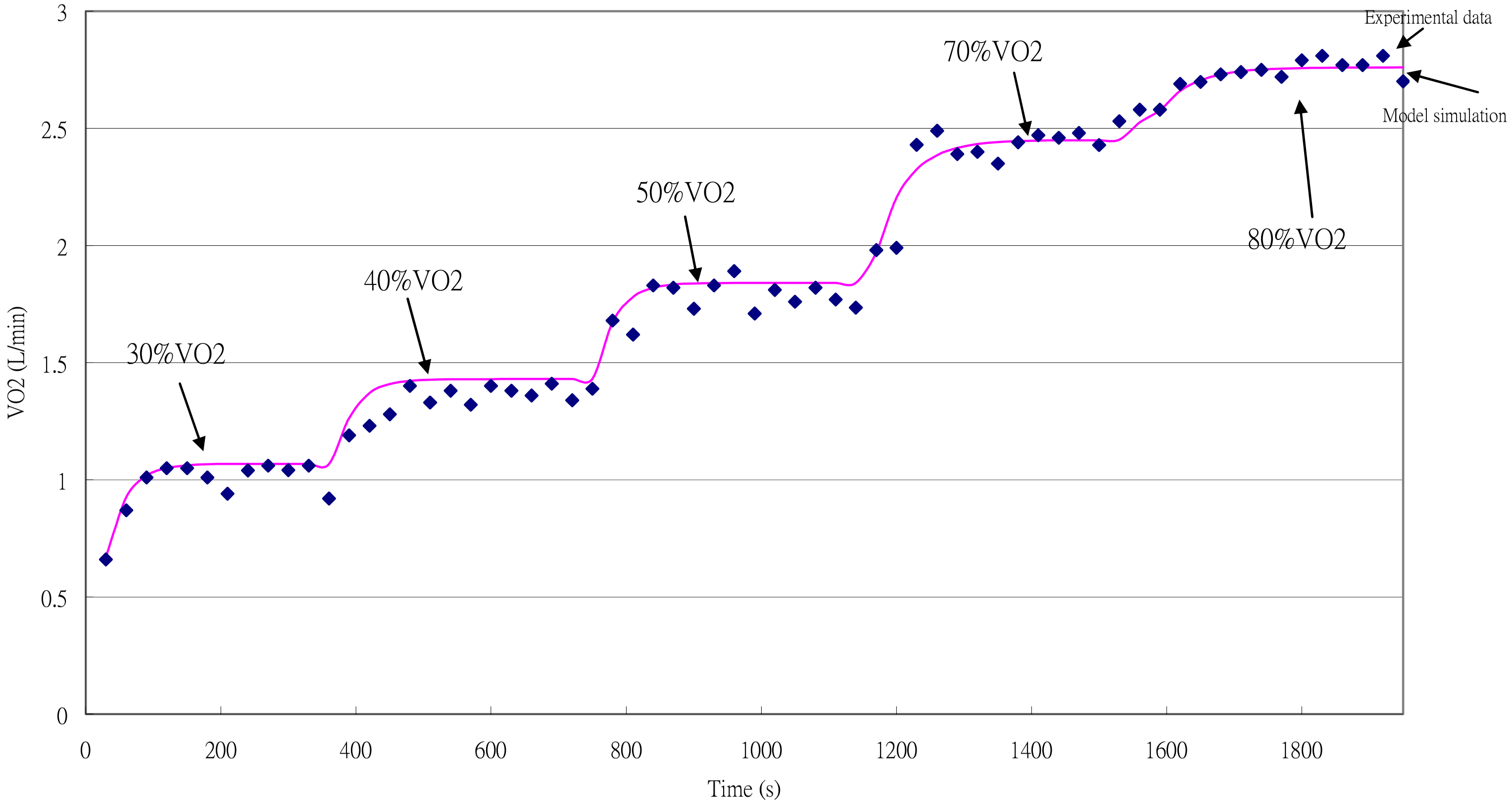


Figure 14 Five stages of continuous VO2 test: Experimental data vs. Model simulation

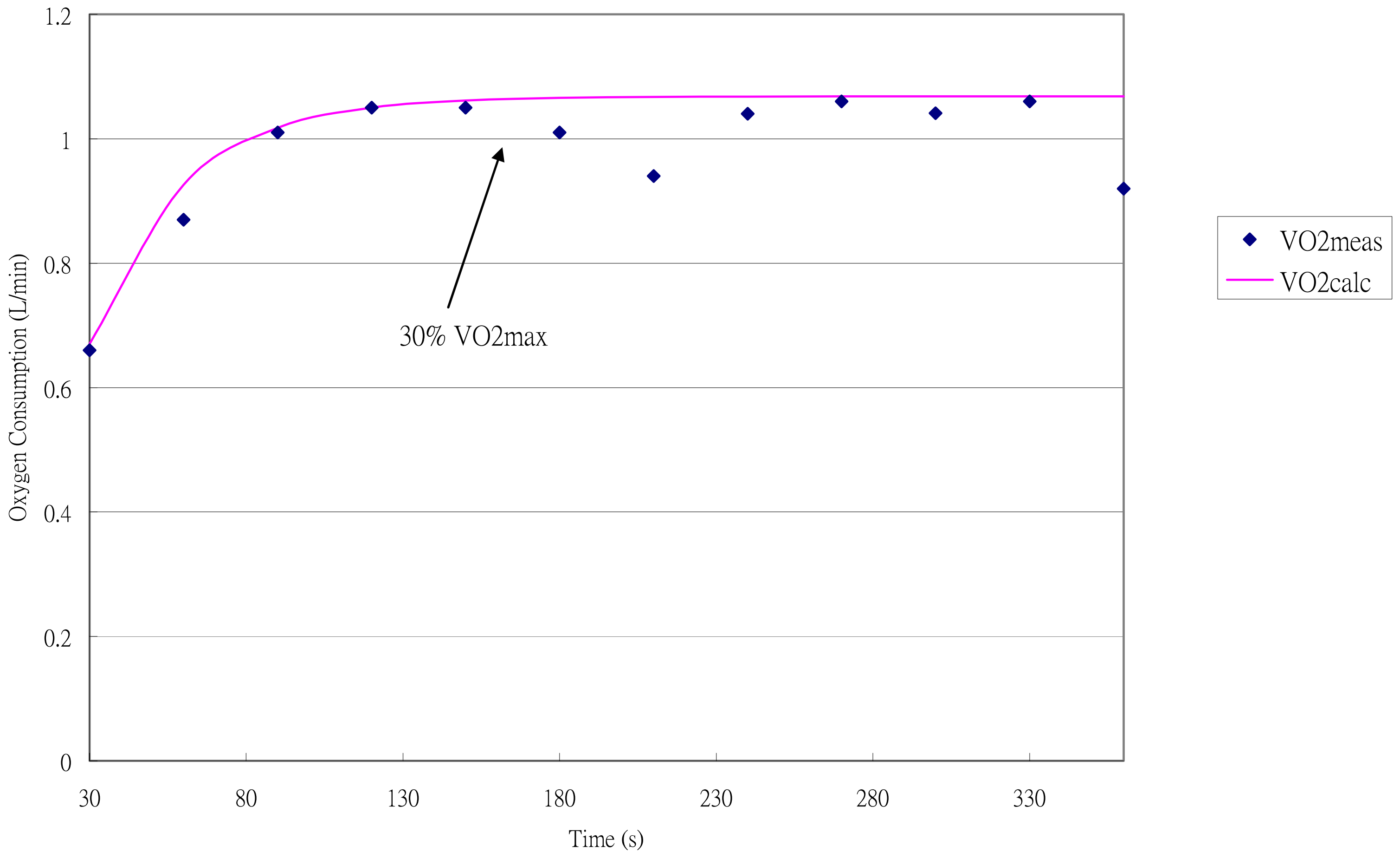


Figure15 Experimental data for 30%VO2max test

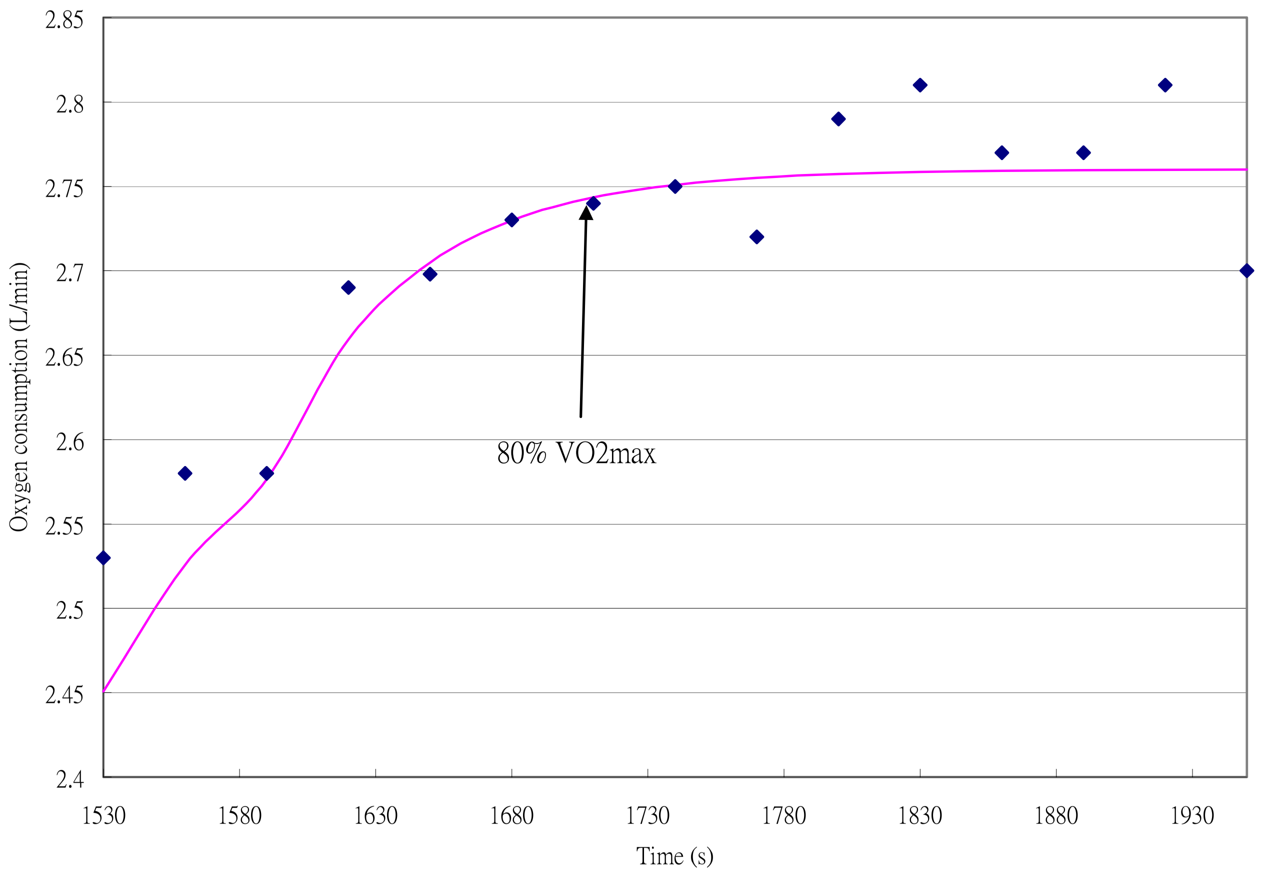


Figure 16 The experimental data for 80% VO2max test

5.2 Performance time (without wearing masks)

A major objective in the current study was to correctly predict exercise performance time. Performance times for individuals exercising at approximant 150W vary from 100 to 2500 seconds during controlled conditions. Table 11 shows measurement and predictions of performance time. The work rate was calculated by the following equation: ($WR_{ext} = \mathrm{m_t} \cdot g \cdot \mathrm{v} \cdot \frac{\mathrm{G}}{100}$)

Table 11. Predict performance time and experimental performance time

Subject ID	Speed (m/sec)	Grade (%)	Calculated Work Rate(W)	Performance time(s)	VO2	Model predict time(s)
145	4.8	6	225.792	290	2.4	180
265	4.2	6	177.8112	584	1.81	234
290	4.2	5	148.176	817	2.31	1043
292	4.6	4.5	125.7732	1132	1.76	1301
293	4.6	4	135.24	1397	1.01	1411
325	4.9	5	153.664	734	2.81	956
328	4.9	7	218.491	884	1.92	180
329	4.8	4	116.6592	1598	1.96	1766
331	5.3	4	145.432	700	2.37	1158
332	3.8	3	83.79	1962	1.29	2520
333	4.4	5	129.36	1423	2.35	1551
337	4.2	6	128.4192	259	1.62	1610
338	3.9	2	61.152	1560	1	2429
339	4.6	4	108.192	242	2.7	2265
340	6.4	4	125.44	628	2.98	1701
341	4.7	6	221.088	1597	1.75	180
346	5	3	102.9	882	1.97	1751
347	4.4	4	117.2864	1329	1.72	1966
351	5.1	5	187.425	775	1.54	523
353	5.6	6	190.9824	480		180
358	4.2	5	144.06	1629	1.62	1182
359	6	5	161.7	680		726

365	4.8	4	122.304	1027		1497
366	4.4	4	137.984	2211		1358
Mean	4.741667	4.6458333	144.5467333	1034.16667	1.9445	1236.167
SD	0.6061605	1.1408984	41.0668646	533.63413	0.5379	726.534

Using this speed and grade information, the current model was used to calculate performance times. Twenty-four subjects' data obtained from the Human Performance Laboratory (University of Maryland, College Park) were used as inputs to the current model. The average experimental performance time for the 24 subjects at 80% $\dot{V}_{o2}$max of exercise intensity without wearing masks was around 1034 sec. The current model predicted the performance time (without wearing a mask) to be 1236 sec. The standard deviation was 534sec, therefore, the two values of performance time are not statistically different. The paired t-test is shown in Table 12. The results showed that there was no significant difference between the current model and the experimental data. From this it can be surmised that predict well. Due to the subjects' physical differences, the real data and predicted data had poor correlation (Figure 17). It is hard to say if the current model is a good predictor for performance, but the results demonstrated that the current model can give a general prediction of average performance time.

Table 12 paired t-test for calculated and measured performance time without masks

	Measured performance time	Calculated performance time
Mean	1034.166667	1236.166667
Variance	297146.4928	527852.9275
Observations	24	24
Pearson Correlation	0.347582206	
Hypothesized Mean Difference	0	
df	23	
t Stat	-1.33475063	
P(T<=t) one-tail	0.097510657	
t Critical one-tail	1.713870006	
P(T<=t) two-tail	0.195021313	
t Critical two-tail	2.068654794	

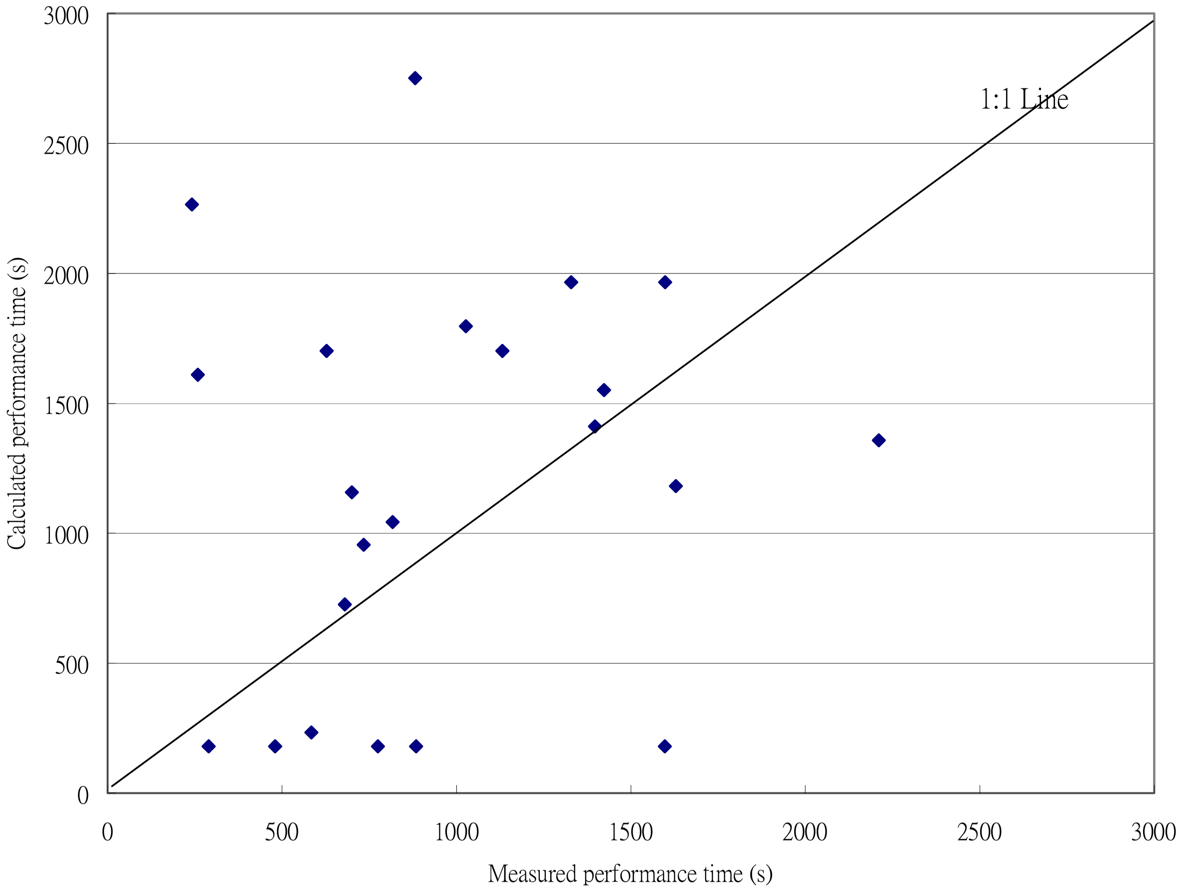


Figure 17 Performance time calculated by the model compared to measured performance time (without wearing mask).

5.3Predicted performance with and without mask

5.3.1 Performance time predictions (with respiratory masks)

One of objectives of the current study was to predict the performance time when subjects wore respirators. Experimental data showed that when subjects wore respirators, oxygen consumption decreased due to hypoventilation (Johnson, 2001). The results from the model simulation showed that when the external work rate was 150W, the oxygen consumption data for a subject wearing an M17 respirator was 2.257 L/min, with the M40, it was 2.198 L/min and it was 2.687L/min without a mask. These values supported the experimental data and indicated that the current model was valid.

Six work rates were selected for comparison (50, 100, 125, 150, 175, and 200W). The model simulation gave results shown in Table 13. The performance time differences between subjects with masks and without masks (M17 and M40) are shown in Figures 18.

Based on these results, the respirator was an important factor that affected performance time. According to these figures, performance time decreased in every level of exercise intensity when subjects wore respiratory masks.

The results also showed that subjects wearing the M40 had longer performance times than when they wore M17 respirators. Subjects with no mask had longer performance times than subjects with masks.

Table 13. Calculated performance time with different respiratory masks

Performance time		No mask	
Work Rate(W)	Time (without mask)(s)	VO_2(L/min)	VE(L/min)
25	24707.42	1.017	19.293
50	11148.59	1.534	26.194
100	4369.17	2.22	44.991

125	3013.288	2.478	51.737	
150	2109.366	2.687	59.853	
200	357.1468	3.255	83.546	
Performance time		M17		
Work Rate(W)	Time (with mask)(s)	Time (without mask)(s)	VO_2(L/min)	VE(L/min)
25	13120.42	24707.42	1.013	17.395
50	6839.608	11148.59	1.112	25.435
100	2653.298	4369.17	1.836	42.449
125	1701.966	3013.288	1.965	50.266
150	1043.372	2109.366	2.257	57.433
200	<180*	357.1468	3.219	79.953
Performance time		M40		
Work Rate(W)	Time (with mask)(s)	Time (without mask)(s)	VO_2(L/min)	VE(L/min)
25	13164.79	24707.42	1.003	17.364
50	6871.558	11148.59	1.034	25.363
100	2673.024	4369.17	1.765	42.312
125	1718.473	3013.288	1.838	50.108
150	1057.555	2109.366	2.198	57.26
200	<180*	357.1468		79.53

* According to Kamon equation limitation, any values under 180 sec show negative values in the current model's output; therefore, data are shown as <180 for all values less than 180 sec.

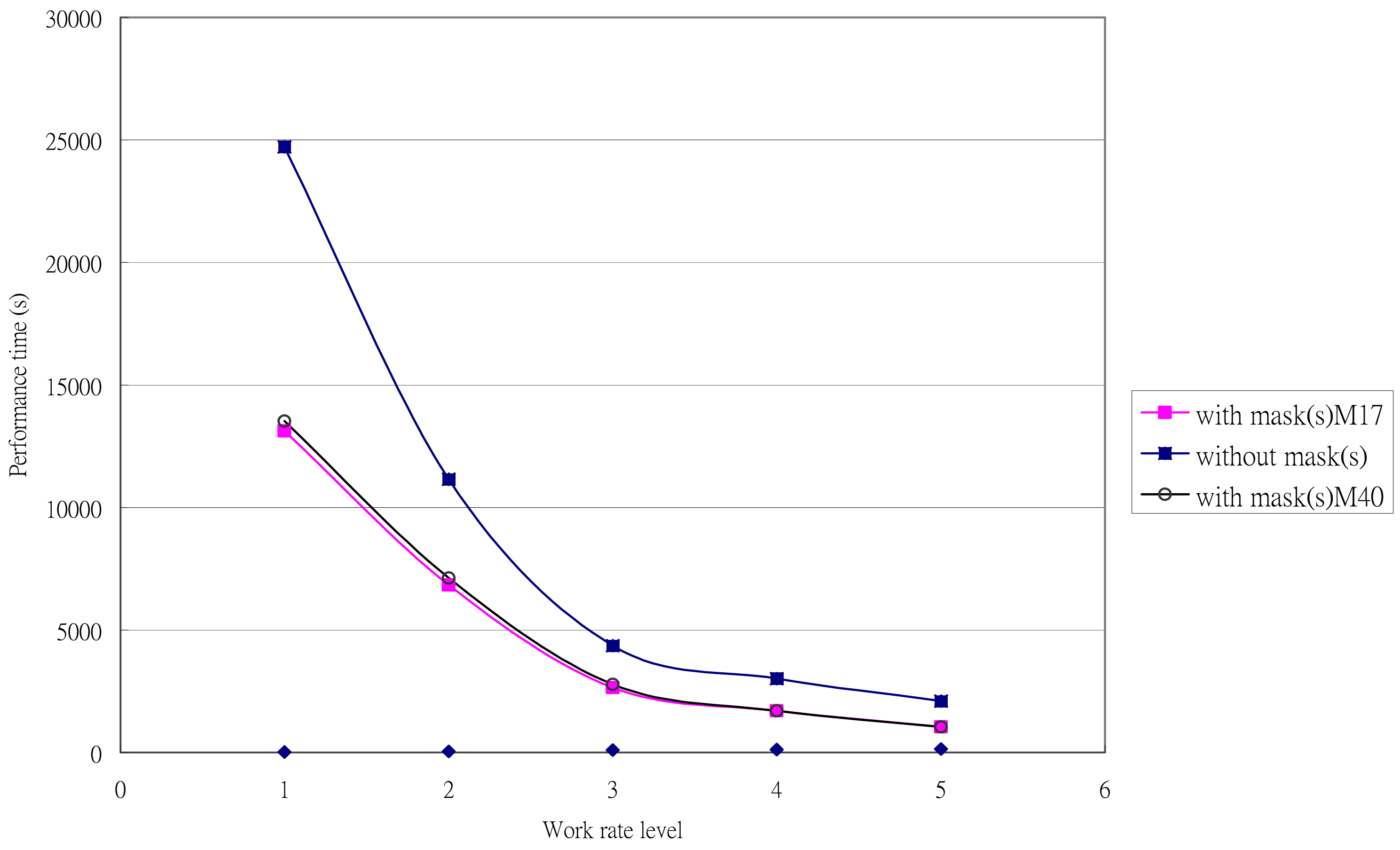


Figure 18 Performance time while wearing M17 and M40 respirators

5.3.2 Calculated VO2 compared to measured VO2 when wearing masks

Model simulations were run for three subjects from the Coyne study (2001) with a combination of different resistances. The subject's weight, $\dot{V}_{02\max}$, treadmill speed and grade, and the respirator characteristics were entered into the model and a simulation was run. Model simulation data were plotted against the measured value and a line of identity. These plots were obtained for steady-state oxygen consumption and minute ventilation.

Plots of the calculated versus measured steady-state oxygen consumption and minute ventilation are shown in Figures 19 and 20. Errors in Coyne's prediction of minute ventilation ranged from 0 to 48%. The oxygen consumption and minute ventilation in Coyne's model were consistently over-predicted. Although Coyne's model had less percent error than the current model, Coyne's model did not make accurate predictions. Some similar results were shown in the previous section (5.1.1) when subjects did not wear masks. The poor correlation of the measured and calculated data was because of individual variation. In general, the current model gave an average prediction for the oxygen consumption and minute ventilation when wearing masks.

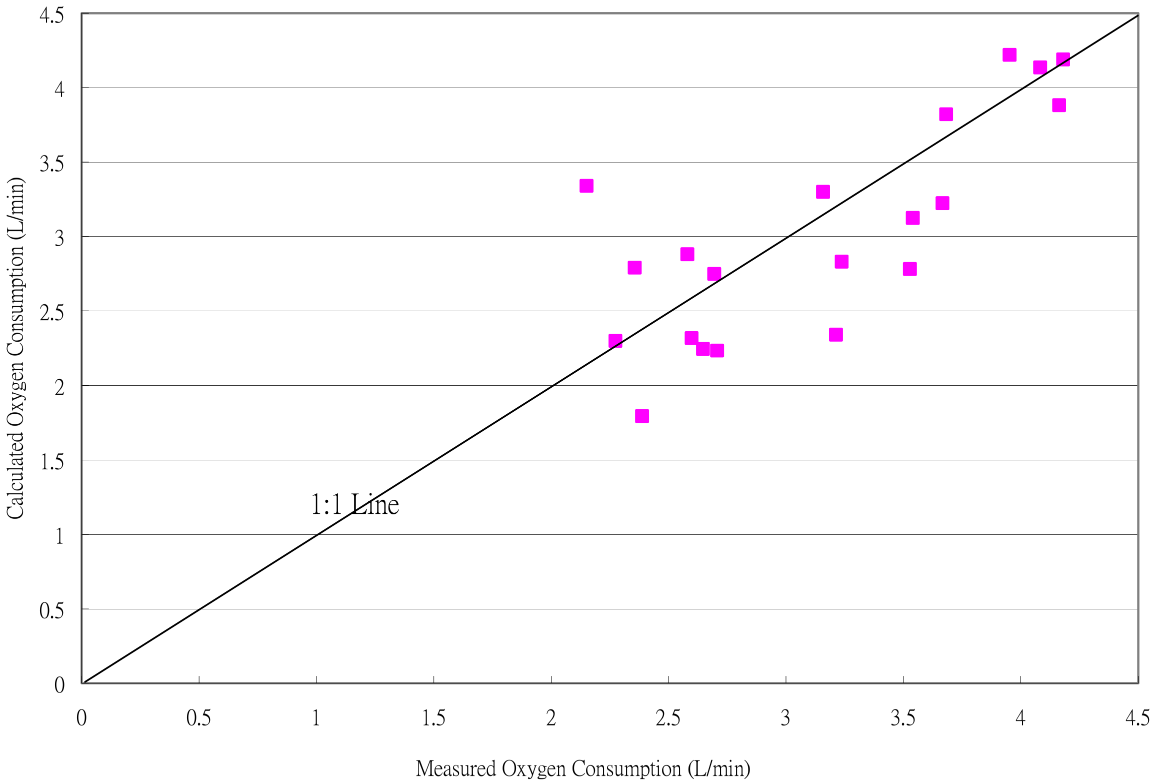


Figure 19 The comparison between calculated oxygen consumption and measured oxygen consumption (with mask)

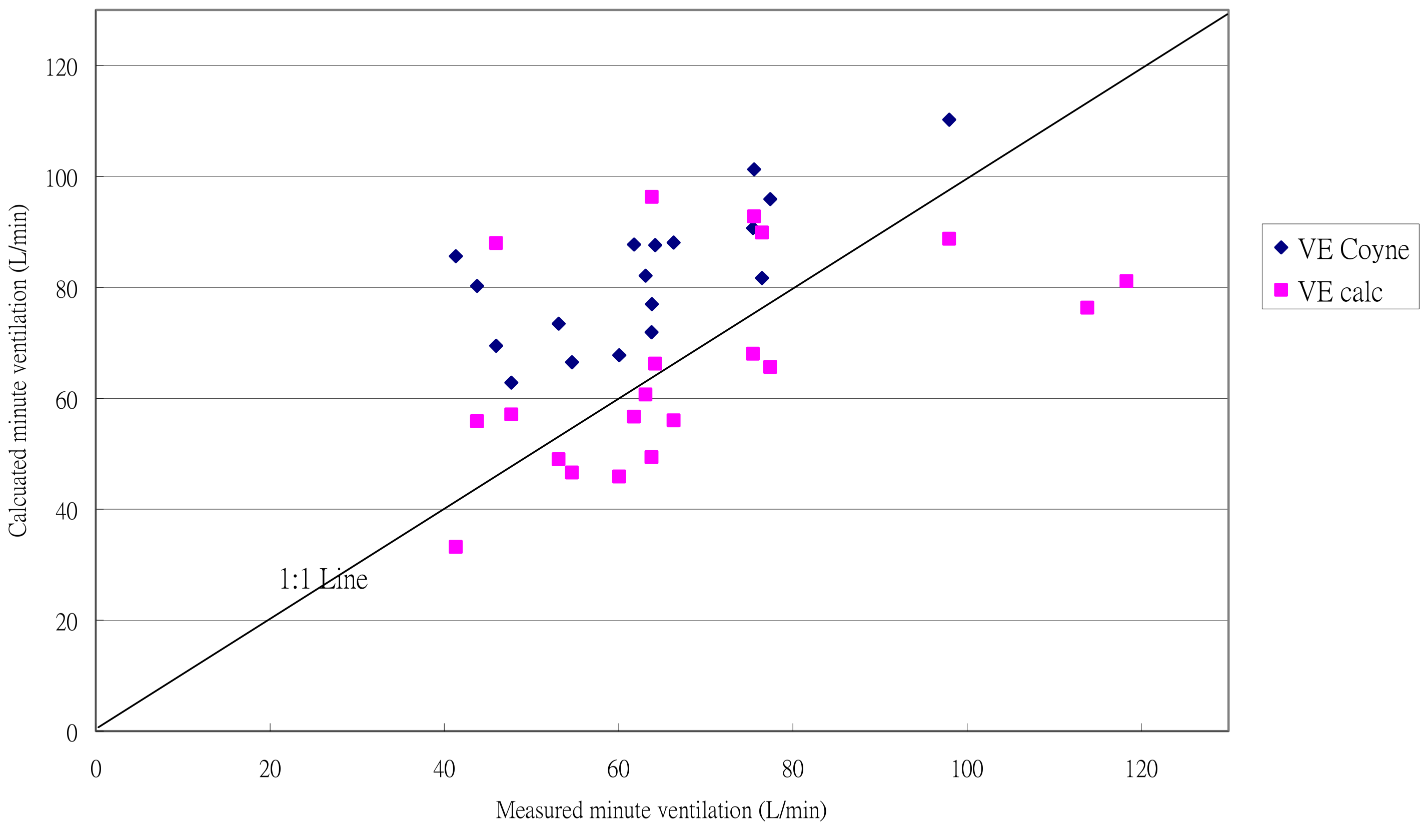


Figure 20 Minute ventilation calculated by the model compared to measured minute ventilation.

5.3.3 Calculating performance time from oxygen deficit equation

Since Kamon's equation was used for subjects who were not wearing masks, the performance time while wearing masks needed to be checked in the current model. From the physiological point of view, the oxygen deficit without mask ($OD_{without}$) will equal to the oxygen deficit with mask(OD_{with}).(Figure 21).

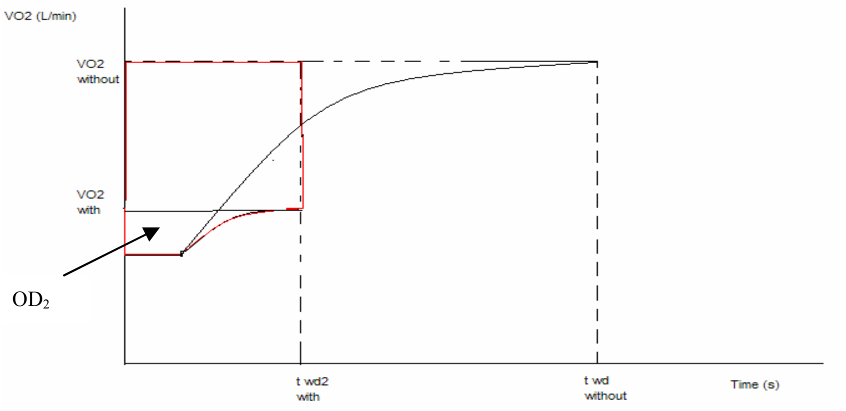


Figure 21. Using the oxygen deficit to calculated performance time with masks

$$OD_{without} = OD_{max} = OD_2 + (\dot{V}_{02}(without) - \dot{V}_{02}(with)) * (t_{wd2}) = OD_{with} \qquad (32)$$

Where t_{wd2} is performance time with masks

Using Eq. 32, t_{wd2} was calculated and the current model could be evaluated. In an ideal situation, the calculated performance time from the model simulation would be equal to $t_{wd2.}$ The results showed that the model simulation of performance time at 200W while wearing an M17 respirator was 180 sec. t_{wd2} calculated from equation 33 was 173 sec. This indicated that the two values of performance time with masks were very close. Thus, the Kamon equation could predict performance time while wearing a respirator. This indicated that the current model gave general predictions for average performance times with and without a mask.

5.3.4 Comparison between measured and calculated performance times (with M17 mask)

Compared to the condition without a mask, the performance time (with the mask) decreased. Twenty-four subjects' data obtained from the Human Performance Laboratory (University of Maryland, College park) were used as input to the current model. The average experimental performance time with the M17 respirator for twenty four subjects at 80% VO_2max exercise intensity was around six minutes and calculated performance time was around nine minutes. Figure 22 shows the comparison between measured and calculated performance time with a mask. The paired t-test results are shown in Table 14. The results showed there was no mean difference between the current model and the experimental data, therefore, the current model can adequately predict performance time.

The difference between the calculated and measured data was within three minutes. Although Figure 22 shows a poor correlation, this may be caused by the individual's variance. It is hard to say if the current model is a good predictor for performance with a mask, but the results demonstrated that the current model gave a general prediction of average performance time.

Table 14 Paired t-test for measured and calculated performance time (with M17 respirator)

	Measured performance time	Calculated performance time
Mean	378.75	556.1667
Variance	44991.85	130926.2
Observations	24	24
Pearson Correlation	0.221636	
Hypothesized Mean Difference	0	
df	23	
t Stat	-2.30735	
P(T<=t) one-tail	0.06519	
t Critical one-tail	1.71387	
P(T<=t) two-tail	0.040379	
t Critical two-tail	2.068655	

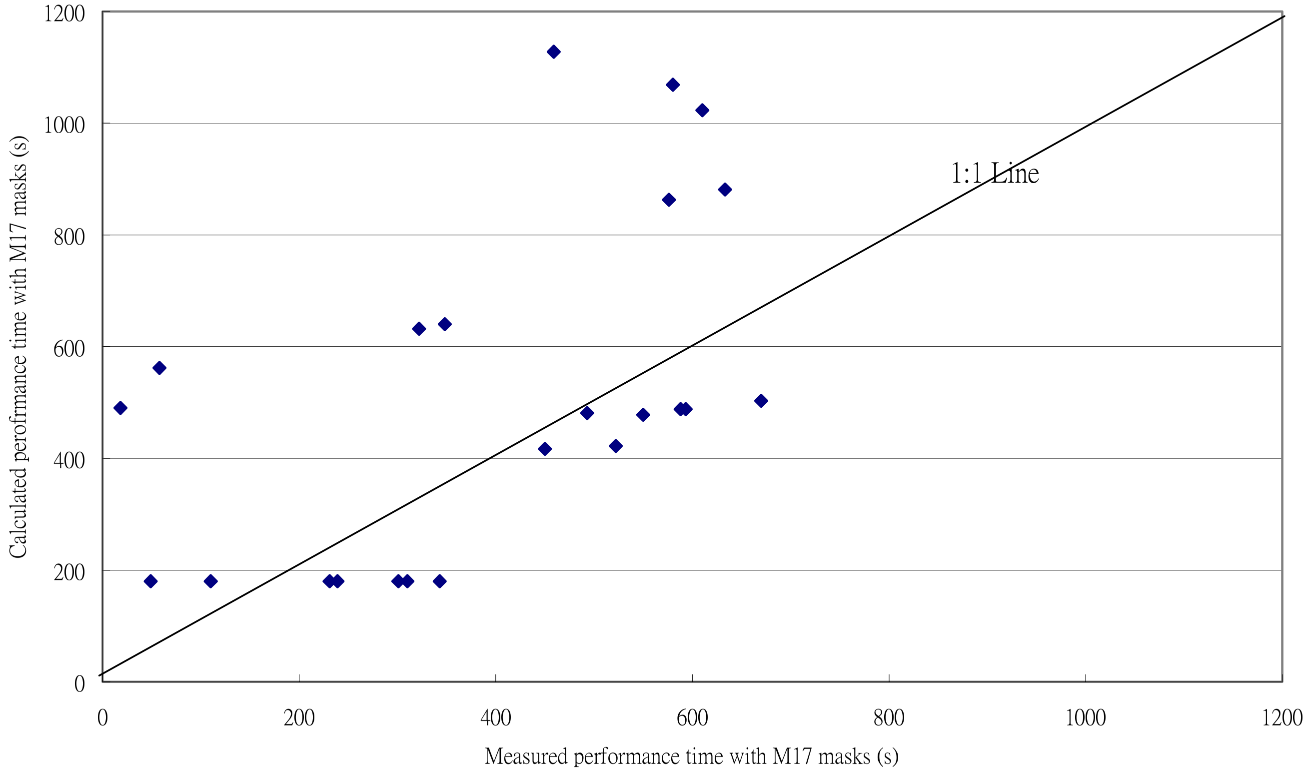


Figure 22 The comparison between measured and calculated performance time with M17 masks

Chapter 6: Conclusions

First, the current model predicted performance time when a subject exercised with and without a mask. Results illustrated that using work rate to predict performance time was better than using oxygen deficits. Thus, the predicted values were reasonable and closer to the experimental data.

Second, adding transient factors into the current model improved the predicted value especially for heavy exercise intensity. The values of minute ventilation, oxygen consumption, and tidal volume were predicted better than the previous model. Therefore, transient factors were found to be very important factors for the whole model.

Third, using the three phase oxygen consumption reflected the real oxygen consumption transition and provided better predictions than Coyne's model. It described 30% and 80%$\dot{V}_{o2\max}$ exercise intensities very well.

Based on the above reasons and results, this model predicted values well. Data for the physical values and performance time in the current model showed that the structure was valid and that the model was capable of making rational predictions for the average effects of respirator wear on the pulmonary system during physical activities.

Chapter 7: Future Studies

The current model predicted performance time during different exercise intensities. However, the oxygen consumption and work rate are not the only factors which affect performance time. For example, emotional states have been shown to elicit increases in airway resistance and performance in asthmatic individual. Other factors such as physical training, age, and pathological conditions can also alter the oxygen consumption responses at the onset of exercise. Furthermore, facial thermal, heat stress, and vision factors all affect exercise performance when a subject wears a respiratory mask.

The slow component of oxygen consumption could delay the attainment of the steady-state $\dot{V}_{02}$ or drive $\dot{V}_{02}$ to the maximum level, depending on the level of exercise intensity. However, there are some differences in oxygen consumption response during heavy exercise between children and adults. Aromon et al. (1991) found that almost 50% of the children in their study did not develop the slow component of $\dot{V}_{02}$ during heavy exercise intensity. Since all subjects in this study were approximately 18-25 years old, this finding could not be tested. In the future, children should be added into this study.

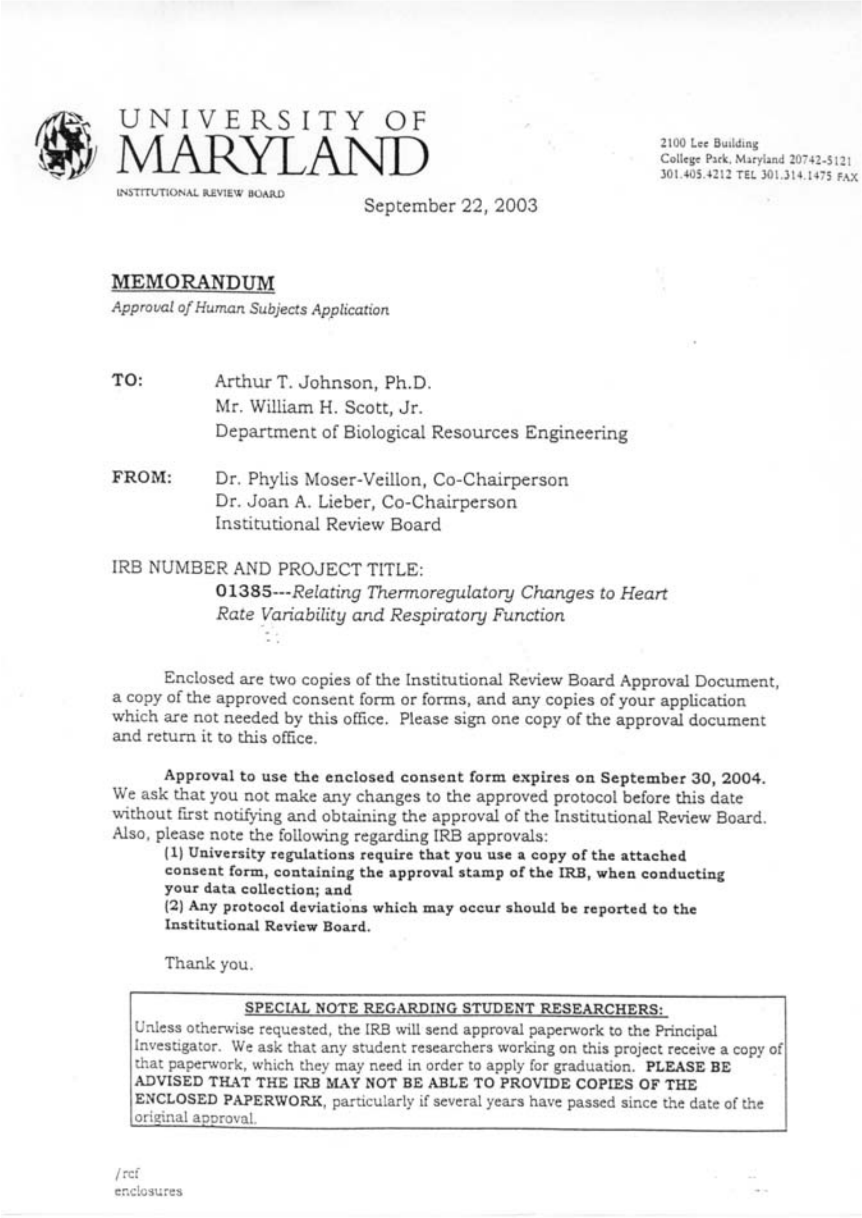
For future studies, there are several possible approaches that could be tested:

1. Compare different emotional conditions of each subject while wearing a respiratory mask during different exercise intensities.
2. Check facial temperature and its relation to performance time.

3. Measure lactic acid level which accumulates in subject’s blood when exercising at different intensities.
4. Measure respiratory mask vision angle and check its effect on performance time.
5. Compare both children and adults during heavy exercise intensities.

APPENDIX

IRB approval document I (01385)



UNIVERSITY OF
MARYLAND
INSTITUTIONAL REVIEW BOARD

2100 Lee Building
College Park, Maryland 20742-5121
301.405.4212 TEL 301.314.1475 FAX

September 22, 2003

MEMORANDUM

Approval of Human Subjects Application

TO: Arthur T. Johnson, Ph.D.
Mr. William H. Scott, Jr.
Department of Biological Resources Engineering

FROM: Dr. Phylis Moser-Veillon, Co-Chairperson
Dr. Joan A. Lieber, Co-Chairperson
Institutional Review Board

IRB NUMBER AND PROJECT TITLE:
01385---*Relating Thermoregulatory Changes to Heart Rate Variability and Respiratory Function*

Enclosed are two copies of the Institutional Review Board Approval Document, a copy of the approved consent form or forms, and any copies of your application which are not needed by this office. Please sign one copy of the approval document and return it to this office.

Approval to use the enclosed consent form expires on September 30, 2004. We ask that you not make any changes to the approved protocol before this date without first notifying and obtaining the approval of the Institutional Review Board. Also, please note the following regarding IRB approvals:

(1) University regulations require that you use a copy of the attached consent form, containing the approval stamp of the IRB, when conducting your data collection; and
(2) Any protocol deviations which may occur should be reported to the Institutional Review Board.

Thank you.

SPECIAL NOTE REGARDING STUDENT RESEARCHERS:

Unless otherwise requested, the IRB will send approval paperwork to the Principal Investigator. We ask that any student researchers working on this project receive a copy of that paperwork, which they may need in order to apply for graduation. **PLEASE BE ADVISED THAT THE IRB MAY NOT BE ABLE TO PROVIDE COPIES OF THE ENCLOSED PAPERWORK**, particularly if several years have passed since the date of the original approval.

/rcf
enclosures

CORRELATING THERMOREGULATORY CHANGES TO HEART RATE VARIABILITY AND RESPIRATORY FUNCTION

Principal Investigators:

Arthur T. Johnson, Ph.D.
Biological Resources Engineering Department
University of Maryland, College, Park

Jonathan Kaufman, Ph.D.
Human Performance Technology Branch
Naval Air Warfare Center Aircraft Division Patuxent River

Co-Investigator:
William H. Scott Jr.
Biological Resources Engineering Department
University of Maryland, College Park

Introduction

The Autonomic Nervous System (ANS) coordinates the functions of all cells of the body to promote homeostasis. ANS monitoring based on real-time heart rate variability (HRv) is a non-invasive measurement utilizing data that is routinely collected via EKG electrodes. Addition of respiratory spectral analysis permits two independent parameters to portray the status of the ANS and provide a measure of overall health. Studies previously conducted by Ansar indicate that there is a predictive nature to real-time HRv. This project will determine the correlation between ANS response and core body temperature, thereby validating the prognostic capabilities of the overall Wireless Fire Fighting Ensemble (WFFE) system and demonstrating the ability to collect and report the data necessary to monitor user well being and prediction health risks.

If you have questions about your safety rights as a research subject you can contact:

IRB Chair
University of Maryland
301 405-4212

or

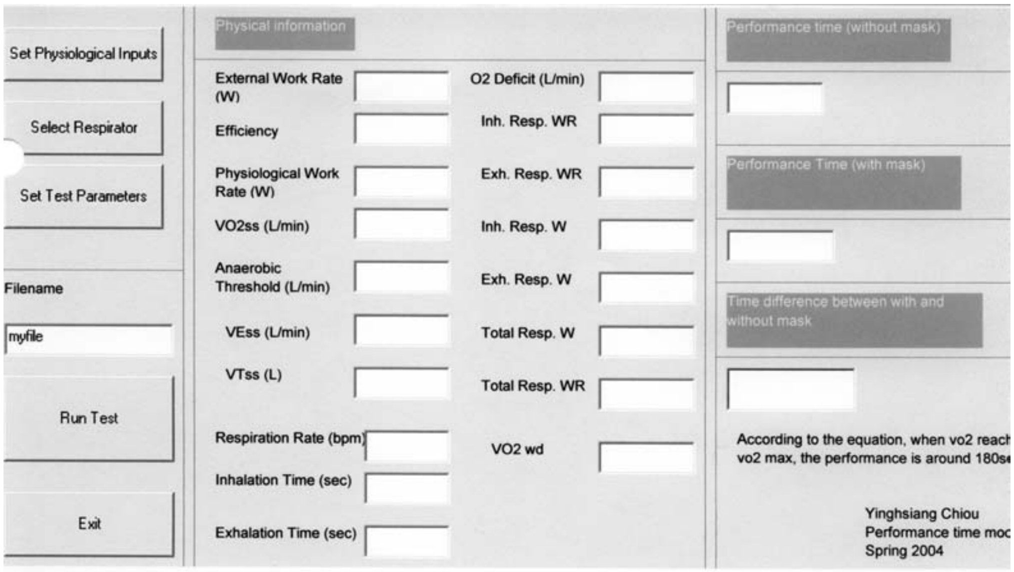
Marc Rogers, Ph.D. Chair
Human Subjects Review Committee
Department of Kinesiology
301 405-2484
mrogers1@umd.edu

IRB APPROVED
VALID UNTIL
SEP 30 2004
UNIVERSITY OF MARYLAND
COLLEGE PARK

8 of 8________________________
initials

Interface of the current model

The program allows the user to investigate changes in pulmonary parameters during exercise with or without a respirator. Once the program is run, the form “Main” is displayed.

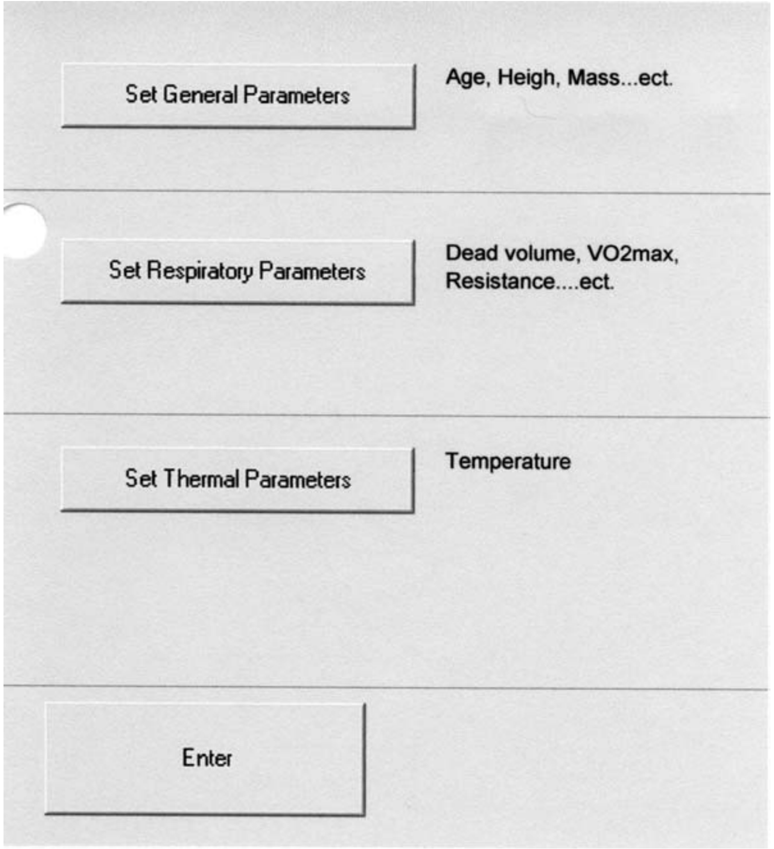


Filename: myfile

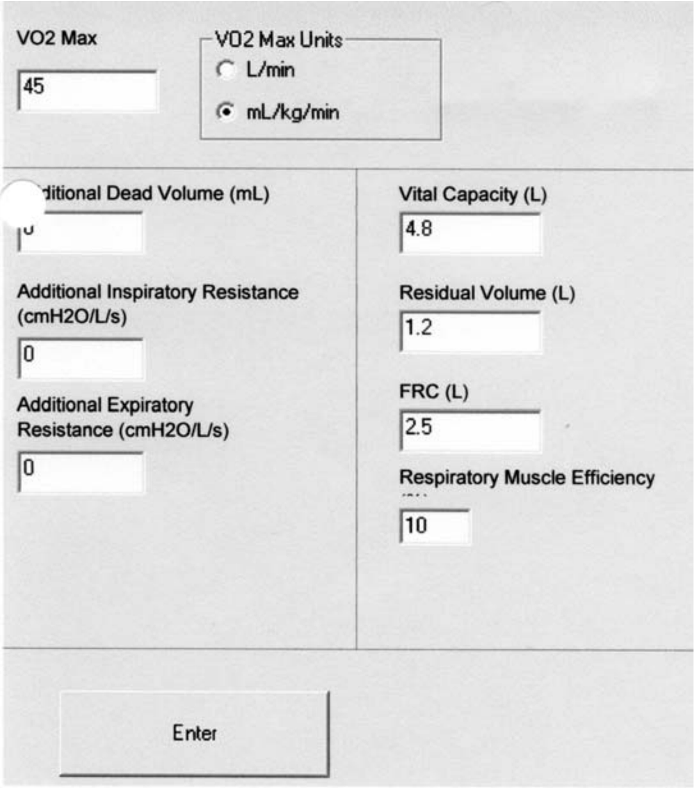
According to the equation, when vo2 reac
vo2 max, the performance is around 180s

Yinghsiang Chiou
Performance time mo
Spring 2004

From this form, the user has the option to change parameters by clicking on the buttons, “Set Physiological Inputs”, “Select Respirator”, and “Set Test Parameters”. The program is run by clicking on the button “Run Test”. Default values are provided for all the parameters so that a simulation may be run without making any changes. The default values also ensure the program will run if the user has not entered a value for one of the parameters.



When “Set Physiological Inputs” button is chosen, the user can enter the general, respiratory, and thermal parameters.



VO2 Max: 45

VO2 Max Units: ○ L/min ● mL/kg/min

Additional Dead Volume (mL): 0

Additional Inspiratory Resistance (cmH2O/L/s): 0

Additional Expiratory Resistance (cmH2O/L/s): 0

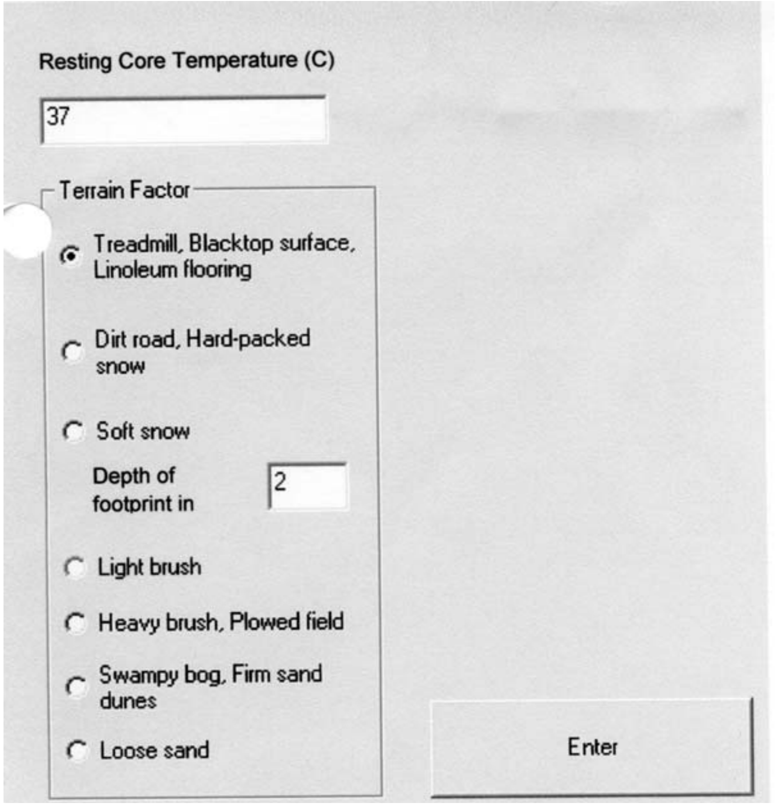
Vital Capacity (L): 4.8

Residual Volume (L): 1.2

FRC (L): 2.5

Respiratory Muscle Efficiency: 10

If the user clicks on the button “Set Respiratory Parameters”, the VO2max may be entered in either relative (mL/kg/min) or absolute (L/min) terms. Additional respiratory resistance and dead volume may be entered.



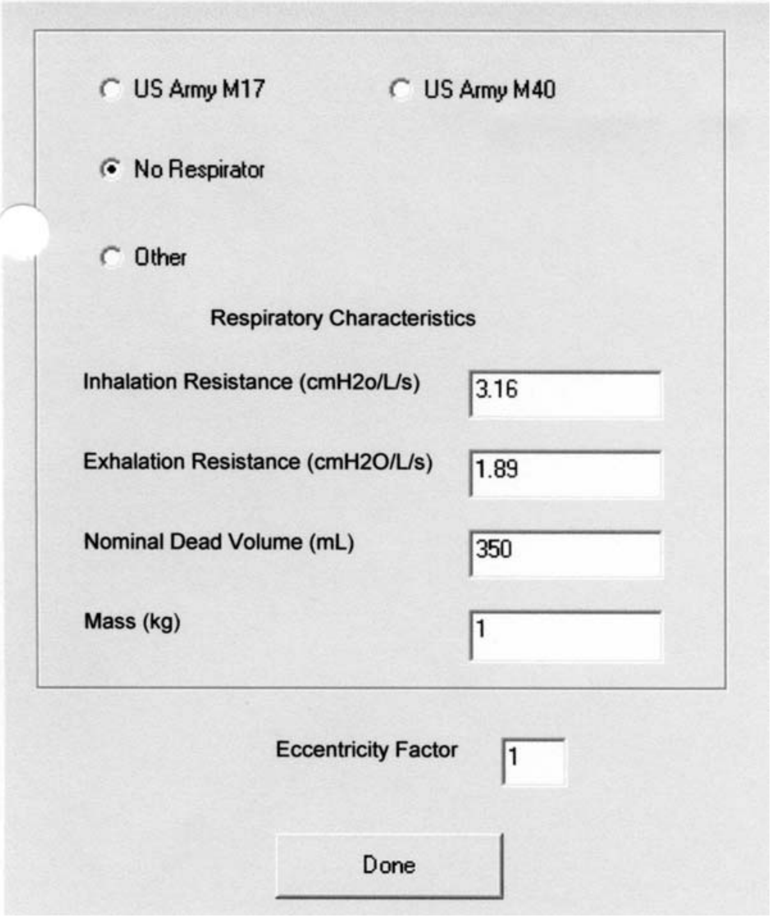
Resting Core Temperature (C)

37

Terrain Factor

- ● Treadmill, Blacktop surface, Linoleum flooring
- ○ Dirt road, Hard-packed snow
- ○ Soft snow
  - Depth of footprint in: 2
- ○ Light brush
- ○ Heavy brush, Plowed field
- ○ Swampy bog, Firm sand dunes
- ○ Loose sand

When the button “Set Thermal Parameters” is clicked, the user may enter the resting core temperature of the subject and the type of exercise which the subject will be walking or running.


○ US Army M17 ○ US Army M40

● No Respirator

○ Other

Respiratory Characteristics

Inhalation Resistance (cmH2o/L/s) 3.16

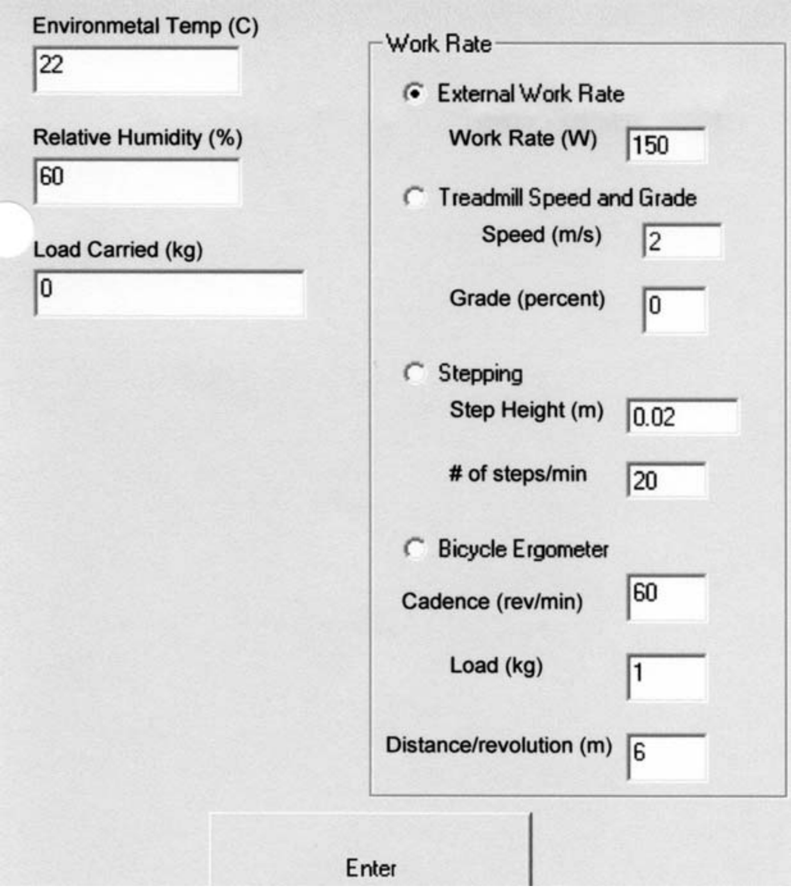
Exhalation Resistance (cmH2O/L/s) 1.89

Nominal Dead Volume (mL) 350

Mass (kg) 1

Eccentricity Factor 1

If the user selects the button “Select Respirator”, the user may select no respirator, the U. S. Army M17, the U.S. Army M40, or another respirator. If the option “Other” is selected, additional the inhalation and exhalation resistance, dead volume, and mass of the respirator may enter.



Environmetal Temp (C) 22

Relative Humidity (%) 60

Load Carried (kg) 0

Work Rate

● External Work Rate

Work Rate (W) 150

○ Treadmill Speed and Grade

Speed (m/s) 2

Grade (percent) 0

○ Stepping

Step Height (m) 0.02

# of steps/min 20

○ Bicycle Ergometer

Cadence (rev/min) 60

Load (kg) 1

Distance/revolution (m) 6

When clicking on the button “Set Test Parameters”, the environmental temperature and humidity, the load carried by the subject, and the work rate may be changed on this form.

Programming code (Visual Basic)

```
Public Function EtaMusc(sgExtW As Single)
   'determine gross muscle efficiency as
   'a function of external work rate
   If sgExtW < 20.1 Then
      EtaMusc = sgExtW / 200
   ElseIf sgExtW < 159.3 Then
      EtaMusc = 0.1003 + 0.0006 * (sgExtW - 20.1)
   ElseIf sgExtW < 240 Then
      EtaMusc = 0.1839 + 0.0002 * (sgExtW - 159.3)
   Else
      EtaMusc = 0.2
   End If

End Function

Public Function MetM(sgSurface As Single, sgMass As Single, sgSpeed As Single,
sgGrade As Single, sgLdCarried)
   'Pandolf (1977) equation for physiological work rate
   Dim sgDiff As Single
   Dim sgWeight As Single
   Dim sgWtCarried As Single
   sgWeight = 9.81 * sgMass
   sgWtCarried = 9.81 * sgLdCarried
   MetM = 0.15 * sgWeight + 0.2 * (sgWeight + sgWtCarried) * (sgWtCarried /
sgWeight) ^ 2 + 0.102 * sgSurface * (sgWeight + sgWtCarried) * (1.5 * sgSpeed ^ 2 +
35 * sgSpeed * sgGrade / 100) - (sgWeight + sgWtCarried) * sgSpeed * sgGrade / 100
End Function

Public Function RR(sgMinVol As Single, sgTidVol As Single)
   'determine respiratory rate
   RR = sgMinVol / sgTidVol
End Function

Public Function VO2fastss(sgWin As Single)

   VO2fastss = 0.0028 * sgWin + 0.4398
End Function
Public Function VO2wd(sgWin As Single)
   'VO2 as a function of work rate
   VO2wd = 0.002952 * sgWin
End Function

Public Function VO2Adj(sgVE As Single)
   'adjust VO2 based on decrease in VE with respirator
```

```
    VO2Adj = 0.034 * sgVE + 0.4322
End Function

Public Function SinWR2(K1 As Single, K2 As Single, K3 As Single, c As Single,
sgMinVol As Single, sgTid As Single, sgT As Single, sgV0 As Single, sgVr As Single,
inFlag As Integer, inMask As Integer, sgEpsilon As Single, sgP As Single)
    'sinusoidal work rate equations
    'from Johnson (1993)
    Dim sgMaxF, sgMaxF2, sgMaxF3 As Single
    Dim WR1, WR2, WR3, WR4, WR5, WR6, WR7 As Single
    Dim inIE As Integer, sgAA As Single, sgAX As Single
    Dim sgV0b As Single, sgVrb As Single, sgTidb As Single, sgMinVolb As Single
    'convert units from L and min to m^3 and sec
    sgV0b = sgV0 / 1000
    sgVrb = sgVr / 1000
    sgTidb = sgTid / 1000
    sgMinVolb = (sgMinVol / 1000) / 60
    If inFlag = 0 Then
        inIE = 1
    Else
        inIE = -1
    End If
    pi = 3.1415962
    pi2 = pi * pi
    sgMaxF = sgMinVolb * sgEpsilon * pi / 2
    sgMaxF2 = sgMaxF ^ 2
    sgMaxF3 = sgMaxF ^ 3
    sgAA = sgV0b * pi / (sgMaxF * sgT) + inIE
    sgAX = Sqr(sgAA * sgAA - 1)
    WR1 = K1 * sgMaxF2 / 2
    WR2 = 4 * K2 * sgMaxF3 / (3 * pi)
    WR3 = (K3 * sgMaxF * pi * (sgAA - sgAX)) / sgT
    WR4a = (2 * sgMaxF2 * sgT) / (pi2 * c)
    WR4b = inIE * sgTidb * (sgV0b - sgVrb) / (sgT * c)
    WR4 = WR4a + WR4b
    WR5 = 0
    WR6 = 0
    If inMask = 1 Then
        WR7 = sgP * sgTidb / sgT 'if a mask is worn, work to open valve
    Else
        WR7 = 0
    End If
    SinWR2 = WR1 + WR2 + WR3 + WR4 + WR5 + WR6 + WR7
End Function
```

```
Public Function HybridExp2WR(K1 As Single, K2 As Single, K3 As Single, c As Single,
sgMinVol As Single, sgVr As Single, inFlag As Integer, sgEpsilon As Single, sgV0 As
Single, sgTid As Single, sgT As Single, sgP As Single, inMask As Integer)
   'hybrid exponential work rate equations
   'from Johnson (1993)
   Dim WR1, WR2, WR3, WR4, WR5, WR6, WR7 As Single
   Dim sgTau As Single, sgTR As Single, sgMT As Single, sgMTau As Single
   Dim sgMaxF As Single, sgMaxF2 As Single, sgMaxF3 As Single
   Dim sgExp8 As Single, sgExp16 As Single, sgExp24 As Single
   Dim sr As Single, cc As Single, L6 As Single, bb As Single
   Dim ss As Single, aa As Single, ep As Single, em As Single
   Dim b As Single, X1 As Single, X2 As Single
   Dim r1 As Single, r2 As Single, r As Single, L5 As Single
   Dim sgMinVolb As Single, sgV0b As Single, sgVrb As Single, sgTidb As Single
   Dim inIE As Integer
   'convert units from L and min to m^3 and sec
   sgMinVolb = (sgMinVol / 1000) / 60
   sgV0b = sgV0 / 1000
   sgVrb = sgVr / 1000
   sgTidb = sgTid / 1000
   If inFlag = 0 Then
      inIE = 1
   Else
      inIE = -1
   End If
   sgTau = (K1 + K2 * sgMinVolb * sgEpsilon + K3 / (sgV0b + inIE * sgTidb / 2)) * c
   sgTR = sgT / sgTau
   sgExp8 = Exp(-0.8 * sgTR)
   sgExp16 = sgExp8 ^ 2
   sgExp24 = sgExp8 * sgExp16
   'sgMaxF = sgMinVolb * sgEpsilon / (0.05 + (1 - sgExp8) / sgTR + 0.05 * sgExp8)
   sgMaxF = sgTidb / (sgTau * (1 - sgExp8) + 0.05 * sgT * (1 + sgExp8))
   sgMaxF2 = sgMaxF ^ 2
   sgMaxF3 = sgMaxF ^ 3
   sgMT = sgMaxF * sgT
   sgMTau = sgMaxF * sgTau
   WR1 = K1 * sgMaxF2 * ((1 + sgExp16) / 15 + (1 - sgExp16) / sgTR) / 2
   WR2 = K2 * sgMaxF3 * ((1 + sgExp24) / 40 + (1 - sgExp24) / (3 * sgTR))
   b = sgV0b / sgMT
   ss = Sqr(20 * b)
   aa = 2 - 2 * ss * Atn(1 / ss)
   ep = (1 + sgExp8)
   em = 1 - sgExp8
   X1 = b + inIE * 0.05
   X2 = X1 + inIE * em / sgTR
   If X1 / X2 < 0 Then
```

```
        'nothing
    Else
        L5 = Log(X1 / X2)
    End If
    bb = -inIE * em - L5 * sgTR * (X1 + inIE / sgTR)
    a = X2 - inIE * 4.95 * sgExp8
    r1 = inIE * 20 * a * sgExp8 + 100 * sgExp16
    r2 = 2 * sgExp8
    r = -r1
    If r > 0 Then
        sr = Sqr(r)
        cc = (-2 * inIE * r1 / sr) * Atn(sgExp8 / sr) - inIE * r2
    Else
        sr = Sqr(-r)
        L6 = inIE * Log((sr + sgExp8) / ((sr - sgExp8)))
        cc = (r1 * L6 / sr) - inIE * r2
    End If
    WR3 = K3 * sgMaxF * (aa + bb + cc) / sgT
    WR4 = sgTidb * (sgTidb / 2 + inIE * (sgV0b - sgVrb)) / (sgT * c)
    WR5 = 0
    WR6 = 0
    If inMask = 1 Then
        WR7 = sgP * sgTidb / sgT 'if a mask is worn, work to open valve
    Else
        WR7 = 0
    End If
    HybridExp2WR = WR1 + WR2 + WR3 + WR4 + WR5 + WR6 + WR7

End Function
Public Function FlowLim2WR(K1 As Single, K2 As Single, K3 As Single, c As Single,
sgI As Single, sgV0 As Single, sgMinVol As Single, sgTid As Single, sgEpsilon As
Single, inFlag As Integer, sgFRC As Single, sgT As Single, sgRV As Single, sgP As
Single, inMask As Integer, sgPm As Single, sgVC)
    'flow-limited hybrid exponential equations
    'from Johnson (1993)
    Dim WR1, WR2, WR3, WR4, WR5, WR6, WR7 As Single
    Dim sgTau As Single, sgTR As Single, sgExp8 As Single
    Dim sgExp16 As Single, sgMaxF As Single, sgMaxF2 As Single, sgMaxF3 As Single
    Dim sgMT As Single, sgMTau As Single, b As Single, ss As Single
    Dim aa As Single, a As Single, r1 As Single, r2 As Single
    Dim r As Single, sr As Single, cc As Single, L6 As Single
    Dim sgExp1 As Single, sgExp9 As Single, c1 As Single, c2 As Single
    Dim c3 As Single, c4 As Single, c5 As Single, c6 As Single
    Dim inIE As Integer, em As Single
    Dim sgV0b As Single, sgMinVolb As Single, sgRVb As Single
    Dim sgTidb As Single, sgFRCb As Single, sgVCb As Single
```

```
'convert units from L and min to m^3 and sec
sgMinVolb = (sgMinVol / 1000) / 60
sgV0b = sgV0 / 1000
sgVCb = sgVC / 1000
sgRVb = sgRV / 1000
sgTidb = sgTid / 1000
sgFRCb = sgFRC / 1000
If inFlag = 0 Then
   inIE = 1
Else
   inIE = -1
End If
sgTau = (K1 + K2 * sgMinVolb * sgEpsilon + K3 / (sgV0b + inIE * sgTidb / 2)) * c
sgTR = sgT / sgTau
em = 1 - Exp(8)
sgExp8 = Exp(-0.8 * sgTR)
sgExp16 = sgExp8 ^ 2
sgExp24 = sgExp8 * sgExp16
sgMaxF = sgMinVolb * sgEpsilon / (0.05 + (1 - sgExp8) / sgTR + 0.05 * sgExp8)
sgMaxF2 = sgMaxF ^ 2
sgMaxF3 = sgMaxF ^ 3
sgMT = sgMaxF * sgT
sgMTau = sgMaxF * sgTau
WR1 = K1 * sgMaxF2 * (1 + sgExp16) / 30
WR2 = K2 * sgMaxF3 * (1 + sgExp24) / 40
b = sgV0b / sgMT
ss = Sqr(20 * b)
'ss = Sqr(20 * sgV0b) / sgMT
aa = 2 - 2 * ss * Atn(1 / ss)
a = b + inIE * 0.05 + inIE * (1 - sgExp8) / sgTR - inIE * 4.95 * sgExp8
r1 = inIE * 20 * a * sgExp8 + 100 * sgExp16
r2 = 2 * sgExp8
r = -r1
If r > 0 Then
   sr = Sqr(r)
   cc = (-2 * inIE * r1 / sr) * Atn(sgExp8 / sr) - inIE * r2
Else
   sr = Sqr(-r)
   L6 = inIE * Log((sr + sgExp8) / ((sr - sgExp8)))
   cc = (r1 * L6 / sr) - inIE * r2
End If
'X = sgV0b / sgMT + inIE * 0.05
'L5 = Log(X / (X + inIE * (1 - sgExp8) / sgTR))
'bb = -inIE * (1 - sgExp8) - L5 * sgTR * (X + inIE / sgTR)
sgV0b = sgRVb - inIE * (0.05 * sgMT * sgMTau)
WR3 = K3 * sgMaxF * (aa + cc) / sgT
```

```
    'aa = sgMaxF * (sgFRCb - sgV0b + sgMaxF * sgT / 40) / (c * 20)
    'bb = sgMaxF * sgExp8 * (sgFRCb - sgV0b + sgMaxF * (sgT / 20 + sgTau * (1 -
sgExp8)) + sgMaxF * sgExp8 * sgT / 40) / (c * 20)
    'WR4 = aa + bb
    'WR4 = sgMaxF * sgT * (sgMaxF * (1 / 40 + sgExp8 / 20 + sgExp16 / 40 + sgExp8 *
em / sgTR) - sgTidb * (sgV0b - sgFRCb) * (1 + sgExp8) / sgT) / (20 * c)
    WR4 = (sgMaxF2 * sgT / (20 * c)) * (1 / 40 + sgExp8 / 20 + sgExp16 / 40 + (sgTau *
sgExp8 / sgT) * (1 - sgExp8)) - (sgV0b - sgFRCb) * (0.05 * sgT * sgVmax) * (1 +
sgExp8) / (c * sgT)
    kmc = c
    WR5 = sgI * sgMaxF2 * (1 - sgExp16) / (2 * sgT)
    sgExp1 = Exp(-0.1 * sgTR)
    sgExp9 = sgExp1 * sgExp8
    c1 = 0.145
    c2 = 0.306
    c3 = 100 * (0.1 * sgMT + 2 * sgMTau + sgRVb) / sgVCb
    c4 = -100 * sgMTau / (sgExp1 * sgVCb)
    c5 = c1 * sgMaxF / sgExp1
    c6 = c2 * sgMaxF / sgExp1
    a = c3 + c4 * sgExp9
    b = c3 + c4 * sgExp1
    WR6 = (sgMaxF * sgTau / sgT) * (4325.651 * (1 - sgExp8) + (11703.94 / (2 * sgVCb))
* sgTau * sgMaxF * (1 - sgExp16))
        'WR6 is pmax*flow during the flow-limited portion of the waveform
    If inMask = 1 Then
        WR7 = 0.05 * sgP * sgMaxF * sgT * (1 + Exp8) 'if a mask is worn, work to open
valve
    Else
        WR7 = 0
    End If
    FlowLim2WR = WR1 + WR2 + WR3 + WR4 + WR5 + WR6

End Function

Public Function Te(sgRPD As Single)
    'exhalation time as a function of respiratory period
    Te = 0.6176 * sgRPD - 0.2145
End Function
Public Function Ti(sgRPD As Single)
    'inhalation time as a function of respiratory period
    Ti = sgRPD - (0.6176 * sgRPD - 0.2145)
End Function

Public Function Trap3WR(K1 As Single, K2 As Single, K3 As Single, c As Single, sgVr
As Single, sgP As Single, inMask As Integer, sgTidal As Single, sgT As Single, sgV0 As
Single, inFlag As Integer, sgMinVol As Single, sgEpsilon As Single)
```

```
'trapezoidal work rate equations
'from Johnson (1993)
Dim sgVmax As Single
Dim WR1, WR2, WR3, WR4, WR7 As Single
Dim s As Single, L2 As Single, q As Single, L2a As Single
Dim q1 As Single, p1 As Single, p As Single, L3 As Single
Dim sgV0b As Single, sgVrb As Single, sgTidalb As Single
Dim inIE As Integer, sgMinVolb As Single
'convert units from L and min to m^3 and sec
sgMinVolb = (sgMinVol / 1000) / 60
sgV0b = sgV0 / 1000
sgVrb = sgVr / 1000
sgTidalb = sgTidal / 1000
If inFlag = 0 Then
   inIE = 1
Else
   inIE = -1
End If
pi = 3.14
'sgVmax = sgTidalb / (0.825 * sgT)
sgVmax = sgMinVolb * sgEpsilon / 0.825
WR1 = 0.730556 * K1 * sgVmax ^ 2
WR2 = 0.8129416 * K2 * sgVmax ^ 3
b = sgV0b / (sgVmax * sgT)
ss = Sqr(20 * b)
aa = 2 - 2 * ss * Atn(1 / ss)
q1 = inIE * 0.4166667 * b + 1.020833
q2 = 0.3333333
q3 = 0.8333333
q = -q1
If q > o Then
   sq = Sqr(q)
   bb = (2 * q1 / sq) * (Atn(1.010417 / sq) - Atn(0.9270833 / sq)) - inIE * q2
Else
   sq = Sqr(-q)
   L2a = Abs((sq + 1) * (sq - q3) / ((sq - 1) * (sq + q3)))
   L2 = inIE * Log(L2a)
   bb = q1 * L2 / sq - inIE * q2
End If
p1 = inIE * 16.66667 * b + 13.75
p2 = 1.666667
p = -p1
If p > 0 Then
   sp = Sqr(p)
   cc = (-inIE * 2 * p1 / sp) * Atn(q3 / sp) - inIE * p2
Else
```

```
        sp = Sqr(-p)
        L3 = inIE * Log(Abs((sp + q3) / (sp - q3)))
        cc = p1 * L3 / sp - inIE * p2
    End If
    WR3 = K3 * sgVmax * (aa + bb + cc) / sgT
    If inFlag = 0 Then
        WR4 = 0.3403343 * (sgVmax ^ 2 * sgT / c) + sgTidalb * (sgV0b - sgVrb) / (sgT * c)
    Else
        WR4 = 0.3403343 * (sgVmax ^ 2 * sgT / c) - sgTidalb * (sgV0b - sgVrb) / (sgT * c)
    End If
    If inMask = 1 Then
        WR7 = sgP * sgTidalb / sgT 'if a mask is worn, work to open valve
    Else
        WR7 = 0
    End If
    Trap3WR = WR1 + WR2 + WR3 + WR4 + WR7
End Function
Public Function V0i(sgVit As Single, sgRes As Single, sgTid As Single, sgFRC As
Single, sgW As Single)
    'determine the starting volume for inhalation
    Dim a As Single, b As Single, c As Single
    Dim sgResb As Single, sgVitb As Single, sgFRCb As Single, sgTidb As Single
    Dim V0itemp As Single
    'convert from L to m^3
    sgResb = sgRes / 1000
    sgVitb = sgVit / 1000
    sgFRCb = sgFRC / 1000
    sgTidb = sgTid / 1000
    a = 6.39
    b = -a * (sgTidb + 2 * sgResb) + 2 * sgVitb
    c = a * sgResb * (sgResb + sgTidb) - sgVitb * (sgTidb + 2 * sgResb + sgVitb)
    V0itemp = (-b + (b * b - 4 * a * c) ^ 0.5) / (2 * a)
    If V0itemp < sgResb Then
        V0itemp = sgResb
    End If
    'for low work rates V0i is FRC
    'for light it is midway between calculated volume and FRC
    If sgW < 5 Then
        V0i = sgFRC '* 1000 'convert back to L
    Else
        If sgW < 35 Then
            V0i = (((sgW - 5) * V0itemp + (35 - sgW) * sgFRC) / 30) * 1000 'convert back to
L
        Else
            V0i = V0itemp * 1000
        End If
```

```
    End If
End Function

Public Function AT(sgMax As Single)
    'determine anaerobic threshold
    AT = 0.8624 * sgMax - 7.1585
End Function
Public Function Vminss(sgPerc As Single, sgMax As Single)
    'determine steady-state VE
    Dim sgVEmax As Single
    Dim sgVEPercMax As Single
    sgVEmax = 20.01 * sgMax + 7.855 'L/min
    sgVEPercMax = 0.0095 * (sgPerc * sgPerc) - 0.133 * sgPerc + 17.153 '% eg 80%
    Vminss = sgVEPercMax * sgVEmax / 100 'L/min
End Function
Public Function VERes(sgPerc As Single, sgInh As Single, sgExh As Single)
    'determine change in VE due to added resistance
    If sgPerc < 30 Then
        VERes = -0.0037 * sgInh - 0.0223 * sgExh
    Else
        If sgPerc < 40 Then
            VERes = -0.0018 * sgInh - 0.0206 * sgExh
        Else
            If sgPerc < 50 Then
                VERes = -0.0065 * sgInh - 0.0469 * sgExh
            Else
                If sgPerc < 80 Then
                    VERes = -0.0156 * sgInh - 0.0846 * sgExh
                Else
                    VERes = -0.0454 * sgInh - 0.0967 * sgExh
                End If
            End If
        End If
    End If
End Function
Public Function VEVD(sgPerc As Single, sgVD As Single)
    'determine change in VE due to added dead space
    Dim VEchange As Single, sgFract As Single
    sgFract = sgPerc / 100
    VEchange = 0.170432 * sgVD - 0.00681 - ((sgFract - 0.15) / 0.15) * (1.8 / 60)
    If VEchange < 0 Then
        VEVD = 0
    Else
        VEVD = VEchange
    End If
End Function
```

```
Public Function VTidss(sgPerc As Single, sgMax As Single)
    'determine steady-state tidal volume
    Dim sgVTmax As Single
    Dim sgVTPercMax As Single
    sgVTPercMax = 0.9987 * sgPerc - 1.6809
    sgVTmax = 0.4864 * sgMax + 0.3016 'L
    VTidss = sgVTPercMax * sgVTmax / 100 'L
End Function
Public Function VTRes(sgPerc As Single, sgInh As Single, sgExh As Single)
    'determine change in VT with added resistance
    If sgPerc < 30 Then
        VTRes = 0
    Else
        If sgPerc < 40 Then
            VTRes = 0.0092 * sgInh + 0.208 * sgExh
        Else
            If sgPerc < 50 Then
                VTRes = 0
            Else
                If sgPerc < 80 Then
                    VTRes = 0
                Else
                    VTRes = -0.0162 * sgInh + 0.0746 * sgExh
                End If
            End If
        End If
    End If

End Function
Public Function VTVD(sgPerc As Single, sgVD As Single)
    'determine the change in tidal volume with added dead space
    Dim VTchange As Single
    Dim sgFract As Single
    sgFract = sgPerc / 100
    If sgPerc < 15 Then
        VTchange = 0.7468 * sgVD - 0.08445
    Else
        If sgPerc < 30 Then
            VTchange = 0.9933 * sgVD - 0.2537
        Else
            VTchange = 0.195 + 0.2517 * sgVD - 0.4256 * sgFract
        End If
    End If
    If VTchange < 0 Then
```

```
      VTVD = 0
   Else
      VTVD = VTchange
   End If

End Function
Public Function O2Def(sgAdj As Single, sgSS As Single)
   'find oxygen deficit
   O2Def = sgSS - sgAdj
End Function
Public Function sgTwd(sgAbsVO2max As Single, sgVO2wd As Single)
  Twd = 7200 * (sgAbsVO2max / sgVO2wd) - 7020

End Function
Public Function sgTwd2(sgAbsVO2max As Single, sgVO2ss As Single)
   Twd2 = 7200 * (sgAbsVO2max / sgVO2ss) - 7020
End Function




Private Sub cmdMainExit_Click()
   End
End Sub

Public Sub cmdRunTest_Click()
   '*****************************************************
   '***** Developed in Visual BASIC 6.0
   '***** Developed by Yinghsiang Chiou
   '***** Last modified 5/20/04
   '*****************************************************
      Dim I As Integer
   'declare metabolic variables
   Dim sgMetM As Single 'physiological work rate, W
   'declare general variables
   Dim sgSubjMass As Single  'subject mass, kg
   Dim sgSubjHt As Single  'subject ht, cm
   Dim inSubjAge As Integer  'subject age,yr
   Dim sgBMI 'body mass index
   Dim sgGender As Single
   Dim inFitness As Integer  'fitness level
   'declare thermal variables
   Dim sgRestCoreTemp As Single 'resting core temp,C
   Dim sgTerrain As Single  'terrain coefficient
   Dim stTerrain As String 'terrain name
   'declare respiratory variables
```

```
Dim sgK1aw As Single 'Rohrer coefficients
Dim sgK2aw As Single
Dim sgK3aw As Single
Dim sgK1Iaw As Single
Dim sgK2Iaw As Single
Dim sgK3Iaw As Single
Dim sgK1Eaw As Single
Dim sgK2Eaw As Single
Dim sgK3Eaw As Single
Dim sgK1I As Single
Dim sgK2I As Single
Dim sgK3I As Single
Dim sgK1E As Single
Dim sgK2E As Single
Dim sgK3E As Single
Dim sgCompliance As Single
Dim sgInertia As Single
Dim sgRestVO2 As Single 'resting VO2
Dim sgVO2max As Single 'VO2max
Dim sgRelVO2max As Single 'VO2max in ml/kg/min
Dim sgAbsVO2max As Single  'VO2max in L/min
'Dim inVO2maxTime As Long 'time variable for later
Dim sgVO2Percent As Single '%VO2max
Dim sgVO2Fract As Single 'fract of VO2max
Dim sgVitCap As Single 'lung vital capacity, L
Dim sgResVol As Single 'lung residual volume, L
Dim sgVrest As Single 'resting volume set = FRC
Dim sgFuncResCap As Single 'functional residual capacity
Dim sgVO2wd As Single
Dim sgV0e As Single 'initial volume for exhalation
Dim sgV0i As Single 'initial volume for inhalation
Dim sgVERadj As Single 'VE adjustment for resistance
Dim sgVTRadj As Single 'VT adjustment for resistance
Dim sgVEVDadj As Single 'VE adjustment for dead space
Dim sgVTVDadj As Single 'VT adjustment for dead space
Dim sgVEadj As Single 'VE adjusted for R and VD
Dim sgVTadj As Single 'VT adjusted for R and VD
Dim sgVO2adj As Single 'VO2 adjusted for R and VD
Dim sgVTss As Single 'steady-state VT, L
Dim sgVEss As Single 'steady-state VE, L/min
Dim sgVO2ss As Single 'steady-state VO2, L/min
Dim sgRelAnThresh As Single 'AT in ml/kg/min
Dim sgAbsAnThresh As Single 'AT in L/min
Dim sgRespRate As Single 'respiratory rate
Dim sgTexp As Single 'exhalation time, sec
Dim sgTinsp As Single 'inhalation time, sec
```

```
 Dim sgRespAddRinh As Single 'added lung R
 Dim sgRespAddRexh As Single 'added lung R
 Dim sgRespAddVD As Single 'added lung VD
 Dim sgEpsilonE As Single 'dimensionless conversion between Texp and Tinsp
 Dim sgEpsilonI As Single 'conversion between Texp and Tinsp
 Dim sgRespPeriod As Single 'respiratory period, sec
 Dim sgRespWRexh As Single 'exh work rate for resp,W
 Dim sgRespWRinh As Single 'inh work rate for resp,W
 Dim sgRespWR As Single 'total resp work rate,W
 Dim sgRespWexh As Single 'exh work, N m
 Dim sgRespWinh As Single 'inh work, N m
 Dim sgRespW As Single 'total resp work, N m
 Dim sgPmax As Single 'max lung pressure
 Dim sgRespMuscEff As Single 'resp muscle efficiency
 'declare test parameters
 Dim sgEnvirTemp As Single 'ambient temp, C
 Dim sgRelHum As Single 'relative humidity, %
 Dim sgExtWorkRate As Single 'external work rate, W
 Dim sgTreadSpeed As Single 'treadmill speed, m/s
 Dim sgTreadGrade As Single 'treadmill grade, %
 Dim sgLoad As Single 'load carried, kg
 Dim sgTotalMass As Single 'load + subjmass + mask mass
 Dim sgTotalLoad As Single 'load + mask mass, kg
 Dim sgPhysWorkRate As Single 'physiological work rate, W
 Dim sgStepRate As Single 'step/min
 'declare respirator parameters
 Dim inRespirator As Integer 'resp worn if > 0
 Dim sgEccentricity As Single 'for later use
 Dim sgMaskRinh As Single 'inh R of mask
 Dim sgMaskRexh As Single 'exh R of mask
 Dim sgMaskVD As Single 'VD of mask
 Dim sgMaskMass As Single 'mass of mask
 Dim sgMaskP As Single 'pressure to open exh valve
 Dim sgDeltaVD As Single 'declare other variables
 Dim sgGravity As Single '9.81 m/s^2
 Dim sgMuscEff As Single 'gross efficiency
 Dim myfilename As String 'file name
 Dim mydate As String 'date
 Dim mytime As String 'time
 Dim stdummy1 As String
 Dim stdummy2 As String
 Dim inWorkFlag As Integer
 Dim sgPerfTime As Single 'performance time, min
 Dim sgMaxDeficit As Single 'max O2 deficit
 Dim sgPerfTime1 As Single 'performance time without mask, min
'Dim sgPerfdiff As Single 'performace time difference, min
```

```
    Dim sgTwd As Single ' without
    Dim sgTwd2 As Single ' with

    '*********************************************
    inWorkFlag = 0
    mydate = Date
    mytime = Time
    sgMaxDeficit = 4.03 'L, taken from Bearden and Moffatt (2000)
    sgGravity = 9.81
    sgMaskP = 59.93 'pressure to open the exhalation valve;from M17 mask
'************************************************
'write start conditions to file
'************************************************
     myfilename = "C:\Documents and Settings\Ken Chiou\Desktop\Ken model"
     Open myfilename & "init" For Output Access Write As #1
     Open myfilename & "resp1" For Output Access Write As #3
     Print #1, "Start Conditions File"
     Print #1, "Trial conducted: "; mydate, mytime
     Print #1,
"**************************************************************************"
     Print #3, "Respiratory Data #1"
     Print #3, "Trial conducted: "; mydate, mytime
     Print #3,
"**************************************************************************"
'******************************************************************
'get values for variables from the forms and write to file
'******************************************************************
    sgSubjMass = frmSetGenParams.txtSubjMass.Text
    sgSubjHt = frmSetGenParams.txtSubjHt.Text / 100
    sgBMI = sgSubjMass / (sgSubjHt ^ 2)
    sgSubjAge = frmSetGenParams.txtSubjAge.Text
    If frmSetGenParams.optFemale.Value = True Then
        sgGender = 0.85
        stdummy1 = "Female"
    Else
        sgGender = 1
        stdummy1 = "Male"
    End If
    If frmSetGenParams.optUntrained.Value = True Then
        inFitness = 0
        stdummy2 = "Untrained"
    Else
        If frmSetGenParams.optTrained.Value = True Then
            inFitness = 1
            stdummy2 = "Trained"
        Else
```

```
        inFitness = 2
        stdummy2 = "Highly Untrained"
      End If
   End If
    Print #1, "Subject Characteristics"
    Print #1, "-----------------------"
    Print #1, "Mass (kg)", sgSubjMass
    Print #1, "Height (m)", sgSubjHt
    Print #1, "Age (yr)", sgSubjAge
    Print #1, "Gender", stdummy1
    Print #1, "Fitness", stdummy2
   '********************************************
   'get thermal values
   '********************************************
   sgRestCoreTemp = frmSetThermParams.txtRestCoreTemp.Text
   If frmSetThermParams.optT1.Value = True Then
      sgTerrain = 1#
   ElseIf frmSetThermParams.optT2.Value = True Then
      sgTerrain = 1.1
   ElseIf frmSetThermParams.optT3.Value = True Then
      sgTerrain = 1.1 + 0.1 * frmSetThermParams.txtDepth.Text
   ElseIf frmSetThermParams.optT4.Value = True Then
      sgTerrain = 1.2
   ElseIf frmSetThermParams.optT5.Value = True Then
      sgTerrain = 1.5
   ElseIf frmSetThermParams.optT6.Value = True Then
      sgTerrain = 1.8
   ElseIf frmSetThermParams.optT7.Value = True Then
      sgTerrain = 2.1
   End If
    Print #1,
"****************************************************************"
    Print #1, "Thermal Inputs"
    Print #1, "----------------------"
    Print #1, "Core Temp", , sgRestCoreTemp
    Print #1, "Terrain Factor", sgTerrain
   '********************************************
   '*****  get respiratory system values
   '********************************************
   If frmSetRespParams.optMaxL.Value = True Then
      sgAbsVO2max = frmSetRespParams.txtVO2Max.Text
      sgRelVO2max = sgAbsVO2max * 1000 / sgSubjMass
   Else
      sgRelVO2max = frmSetRespParams.txtVO2Max.Text
      sgAbsVO2max = sgRelVO2max * sgSubjMass / 1000
   End If
```

```
  sgVitCap = frmSetRespParams.txtVC.Text
  sgResVol = frmSetRespParams.txtRV.Text
  sgFuncResCap = frmSetRespParams.txtFRC.Text
  sgRespMuscEff = frmSetRespParams.txtRespMuscEff.Text
  sgRespAddRinh = frmSetRespParams.txtAddInspR.Text
  sgRespAddRexh = frmSetRespParams.txtAddExpR.Text
  sgRespAddVD = frmSetRespParams.txtAddVD.Text
  Print #1,
"***********************************************************************"
  Print #1, "Respiratory Inputs"
  Print #1, "------------------"
  Print #1, "VO2 max (L/min)", , sgAbsVO2max
  Print #1, "VO2max (mL/kg/min)", , sgRelVO2max
  Print #1, "Vital Capacity (L)", , sgVitCap
  Print #1, "Residual Volume (L)", , sgResVol
  Print #1, "Functional Residual Capacity (L)", sgFuncResCap
  Print #1, "Resp. Musc. Eff. (%)", , sgRespMuscEff
  Print #1, "Additional Resp. Res. Inh. (cmH20/L/s)", sgRespAddRinh
  Print #1, "Additional Resp. Res. Exhh. (cmH20/L/s)", sgRespAddRexh
  Print #1, "Additional Resp. Dead Vol. (L)", sgRespAddVD
   '************************************************
   'get respirator information
   '************************************************
   sgEccentricity = frmSelectRespirator.txtEccentricity.Text
   If frmSelectRespirator.optM17.Value = True Then
     stdummy1 = "M17"
     inRespirator = 1
     sgMaskRinh = 3.4
     sgMaskRexh = 1.3
     sgMaskVD = 350 / 1000 'L
     sgMaskMass = 1 * sgEccentricity
   Else
     If frmSelectRespirator.optM40.Value = True Then
        stdummy1 = "M40"
        inRespirator = 1
        sgMaskRinh = 3.17
        sgMaskRexh = 1.69
        sgMaskVD = 300 / 1000 'L
        sgMaskMass = 0.7 * sgEccentricity
     Else
        If frmSelectRespirator.optOther.Value = True Then
           stdummy1 = "Other"
           inRespirator = 1
           sgMaskRinh = frmSelectRespirator.txtRinh.Text
           sgMaskRexh = frmSelectRespirator.txtRexh.Text
           sgMaskVD = frmSelectRespirator.txtRVD.Text / 1000 'L
```

```
        sgMaskMass = frmSelectRespirator.txtRMass.Text * sgEccentricity
      Else
        If frmSelectRespirator.optNone.Value = True Then
          stdummy1 = "None"
          inRespirator = 0
          sgMaskRinh = 0
          sgMaskRexh = 0
          sgMaskVD = 0
          sgMaskMass = 0
        End If
      End If
    End If
   End If
  Print #1,
"*****************************************************************"
  Print #1, "Respirator Selected"
  Print #1, "-------------------"
  Print #1, stdummy1
  If inRespirator = 1 Then
    Print #1, "Mask Inh. Res. (cmH20/L/s)", sgMaskRinh
    Print #1, "Mask Exh. Res. (cmH20/L/s)", sgMaskRexh
    Print #1, "Mask Dead Vol. (L)", sgMaskVD
    Print #1, "Mask Mass (kg)", sgMaskMass
  End If
  '********************************************
  'get test values
  '********************************************
  sgEnvirTemp = frmSetTestParams.txtEnvirTemp.Text
   sgLoad = frmSetTestParams.txtLoad.Text
   sgRelHum = frmSetTestParams.txtRelHum.Text
   Print #1,
"*****************************************************************"
   Print #1, "Test Inputs"
   Print #1, "-----------"
   Print #1, "Environ. Temp.(C)", sgEnvirTemp
   Print #1, "Rel. Humidity (%)", sgRelHum
   Print #1, "Load Carried (kg)", sgLoad
   If frmSetTestParams.optExtWR.Value = True Then
     sgExtWorkRate = frmSetTestParams.txtExtWR.Text
     inWorkFlag = 1
     Print #1, "External Work Rate (W)", sgExtWorkRate
     If inRespirator = 1 Then
       sgExtWorkRate = sgExtWorkRate * (1 + (sgMaskMass + sgLoad) / sgSubjMass)
       Print #1, "Ext. WR Adjusted for Total Load (W)", sgExtWorkRate
     End If
   Else
```

```
      If frmSetTestParams.optTreadmill = True Then
         sgTreadSpeed = frmSetTestParams.txtSpeed.Text
         sgTreadGrade = frmSetTestParams.txtGrade.Text
         sgExtWorkRate = (sgSubjMass + sgLoad + sgMaskMass) * sgGravity *
sgTreadSpeed * sgTreadGrade / 100
         Print #1, "Treadmill Speed (m/s)", sgTreadSpeed
         Print #1, "Treadmill Grade (%)", sgTreadGrade
         Print #1, "Ext. WR Adjusted for Total Load (W)", sgExtWorkRate
         inWorkFlag = 2
      Else
         If frmSetTestParams.optBike = True Then
            sgCadence = frmSetTestParams.txtCadence
            sgBikeLoad = frmSetTestParams.txtBikeLoad
            sgBikeDistance = frmSetTestParams.txtBikeDistance
            sgExtWorkRate = sgCadence * sgBikeLoad * sgBikeDistance * sgGravity / 60
            Print #1, "External Work Rate (W)", sgExtWorkRate
            Print #1, "Cadence", sgCadence
            Print #1, "Bike Load (kg)", sgBikeLoad
            Print #1, "Bike Distance per rev. (m)", sgBikeDistance
         Else
            If frmSetTestParams.optStep = True Then
               sgStepHt = frmSetTestParams.txtStepHt
               sgStepRate = frmSetTestParams.txtStepNum / 60
               sgExtWorkRate = sgStepHt * (sgSubjMass + sgLoad + sgMaskMass) *
sgStepRate * sgGravity
               Print #1, "Ext. WR Adjusted for Total Load (W)", sgExtWorkRate
               Print #1, "Step Height (m)", sgStepHt
               Print #1, "Step Rate (steps/min)", sgStepRate
            End If
         End If
      End If
    End If
    Close #1
'********************************************
    sgMuscEff = EtaMusc(sgExtWorkRate)
    sgTotalMass = sgSubjMass + sgLoad + sgMaskMass
    sgTotalLoad = sgLoad + sgMaskMass
    'If (sgTreadGrade = 0) And inWorkFlag = 2 Then
    If inWorkFlag = 2 Then
      sgPhysWorkRate = MetM(sgTerrain, sgSubjMass, sgTreadSpeed, sgTreadGrade,
sgTotalLoad)
          Else
      If sgExtWorkRate = 0 Then
         sgPhysWorkRate = 105
      Else
         sgPhysWorkRate = sgExtWorkRate / sgMuscEff
```

```
  End If
End If
If sgPhysWorkRate < 105 Then
  sgPhysWorkRate = 105
End If
If (inRespirator > 0) And (inWorkFlag = 2) Then
  sgPhysWorkRate = sgPhysWorkRate * (1 + (sgMaskMass + sgLoad) / sgSubjMass)
End If
sgVO2ss = VO2fastss(sgPhysWorkRate) 'L/min
sgVO2wd = VO2wd(sgPhysWorkRate)
sgVO2Fract = sgVO2ss / sgAbsVO2max
sgVO2Percent = sgVO2Fract * 100
sgRelAnThresh = AT(sgRelVO2max)  'ml/kg/min
sgAbsAnThresh = sgRelAnThresh * sgSubjMass / 1000
sgVEss = Vminss(sgVO2Percent, sgAbsVO2max) 'L/min
sgVTss = VTidss(sgVO2Percent, sgAbsVO2max) 'L
If inRespirator = 0 Then
  sgVEadj = sgVEss
  sgVTadj = sgVTss
  sgVO2adj = sgVO2ss
Else
  sgVERadj = VERes(sgVO2Percent, sgMaskRinh, sgMaskRexh) * 60 'L/min
  sgVTRadj = VTRes(sgVO2Percent, sgMaskRinh, sgMaskRexh) 'L
  sgVEVDadj = VEVD(sgVO2Percent, sgMaskVD) / 60  'L/min
  sgVTVDadj = VTVD(sgVO2Percent, sgMaskVD)  'L
  sgVEadj = sgVEss + sgVERadj + sgVEVDadj  'L/min
  sgVTadj = sgVTss + sgVTRadj + sgVTVDadj  'L
  sgVO2adj = VO2Adj(sgVEadj)   'L/min
End If
sgO2Deficit = O2Def(sgVO2adj, sgVO2ss) 'L/min
sgRespRate = RR(sgVEadj, sgVTadj) 'breaths/min
sgRespPeriod = 1 / (sgRespRate / 60) 'sec
sgTexp = Te(sgRespPeriod)  'sec
sgTinsp = Ti(sgRespPeriod) 'sec
sgEpsilonI = 1 + (sgTexp / sgTinsp)
sgEpsilonE = 1 + (sgTinsp / sgTexp)
If sgGender = 0.85 Then
  sgPmax = 6468
Else
  sgPmax = 9996
End If
'***** Set Rohrer coefficients
sgK1aw = 100000 'N s/m^5
sgK2aw = 10000000 'N s^2/m^8
sgK3aw = 125 'N s/m^2
sgK1lt = 40000#
```

```
    sgK1cw = 200000#
    If sgGender = 0.85 Then
      myfactor = 0.7 'if female,increase aw coefficients
    Else
      myfactor = 1
    End If
    sgK1Iaw = sgK1aw / myfactor
    sgK2Iaw = sgK2aw / myfactor
    sgK3Iaw = sgK3aw / myfactor
    'exhalation aw values are 10% higher
    sgK1Eaw = 1.1 * sgK1aw / myfactor
    sgK2Eaw = 1.1 * sgK2aw / myfactor
    sgK3Eaw = 1.1 * sgK3aw / myfactor
    sgK1I = sgK1Iaw + sgK1lt + sgK1cw
    sgK2I = sgK2Iaw
    sgK3I = sgK3Iaw
    sgK1E = sgK1Eaw + sgK1lt + sgK1cw
    sgK2E = sgK2Eaw
    sgK3E = sgK3Eaw
    'if a respirator is worn K1 and K2 values are affected
    'values are for an M17 mask
    If inRespirator > 0 Then
      sgK1I = sgK1I + 322700
      sgK1E = sgK1E + 66290
      sgK2I = sgK2I + 56090000
      sgK2E = sgK2E + 13760000
    End If
    sgCompliance = 0.000001 'm^5/N
    sgInertia = 2600 'N s^2/m^5
    sgVrest = sgFuncResCap
    'sgVC and sgRV are entered by the user
    sgV0i = V0i(sgVitCap, sgResVol, sgVTadj, sgFuncResCap, sgExtWorkRate) 'L
    sgV0e = sgV0i - sgVTadj 'L
'*********************************************
    If sgVO2Percent < 40 Then
      sgRespWRinh = SinWR2(sgK1I, sgK2I, sgK3I, sgCompliance, sgVEadj, sgVTadj, sgTinsp, sgV0i, sgVrest, 0, inRespirator, sgEpsilonI, sgMaskP)
      sgRespWRexh = HybridExp2WR(sgK1E, sgK2E, sgK3E, sgCompliance, sgVEadj, sgVrest, 1, sgEpsilonE, sgV0e, sgVTadj, sgTexp, sgMaskP, inRespirator)
      'sgRespWRinh = SinWR2(sgK1I, sgK2I, sgK3I, sgCompliance, sgVEadj, sgVTadj, sgTinsp, sgV0i, sgVRest, 0, inRespirator, sgEpsilonI, sgMaskP)
      'sgRespWRexh = HybridExp2WR(sgK1E, sgK2E, sgK3E, sgCompliance, sgVEadj, sgVRest, 1, sgEpsilonE, sgV0e, sgVTadj, sgTexp, sgMaskP, inRespirator)
    Else
      sgRespWRinh = Trap3WR(sgK1I, sgK2I, sgK3I, sgCompliance, sgVrest, sgMaskP, inRespirator, sgVTadj, sgTinsp, sgV0i, 0, sgVEadj, sgEpsilonI)
```

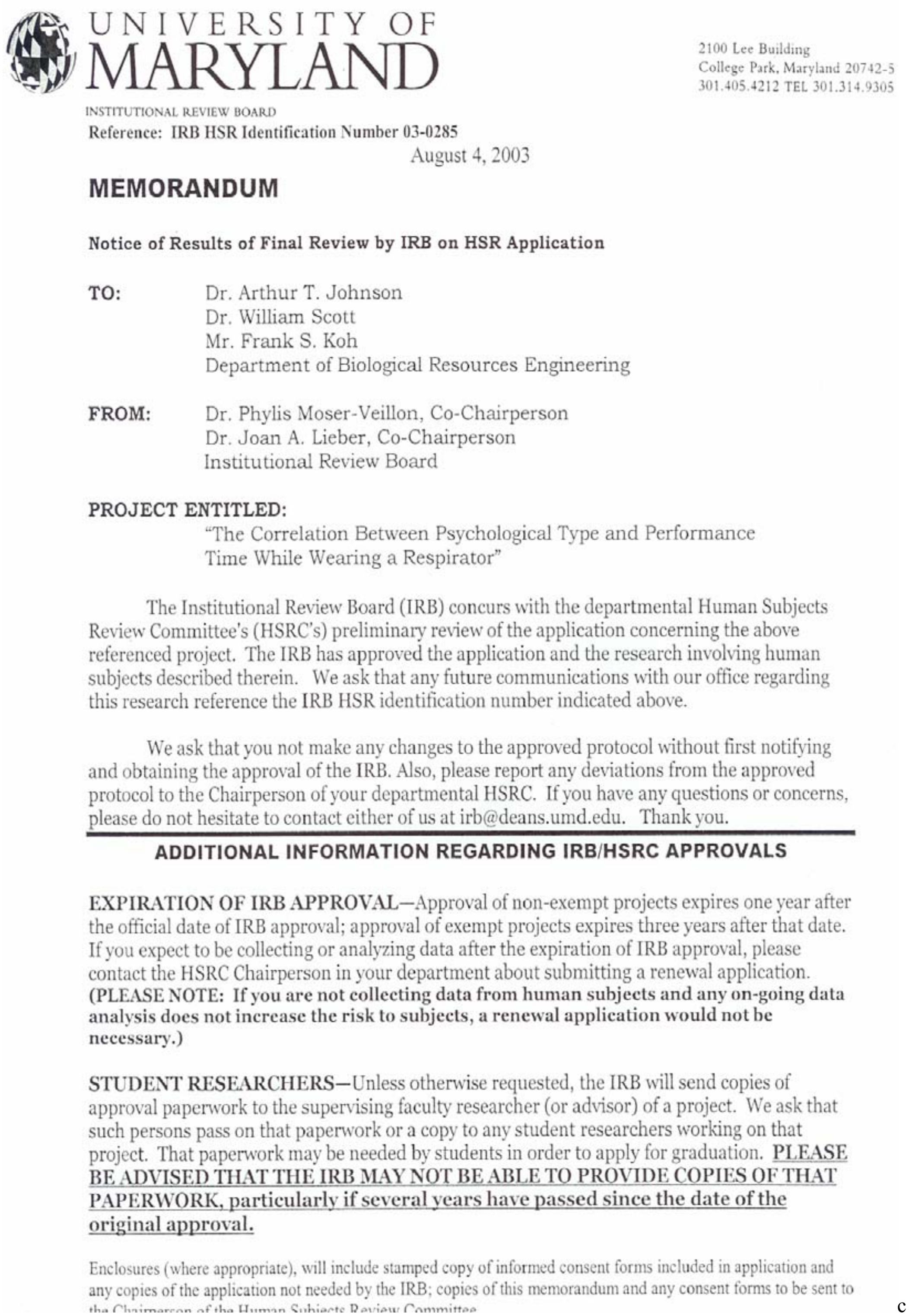
```
      'sgRespWRinh = TrapWR(sgK1I, sgK2I, sgK3I, sgCompliance, sgVRest, sgMaskP,
inRespirator, sgVTadj, sgTinsp, sgV0i, 0)
      If sgTexp < 0.66 Then
        sgRespWRexh = FlowLim2WR(sgK1E, sgK2E, sgK3E, sgCompliance, sgInertia,
sgV0e, sgVEadj, sgVTadj, sgEpsilonE, 1, sgFuncResCap, sgTexp, sgResVol, sgMaskP,
inRespirator, sgPmax, sgVitCap)
        'sgRespWRexh = FlowLim2WR(sgK1E, sgK2E, sgK3E, sgCompliance, sgInertia,
sgV0e, sgVEadj, sgVTadj, sgEpsilonE, 1, sgFuncResCap, sgTexp, sgVRest, sgMaskP,
inRespirator, sgPmax, sgVitCap)
      Else
        sgRespWRexh = Trap3WR(sgK1E, sgK2E, sgK3E, sgCompliance, sgVrest,
sgMaskP, inRespirator, sgVTadj, sgTexp, sgV0e, 1, sgVEadj, sgEpsilonE)
        'sgRespWRexh = TrapWR(sgK1E, sgK2E, sgK3E, sgCompliance, sgResVol,
sgMaskP, inRespirator, sgVTadj, sgTexp, sgV0e, 1)
      End If
    End If
    sgRespWexh = sgRespWRexh * sgTexp
    sgRespWinh = sgRespWRinh * sgTinsp
    sgRespW = sgRespWexh + sgRespWinh
    sgRespWR = sgRespW / sgRespPeriod

   sgTwd = 7200 * (sgAbsVO2max / sgVO2wd) - 7020
   sgTwd2 = 7200 * (sgAbsVO2max / sgVO2ss) - 7020
   sgTwd3 = 7200 * (sgAbsVO2max / sgVO2wd) - 7020
   If frmSelectRespirator.optM17.Value = True Then
     sgTwd2 = 7200 * (sgAbsVO2max / sgVO2ss) - 7020
    Else
      If frmSelectRespirator.optM40.Value = True Then
        sgTwd2 = 7200 * (sgAbsVO2max / sgVO2ss) - 7020
      Else
        If frmSelectRespirator.optOther.Value = True Then
         sgTwd2 = 7200 * (sgAbsVO2max / sgVO2ss) - 7020
        Else
          If frmSelectRespirator.optNone.Value = True Then
            sgTwd2 = sgTwd

          End If
        End If
      End If
    End If



   sgPerfdiff = sgTwd - sgTwd2     'difference between with mask and without mask

'*****************************************
```

```
'***** print values to screen
'********************************************
    frmMain.txtExtWR.Text = sgExtWorkRate
    frmMain.txtEff.Text = sgMuscEff
    frmMain.txtPhysWR.Text = sgPhysWorkRate

    frmMain.txtVEss.Text = sgVEss
    frmMain.txtVTss.Text = sgVTss
    'frmMain.txtVERes.Text = sgVERadj
    'frmMain.txtVTRes.Text = sgVTRadj
    'frmMain.txtVEVD.Text = sgVEVDadj
    'frmMain.txtVTVD.Text = sgVTVDadj
    'frmMain.txtVEadj.Text = sgVEadj
    'frmMain.txtVTadj.Text = sgVTadj
    'frmMain.txtVO2adj.Text = sgVO2adj
    frmMain.txtO2Def.Text = sgO2Deficit
    frmMain.txtRespRate.Text = sgRespRate
    frmMain.txtTinh.Text = sgTinsp
    frmMain.txtTexh.Text = sgTexp
    'frmMain.txtVO2Perc.Text = sgVO2Percent
    frmMain.txtAbsAT.Text = sgAbsAnThresh
    'frmMain.txtV0i.Text = sgV0i
    'frmMain.txtV0e.Text = sgV0e
    frmMain.txtWRi.Text = sgRespWRinh
    frmMain.txtWRe.Text = sgRespWRexh
    frmMain.txtWi.Text = sgRespWinh
    frmMain.txtWe.Text = sgRespWexh
    frmMain.txtTotalW.Text = sgRespW
    frmMain.txtTotalWR.Text = sgRespWR
    'frmMain.txtPerfTime.Text = sgPerfTime
    'frmMain.txtPerfTime1.Text = sgPerfTime1
    frmMain.txtPerfdiff.Text = sgPerfdiff
    frmMain.TxtVO2wd.Text = sgVO2wd
    frmMain.txtTwd.Text = sgTwd
    frmMain.txtTwd2.Text = sgTwd2
'***************************************************************
'***** write data to files
'***************************************************************
    Print #3, "External Work Rate (W)", sgExtWorkRate
    Print #3, "Gross Efficiency (%)", sgMuscEff * 100
    Print #3, "Physiological Work Rate (W)", sgPhysWorkRate
    Print #3, "Required VO2 (L/min)", sgVO2ss
    Print #3, "VE ss (L/min)", , sgVEss
    Print #3, "VT ss (L)", , sgVTss
   ' Print #3, "VE Resist. Change (L/min)", sgVERadj
    'Print #3, "VT Resist. Change (L)", sgVTRadj
```

```
    'Print #3, "VE Dead Vol. Change (L/min)", sgVEVDadj
    'Print #3, "VT Dead Vol. Change (L)", sgVTVDadj
    'Print #3, "Adjusted VE (L/min)", sgVEadj
   ' Print #3, "Adjusted VT (L)", sgVTadj
    Print #3, "Adjusted VO2 (L/min)", sgVO2adj
    Print #3, "O2 Deficit (L/min)", sgO2Deficit
    Print #3, "Respiration Rate (bpm)", sgRespRate
    Print #3, "T inh (sec)", , sgTinsp
    Print #3, "T exh (sec)", , sgTexp
    Print #3, "%VO2max", , sgVO2Percent
    Print #3, "Resp WR inh (W)", sgRespWRinh
    Print #3, "Resp WR exh (W)", sgRespWRexh
    Print #3, "Resp W inh (N m)", sgRespWinh
    Print #3, "Resp W exh (N m)", sgRespWexh
    Print #3, "Total Resp Work (N m)", sgRespW
    Print #3, "Resp Work Rate (W)", sgRespWR
    Print #3, "VO2wd (L)", sgVO2wd
    Print #3, "Twd", sgTwd
    Print #3, "Twd2", sgTwd2
     Close #3
     'frmMain.txtDoneNow.Text = "ALL DONE!"

End Sub

Private Sub cmdSelectRespirator_Click()
    frmSelectRespirator.Show
End Sub

Private Sub cmdSetPhysInput_Click()
    frmSetPhysInput.Show
End Sub


Private Sub cmdSetTestInput_Click()
    frmSetTestParams.Show
End Sub


Private Sub cmdStopParams_Click()
    frmSetStopParams.Show
End Sub

Private Sub PerfTime1_Change()

End Sub
```

```
Private Sub performancediff_Change()

End Sub

Private Sub Perfdiff_Change()

End Sub

Private Sub Label12_Click()

End Sub

Private Sub txtstartfile_Click()
   SendKeys "{Home}+{End}"

End Sub
```

IRB approval document II(03-0285)



UNIVERSITY OF
MARYLAND
INSTITUTIONAL REVIEW BOARD

2100 Lee Building
College Park, Maryland 20742-5
301.405.4212 TEL 301.314.9305

Reference: IRB HSR Identification Number 03-0285

August 4, 2003

MEMORANDUM

Notice of Results of Final Review by IRB on HSR Application

TO: Dr. Arthur T. Johnson
Dr. William Scott
Mr. Frank S. Koh
Department of Biological Resources Engineering

FROM: Dr. Phylis Moser-Veillon, Co-Chairperson
Dr. Joan A. Lieber, Co-Chairperson
Institutional Review Board

PROJECT ENTITLED:
"The Correlation Between Psychological Type and Performance
Time While Wearing a Respirator"

The Institutional Review Board (IRB) concurs with the departmental Human Subjects Review Committee's (HSRC's) preliminary review of the application concerning the above referenced project. The IRB has approved the application and the research involving human subjects described therein. We ask that any future communications with our office regarding this research reference the IRB HSR identification number indicated above.

We ask that you not make any changes to the approved protocol without first notifying and obtaining the approval of the IRB. Also, please report any deviations from the approved protocol to the Chairperson of your departmental HSRC. If you have any questions or concerns, please do not hesitate to contact either of us at irb@deans.umd.edu. Thank you.

ADDITIONAL INFORMATION REGARDING IRB/HSRC APPROVALS

EXPIRATION OF IRB APPROVAL—Approval of non-exempt projects expires one year after the official date of IRB approval; approval of exempt projects expires three years after that date. If you expect to be collecting or analyzing data after the expiration of IRB approval, please contact the HSRC Chairperson in your department about submitting a renewal application. **(PLEASE NOTE: If you are not collecting data from human subjects and any on-going data analysis does not increase the risk to subjects, a renewal application would not be necessary.)**

STUDENT RESEARCHERS—Unless otherwise requested, the IRB will send copies of approval paperwork to the supervising faculty researcher (or advisor) of a project. We ask that such persons pass on that paperwork or a copy to any student researchers working on that project. That paperwork may be needed by students in order to apply for graduation. **PLEASE BE ADVISED THAT THE IRB MAY NOT BE ABLE TO PROVIDE COPIES OF THAT PAPERWORK, particularly if several years have passed since the date of the original approval.**

Enclosures (where appropriate), will include stamped copy of informed consent forms included in application and any copies of the application not needed by the IRB; copies of this memorandum and any consent forms to be sent to the Chairperson of the Human Subjects Review Committee

c

The Correlation between Psychological Type and Performance Time while Wearing a Respirator

I, ____________________, state that I am over 18 years of age, in good physical health, and wish to participate in a program of research being conducted by Arthur T. Johnson, Ph.D., and Frank (Chong S.) Koh at the University of Maryland, College Park, Department of Biological Resource Engineering.

The purpose of this investigation is to obtain information on how much performance decrement is attributable to specific dominant character traits of the individual.

I have been provided with this informed consent document, which describes the test procedures and methods. This document must be read and signed before I am permitted to participate in this investigation. Next, I will be asked to complete a brief medical history questionnaire. An investigator will be present to review the informed consent document and medical history questionnaire and to provide any answers to questions regarding this investigation.

Information about dominant character traits will be discerned by answering questions from Keirsey Temperament Sorter II (KTS-II). Other considerations are height, weight, age, sex, respiratory resistance, overall physical condition, and CO_2 sensitivity.

I will participate in exercise testing which may require me, at my discretion, to walk or run on a treadmill. During the orientation, I will be administered the KTS-II, CO_2 sensitivity and Maximal oxygen consumptions (VO_2 max). For CO_2 sensitivity, I will be required to empty my lung of air then take a deep breath and then hold as long as possible. This procedure will be repeated twice with 60-second breaks between the first and second attempts. In addition, I will place a 6 L breathing bag over my mouth and nose normally until my discretion for termination. Every thirty seconds, I will indicate my level of anxiety on a Visual Analog Scale (VAS) with "no anxiety at all" and "the worst anxiety ever" on a scale from 1-5 every thirty seconds. VO_2 max will be determined using a standard Bruce incremental treadmill exercise protocol. My maximal fitness capacity will be ascertained from an exercise test in which the speed and grade of the treadmill is incrementally increased every three minutes until I am too tired to continue exercising.

Three test conditions will follow. In each of the three conditions, I will don a respirator and exercise on the treadmill at 80% to 85% VO_2 max until fatigue. At that time, I will inform the investigators, and the testing will terminate. Each test condition will be scheduled as to give at least a day of rest. The respirator testing period will consist of a 5-10 minute warm-up period and a testing period which in total will take about 1 hour for each condition. The respirator's inhalation resistance would be changed for each of the

Initial after reading

session. Profile of Mood States (POMS) and Speilberger State-Trait inventory will be given pre and post all conditions CO_2 sensitivity. In summary there will be 4 conditions if you include VO_2 max session.

Any information collected is confidential and will be made accessible only to those individuals directly involved in the collection and analysis of this information. All personal information will be concealed by my personal identification number, which will be used whenever references are made regarding this investigation. Confidentiality is maintained by storing this information in the office of the investigators

Because this investigation involves strenuous exercise, risk of cardiovascular stress exists; however, I will be screened prior to testing to minimize this risk. An additional risk of falling or stumbling on the treadmill exists. The investigators will be present near the treadmill while I exercise to monitor my movement and to stabilize me if needed. Further, I will be informed of any adjustments to speed or grade of the treadmill prior to the change.

This investigation will not provide any monetary or short-term benefits to its participants. Instead, it is designed to help the investigators gather information and correlate between psychological type and performance time while wearing a respirator. I am free to ask questions or withdraw from this investigation at any time without fear of penalty. I may express this desire through written or verbal communication.

The University of Maryland does not provide any medical or hospitalization insurance for participants in this research study, nor will the University of Maryland provide any compensation for any injury sustained as a result of participation in this research study, except as required by law.

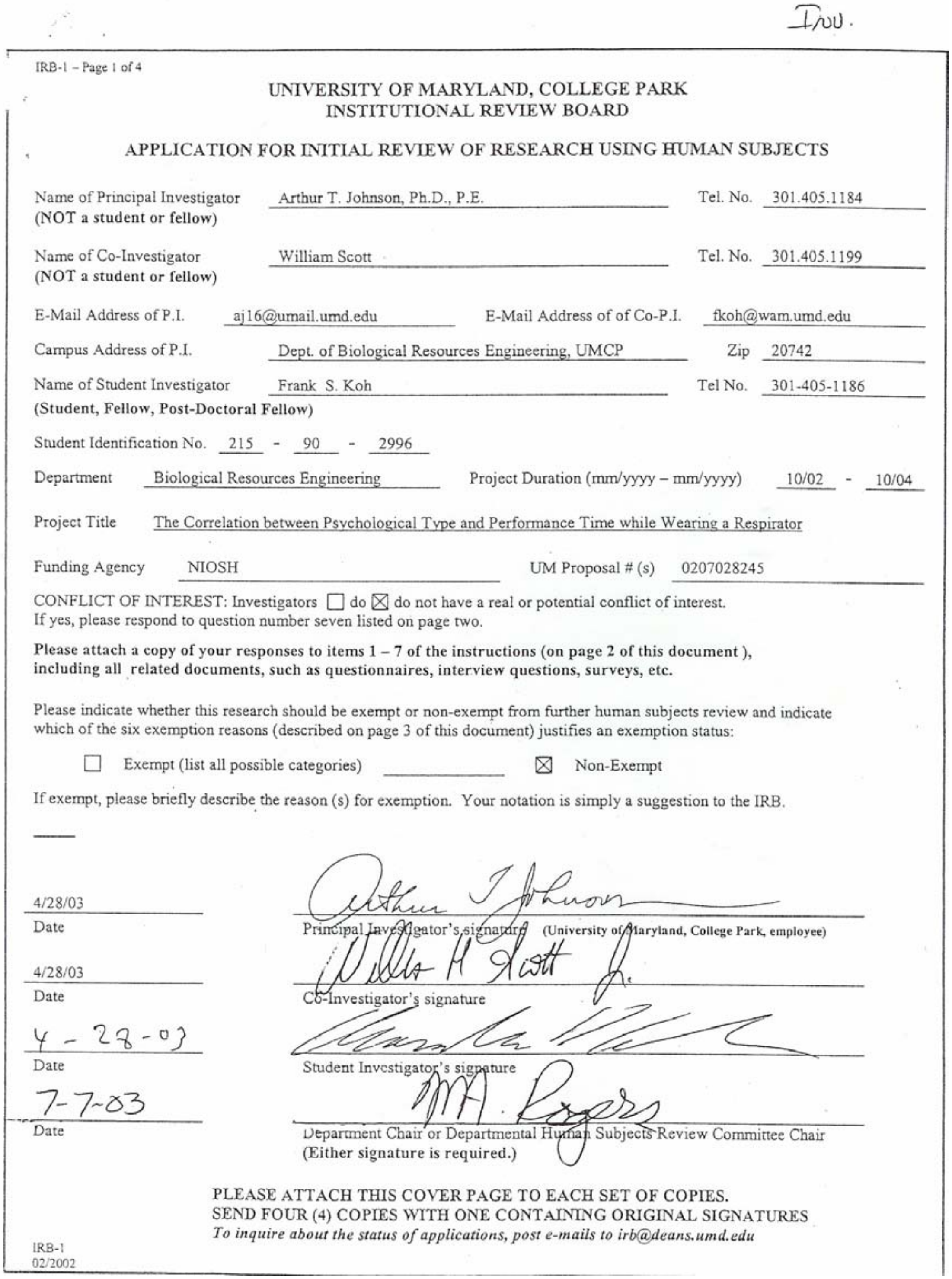
Principal investigators:
Arthur T. Johnson, Ph.D., P.E., and William H. Scott and Frank Koh
Department of Biological Resources Engineering, University of Maryland
College Park, MD 20742
(301) 405-1186

Name of subject ____________________________

Signature of subject ____________________________ Date __________________

Initial after reading ___

IRB APPROVED
VALID UNTIL
AUG 31 2004
UNIVERSITY OF MARYLAND
COLLEGE PARK



Inv.

IRB-1 – Page 1 of 4

UNIVERSITY OF MARYLAND, COLLEGE PARK
INSTITUTIONAL REVIEW BOARD

APPLICATION FOR INITIAL REVIEW OF RESEARCH USING HUMAN SUBJECTS

Name of Principal Investigator **(NOT a student or fellow)** Arthur T. Johnson, Ph.D., P.E. Tel. No. 301.405.1184

Name of Co-Investigator **(NOT a student or fellow)** William Scott Tel. No. 301.405.1199

E-Mail Address of P.I. aj16@umail.umd.edu E-Mail Address of of Co-P.I. fkoh@wam.umd.edu

Campus Address of P.I. Dept. of Biological Resources Engineering, UMCP Zip 20742

Name of Student Investigator Frank S. Koh Tel No. 301-405-1186
(Student, Fellow, Post-Doctoral Fellow)

Student Identification No. 215 - 90 - 2996

Department Biological Resources Engineering Project Duration (mm/yyyy – mm/yyyy) 10/02 - 10/04

Project Title The Correlation between Psychological Type and Performance Time while Wearing a Respirator

Funding Agency NIOSH UM Proposal # (s) 0207028245

CONFLICT OF INTEREST: Investigators ☐ do ☒ do not have a real or potential conflict of interest.
If yes, please respond to question number seven listed on page two.

Please attach a copy of your responses to items 1 – 7 of the instructions (on page 2 of this document), including all related documents, such as questionnaires, interview questions, surveys, etc.

Please indicate whether this research should be exempt or non-exempt from further human subjects review and indicate which of the six exemption reasons (described on page 3 of this document) justifies an exemption status:

☐ Exempt (list all possible categories) ☒ Non-Exempt

If exempt, please briefly describe the reason (s) for exemption. Your notation is simply a suggestion to the IRB.

4/28/03
Date

Arthur T Johnson
Principal Investigator's signature **(University of Maryland, College Park, employee)**

4/28/03
Date

Willis H Scott Jr.
Co-Investigator's signature

4-28-03
Date

Student Investigator's signature

7-7-03
Date

M.A. Rogers
Department Chair or Departmental Human Subjects Review Committee Chair
(Either signature is required.)

PLEASE ATTACH THIS COVER PAGE TO EACH SET OF COPIES.
SEND FOUR (4) COPIES WITH ONE CONTAINING ORIGINAL SIGNATURES
To inquire about the status of applications, post e-mails to irb@deans.umd.edu

IRB-1
02/2002

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