Modeling Human Performance Limitations in the Submerged Environment

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Background

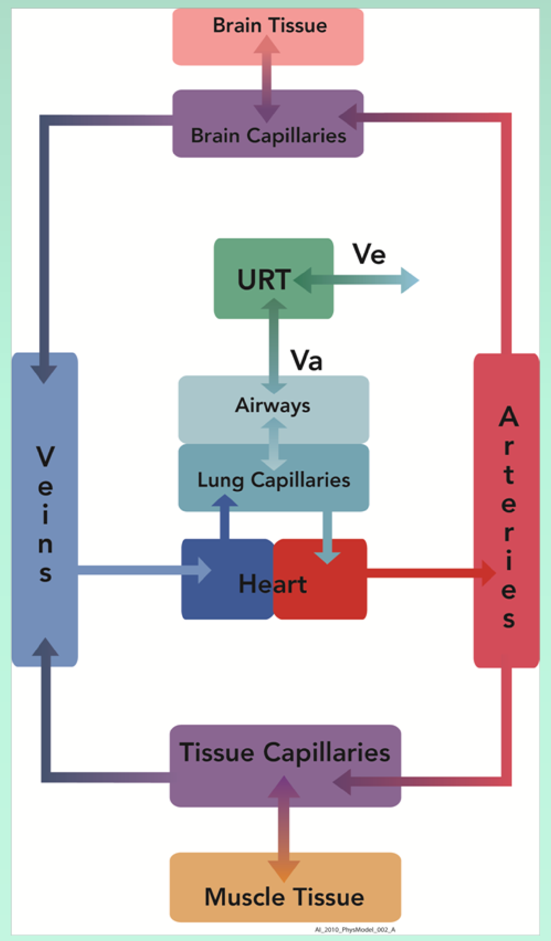
Modeling respiratory and inert gas exchange in the submerged environment is beneficial in developing predictive tools to estimate human performance limitations, as well as tracking dynamic gas concentrations relevant to diving/decompression illness. Physical performance is a function of both locomotor and respiratory muscle fatigue, and the performance-limiting factor is not easily predicted in the submerged environment where additional breathing resistance can increase the lung workload.

The purpose of this study is to develop a mathematical model capable of predicting human physical performance and fatigue limitations in a submerged environment.

Methods

Dynamic Physiology Model (DPM)

The DPM is a collection of independent physiological models integrated into a single compartmentalized mathematical model with the ability to predict the physiological impact (e.g. ventilatory response, blood gas levels, gas exchange, metabolism) caused by external stimuli (e.g. toxic gas exposure, exercise)[1]. The DPM accounts for blood circulation, tissue metabolism, pulmonary gas exchange, and ventilatory control. The pulmonary system incorporates an asymmetric branching airway structure with heterogeneous ventilation and perfusion of lung segments.



The DPM has been validated for conditions such as toxic gas exposure, exercise, temperature, and lung injury. The model is capable of predicting time-to-fatigue of locomotor muscles for various types of exercise (e.g. cycling, running) and other loading conditions.

Work of Breathing

The DPM was expanded to calculate real-time work of breathing using equations derived by Crossfill[2]. Total respiratory energy is the integration of work over time.

$$W = \frac{f}{2C}\left(\frac{\dot{V}_A}{f} + V_D\right)^2 + \frac{\pi^2 R}{4}\left(\dot{V}_A + fV_D\right)^2$$

f = frequency, C = compliance, R = resistance,

$\dot{V}_A$ = alveolar ventilation, and V_D = dead volume

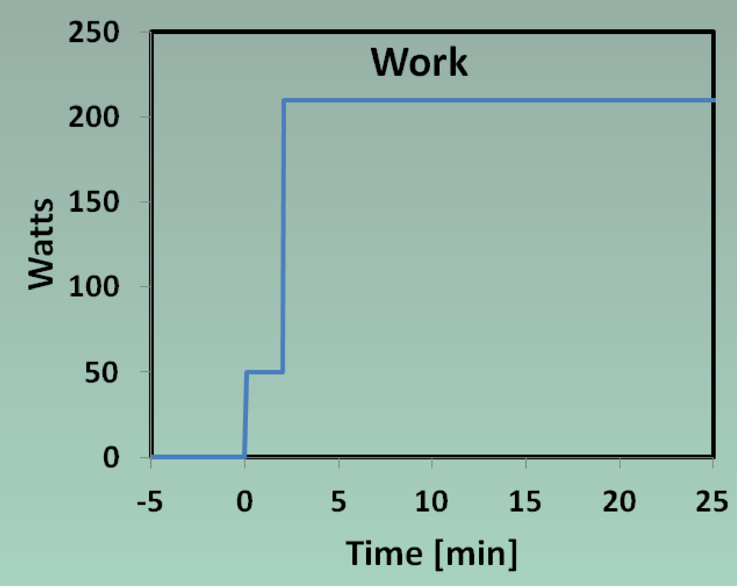
Experimental Data

Simulations were performed to match experimental conditions reported by Shykoff et al[3]. Test conditions include ergometer work in air or pure O_2, with exposure to 1, 2 or 3% CO_2 and increased breathing resistance, approximating the use of rebreathers.

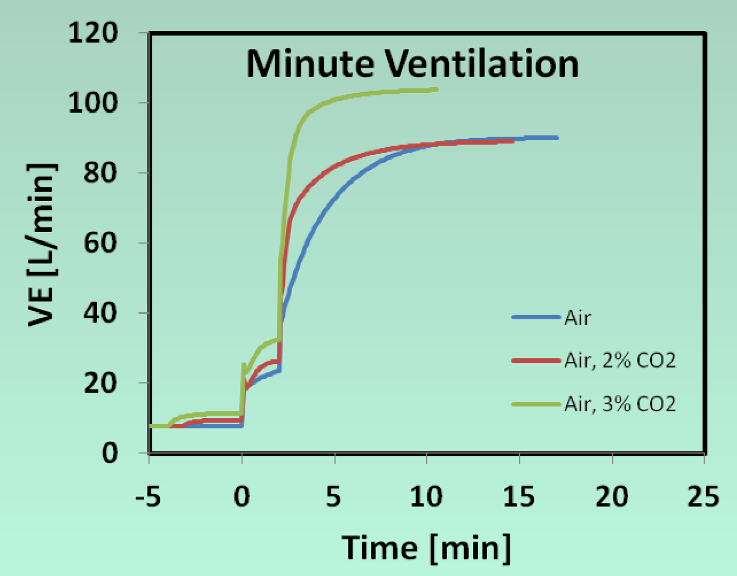
Condition	Time to Fatigue [min]	Respiratory Fatigue %
Air	17	0
Air, 2% CO_2	14.6	18.2
Air, 3% CO_2	10.5	50
Air, moderate R	18.4	45.5
Air, high R	17.5	41.7
Air, moderate R, 1% CO_2	16.6	50
Air, moderate R, 2% CO_2	14.4	75
O_2	19.2	0
O_2, moderate R	24.4	12.5
O_2, 2% CO_2	22.1	14.3
O_2, moderate R, 2% CO_2	21.1	14.3

Results

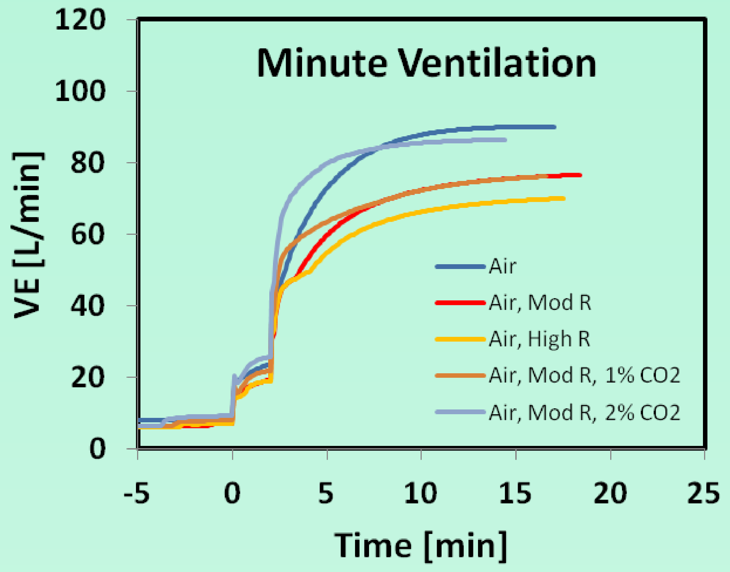
Exercise Response



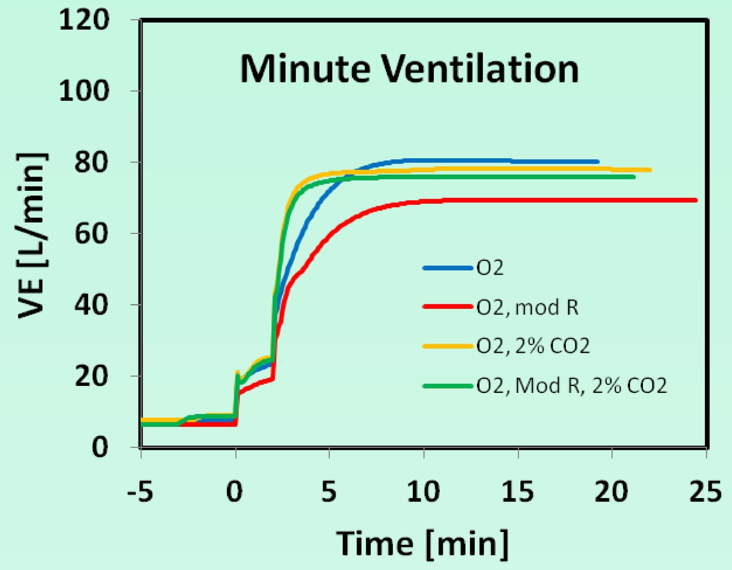
Exercise profile for simulated ergometer experiments
- 5 minute equilibration period
- 2 minute warm-up (50 Watts)
- Exercise to fatigue (210 Watts)



Transient ventilation response to exercise in air with CO_2 exposure.
- Increasing CO_2 decreases time to fatigue
- Increasing CO_2 increases minute ventilation

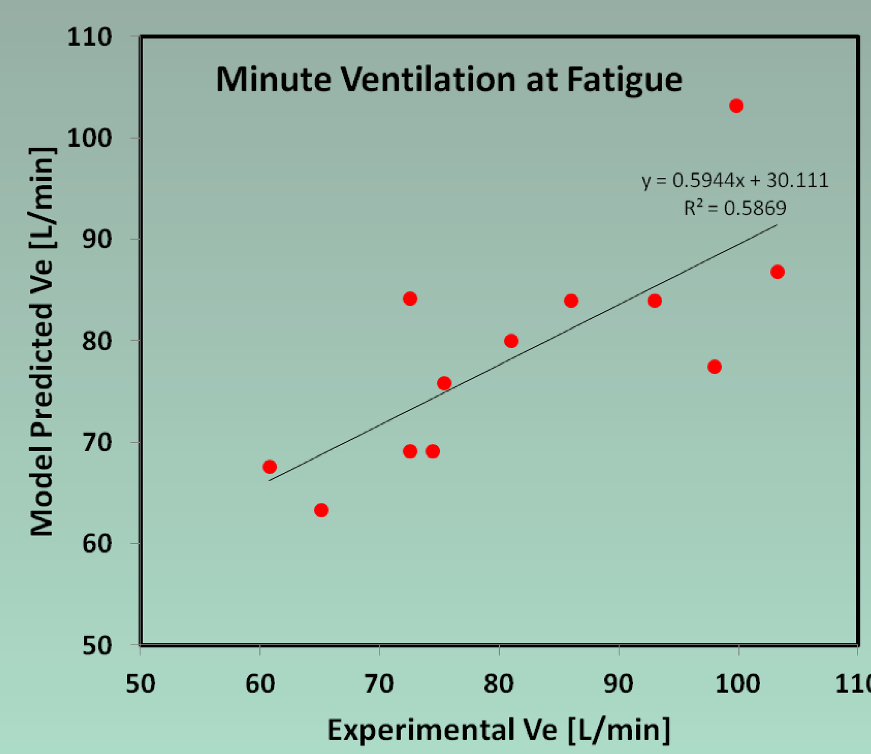


Transient ventilation response to exercise in air with increased breathing resistance and CO_2 exposure.
- Increasing resistance decreases ventilation
- Increasing CO_2 offsets the ventilation decrease from increasing resistance

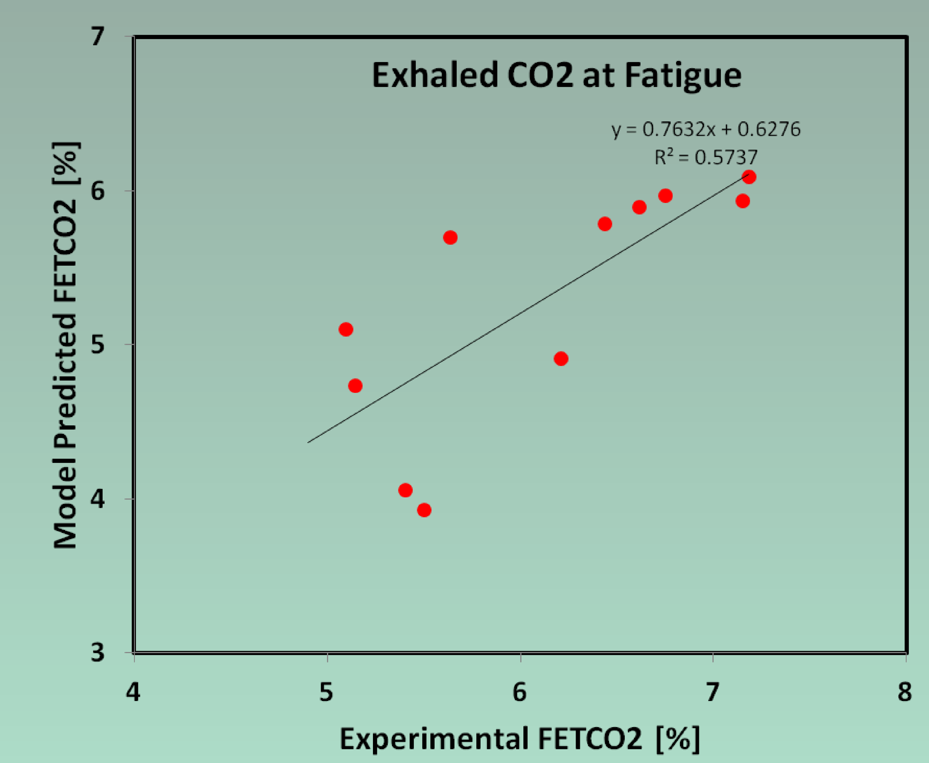


Transient ventilation response to exercise in O_2 with increased breathing resistance and CO_2 exposure.
- Increasing resistance decreases ventilation; time to fatigue is extended
- Increasing CO_2 offsets the ventilation decrease from increasing resistance

Predicted vs. Experimental Exercise Response

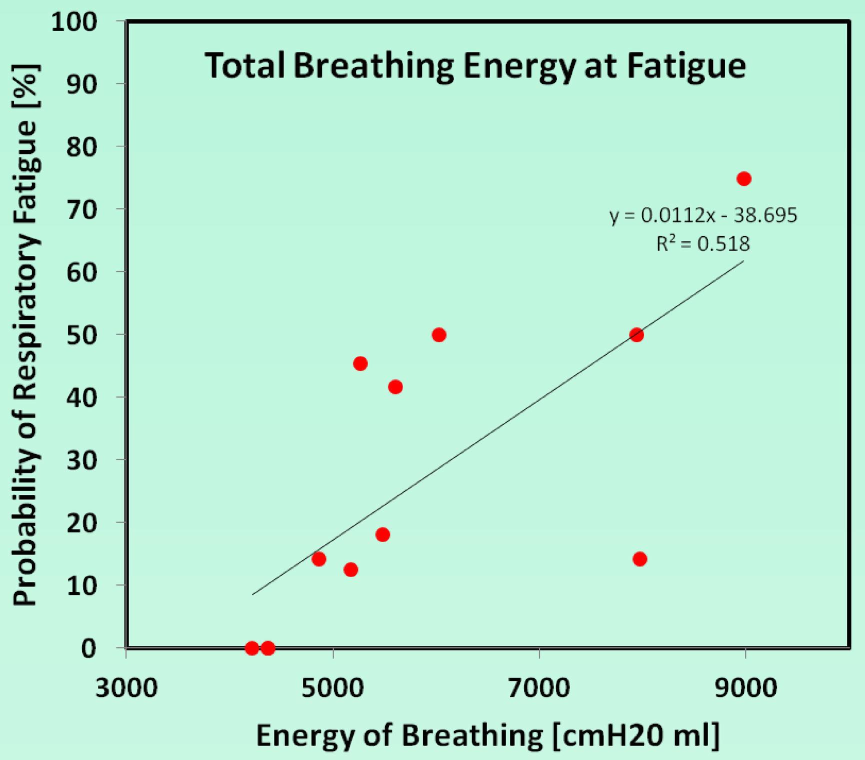


Experimental[3] vs. simulated minute ventilation at time of fatigue.
- The model predicts the trends seen experimentally under all exposure conditions
- On average the model under-predicts VE

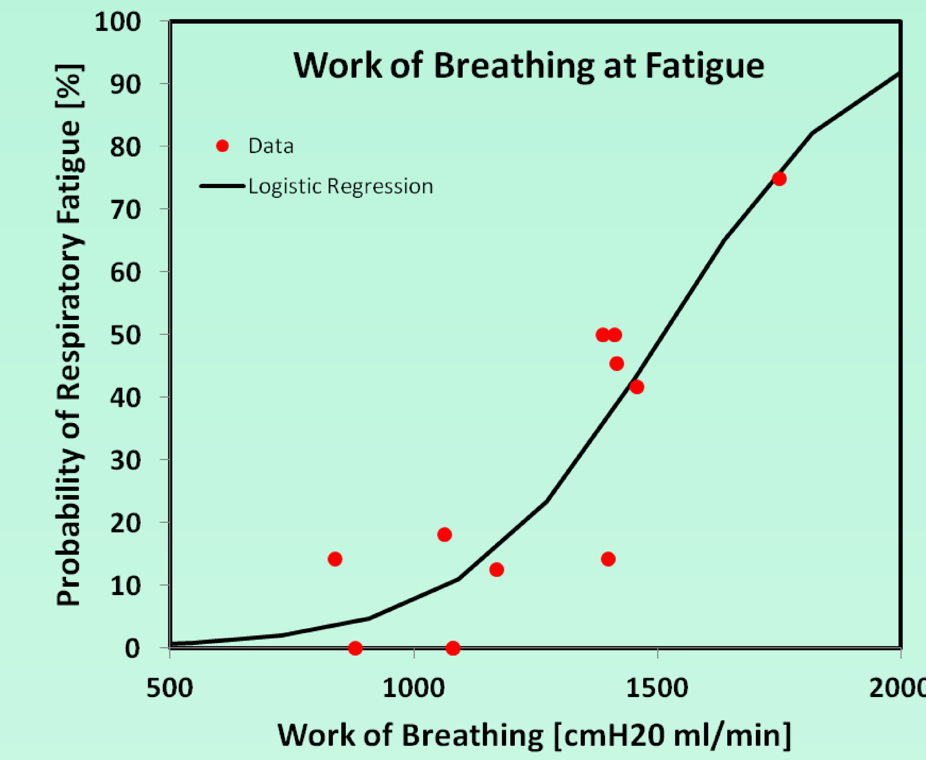


Experimental[3] vs. simulated exhaled CO_2 at time of fatigue.
- The model predicts the trends seen experimentally under all exposure conditions
- The model under-predicts exhaled CO2 fraction

Respiratory Fatigue Correlations



Probability of respiratory fatigue vs. total breathing energy
- Total respiratory muscle energy expenditure is the integral of the work of breathing
- Increased total breathing energy is associated with chance of respiratory fatigue observed experimentally



Probability of respiratory fatigue vs. work of breathing at fatigue time
- Increased WOB increases chance of respiratory fatigue ending exercise observed experimentally
- A logistic regression of the data provides a fatigue response prediction curve

Conclusions

- The DPM is able to simulate the real-time physiologic response to exercise, CO_2 exposure, and altered breathing resistance relevant to diving conditions and the use of rebreathers.
- The DPM is able to recreate trends seen experimentally in VE and FECO2 response to exercise
- Simulated work of breathing and total energy of breathing is positively associated with increased chance of respiratory fatigue ending exercise
- The DPM provides quantitative measures to identify the likelihood of respiratory fatigue following submersion
- Future work will incorporate the probability of respiratory fatigue into an individualized physical performance model to predict performance limiting conditions that are not experimentally obtainable

References

1. Shelley et al, 2014. An integrated physiology model to study regional lung damage effects and the physiologic response. Theor. Biol Med Model. Jul 21;11:32
2. Crossfill and Widdicombe, 1961. Physical characteristics of the chest and lungs and the work of breathing in different mammalian species. J Physiol, 158, 1-14.
3. Shykoff et al, 2010. Effects of carbon dioxide and UBA-like breathing resistance on exercise endurance. NEDU TR 10-03.