



# Effects of Combinations of Breathing Resistance and Inspired CO<sub>2</sub>

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# Effects at Heavy Exercise of Combinations of Breathing Resistance and Inspired CO<sub>2</sub>

or

## The Hazard Built into your Breathing Gear



With breathing gear, resistance to breathing and inspired  $\text{CO}_2$  are often both unavoidable.



# Background 1

Breathing resistance reduces endurance to heavy exercise.

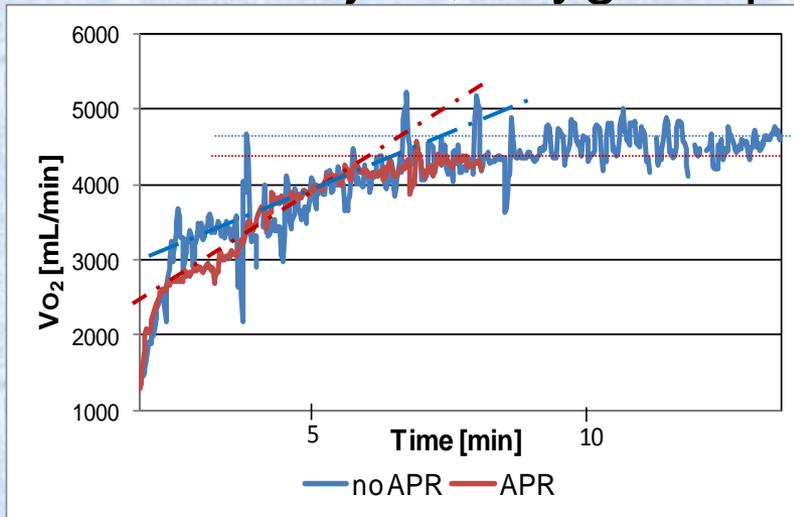
- (Craig, Blevins, and Cummings, *J Applied Physiol* 1970)
  - Uphill walking endurance time was approximately halved when the laminar breathing resistance approximately tripled.
- (Caretta and Whitley, *Ergonomics* 1998)
  - Run times at 85%  $VO_2$  max were reduced by 70% by an orifice with a large pressure drop.
- (Johnson et al., *AIHA Journal* 1999)
  - A gas mask reduced uphill walking time at 85%  $VO_2$  max. The reduction was directly proportional to the increase in inspiratory filter resistance.



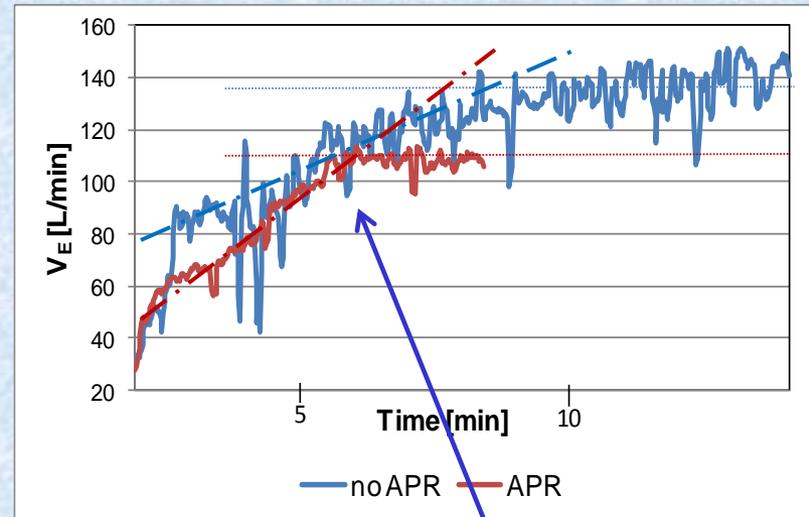
# Drift in $V_E$ , $VO_2$

(NEDU data)

Endurance running with and without APR  
One subject, oxygen uptake and minute ventilation



Rate of oxygen uptake



Respiratory Minute Ventilation ( $V_E$ )

Running at 85%  $VO_2$  max stops shortly after  $V_E$  “hits the ceiling.”



## Background 2

Inspired CO<sub>2</sub> alone may affect heavy exercise.

- (Menn, Sinclair, and Welch, *J Appl Physiol* 1970)
  - Subjects inhaling 2% CO<sub>2</sub> cycled at 67% VO<sub>2</sub> max for 30 minutes without symptoms.
  - Arterial CO<sub>2</sub> partial pressure (PaCO<sub>2</sub>) and pH at the end of exercise were more than two standard deviations from normal laboratory values.
- (Poon and Greene, *J Appl Physiol* 1985)
  - Inspired CO<sub>2</sub> steepens the increase in V<sub>E</sub> as a function of carbon dioxide production.



# Physiology Refresher, 1

- For every 10 molecules of  $O_2$  consumed, between 7 and 10 molecules of  $CO_2$  are produced and taken up by the blood.
  - 7 if fat is burned, 10 if carbohydrate is used
- $PaCO_2$ , the amount of  $CO_2$  in arterial blood, represents a balance of the rate of  $CO_2$  production in the body and the rate of  $CO_2$  removal in the lungs.
- When blood leaves healthy lungs,  $PaCO_2 =$  alveolar  $CO_2$  ( $P_A CO_2$ ). To control  $PaCO_2$ , the body adjusts  $P_A CO_2$  through breathing.
- When breathing is easy, normal  $PaCO_2$  is 40 Torr (mm Hg), standard deviation 2 Torr. Changes in  $PaCO_2$  drive ventilation.



# Physiology Refresher, 2

- Higher flow means more work of breathing, particularly in the presence of external resistance.
- If the flow is turbulent (e.g., orifice flow), pressure for flow and work of breathing increase as the square of the flow.
- If breathing is difficult, the body allows  $\text{PaCO}_2$  to rise (Milic-Emili and Tyler, 1963) to achieve the “least bad” combination of fatigue and chemical imbalance (Poon, 1987).



# Considerations for combined resistance and inspired CO<sub>2</sub>

- Inspired CO<sub>2</sub> with resistance might
  - increase work of breathing more than resistance alone and limit exercise sooner
  - might provoke hypercapnia more than resistance alone, up to dangerous levels of PaCO<sub>2</sub>.
- Hypercapnia is sometimes defined as PaCO<sub>2</sub> > 45 Torr. Clinicians call PaCO<sub>2</sub> > 50 Torr a sign of respiratory failure. Cognitive impairment has been reported at end tidal PCO<sub>2</sub> (P<sub>ET</sub>CO<sub>2</sub>) > 51 Torr (Sayers et al., 1967) .
  - P<sub>ET</sub>CO<sub>2</sub> approximates P<sub>A</sub>CO<sub>2</sub>



# Why we care: Hypercapnia symptoms

## Mild hypercapnia

- Migraine-like headache
- Increased breathing frequency
- Rapid heart rate
- Nausea, vertigo

## Severe hypercapnia

- High CO<sub>2</sub> is narcotic
  - confusion, anxiety, or euphoria
  - Drowsiness
  - Loss of consciousness

## Moderate hypercapnia

- Sweating, flushed, hot feeling
- Dyspnea
- Ringing of the ears, other CNS-type symptoms



# Hypothesis

Elevated inspired  $\text{CO}_2$  plus inspiratory and expiratory loading will reduce the duration of heavy endurance exercise more than will either inspired  $\text{CO}_2$  or resistance alone.

Breathing resistance of interest:  
loading matched to that of a rebreather underwater breathing apparatus (UBA): asymmetrical inspiratory and expiratory resistance



# Endurance cycle ergometer exercise at 85% $\dot{V}O_2$ max



R = resistance	Background air			
	Inspired $CO_2$ 0%	1%	2%	3%
Minimal R	X		X	X
Moderate R	X	X	X	
High R	X			

“Minimal” resistance (R) was that of tubes and Hans-Rudolph valves.

Expiratory  $WOB/V_T = 2$  kPa, inspiratory  $WOB/V_T = 1$  kPa

- at 100 L/min = “moderate” resistance, or
- at 80 L/min = “high” resistance



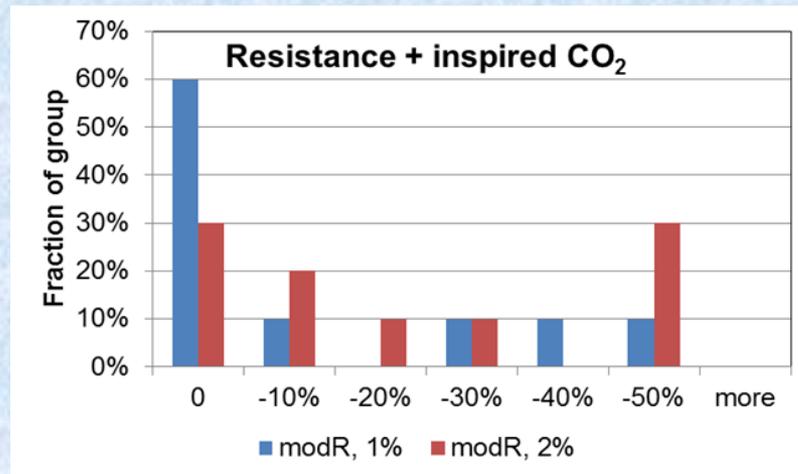
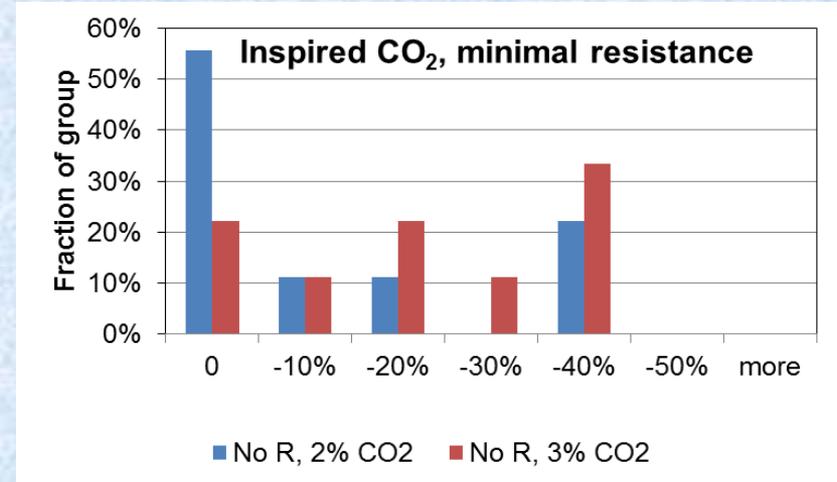
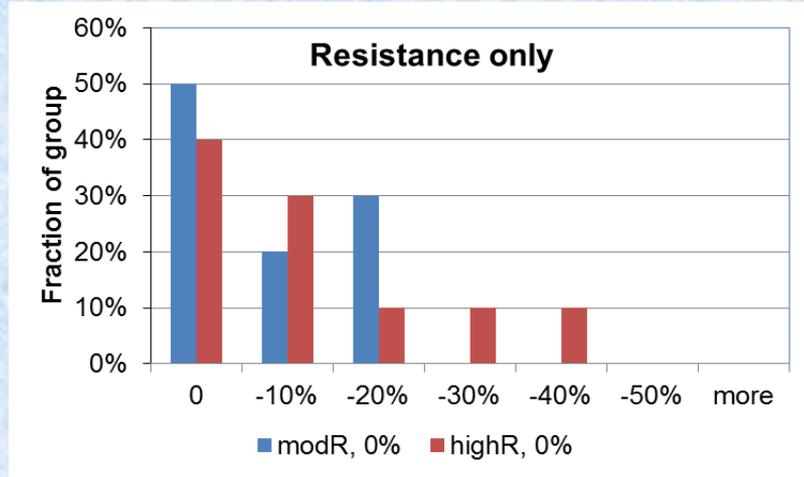
# Subject Characteristics

Experiments in air were done in two phases with different subjects

	<b>Phase 1 CO<sub>2</sub> in air, no R</b>	<b>Phase 2 CO<sub>2</sub> in air, ± R</b>
Participants finishing	10 men, 2 women	10 men, 2 women
Median values, with minimum to maximum in parentheses.		
Age (years)	35.5 (27– 40)	38.5 (32 – 47)
Height (cm)	175 (160 – 190)	173 (160 – 185)
Body mass (kg)	82 (73–107)	81 (62–107)

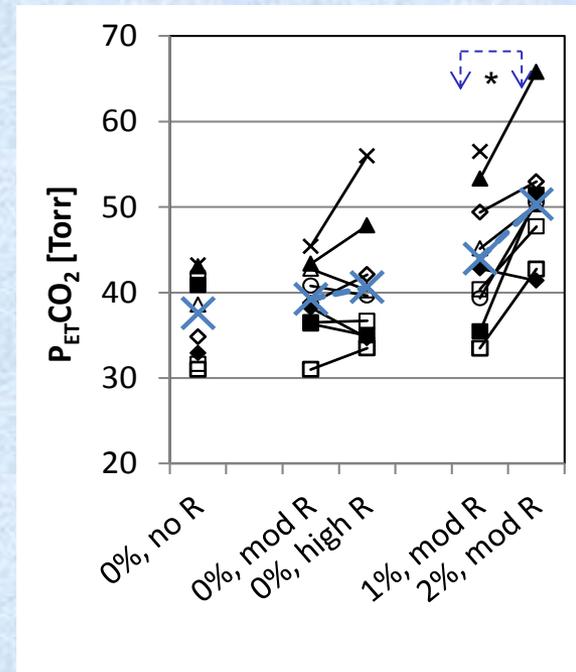
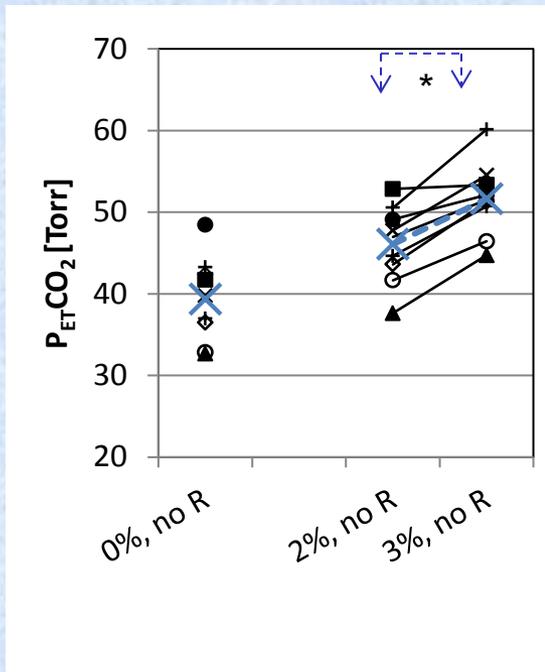


# Frequency of occurrence, reduced endurance times





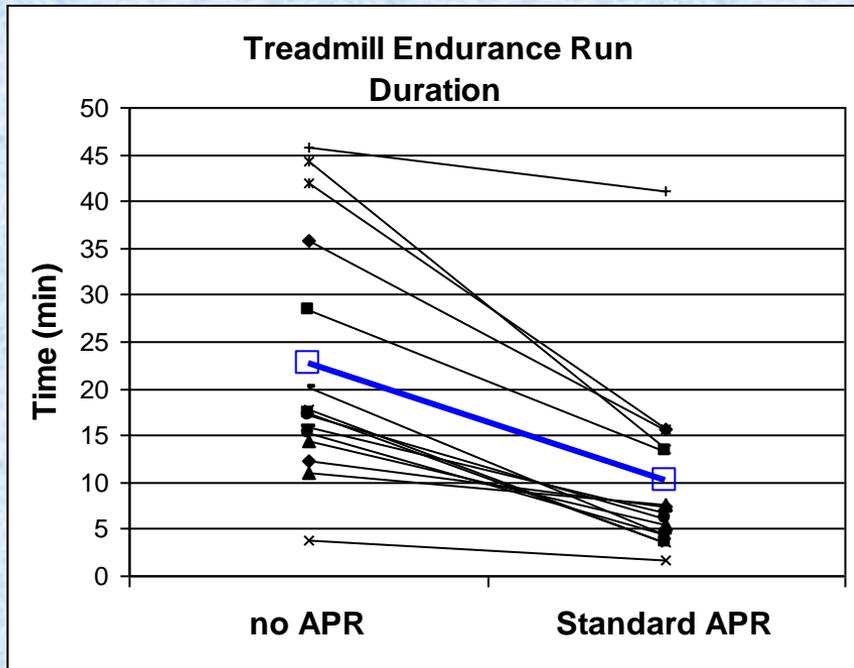
# CO<sub>2</sub> at the end of endurance cycling



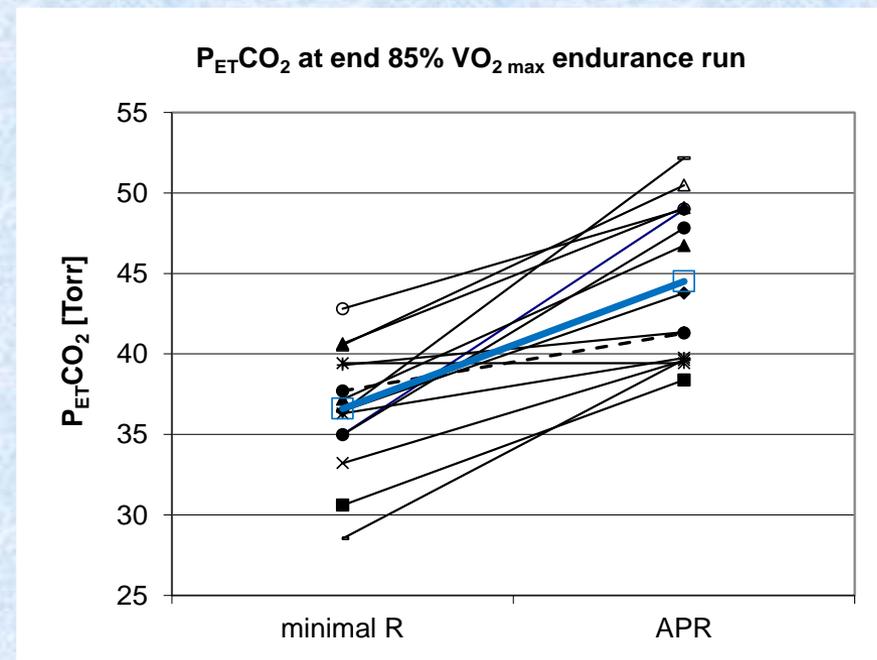
\* Indicates a significant difference from minimal R, 0% CO<sub>2</sub>



# For comparison: Treadmill running with single-filter passive APR (Different subjects)



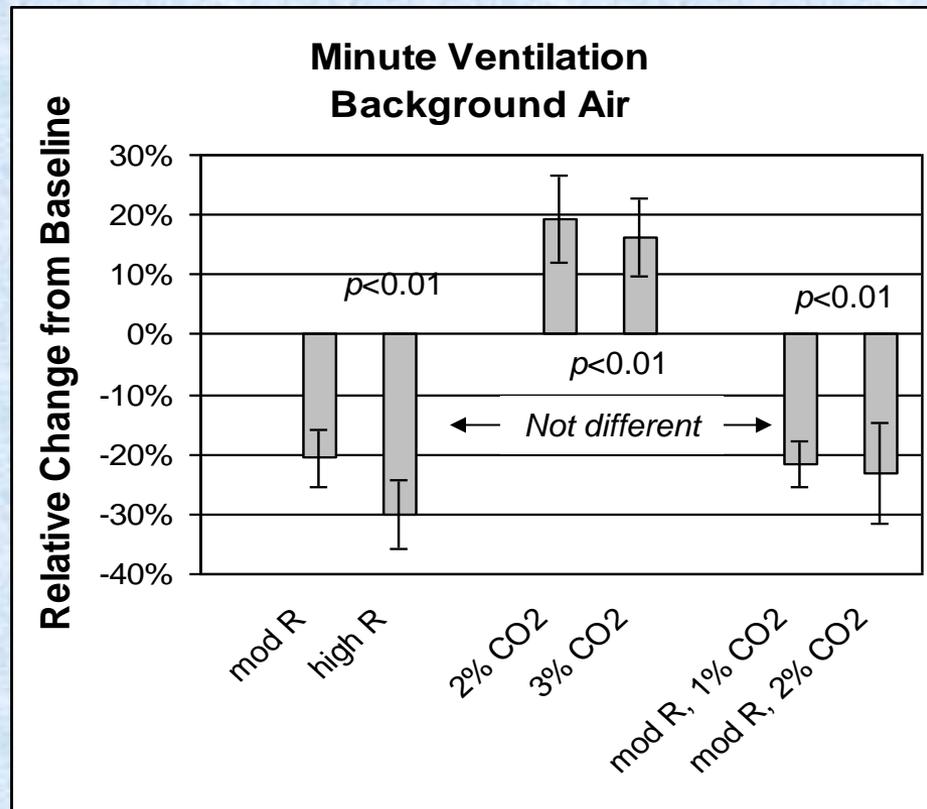
Mean decrease: 57%





# Minute ventilation at end of cycle endurance

Mean change from control. Error bars show SE.



Differences from minimal R, 0% CO<sub>2</sub>



# Symptoms reported

	# complaining about breathing	Other symptoms
Minimal R, 0% CO <sub>2</sub>	0	Headache
Minimal R, 2% CO <sub>2</sub>	2	Headache – 2 subjects Vertigo
Minimal R, 3% CO <sub>2</sub>	5	Headache Headache with “red tunnel vision” Nausea, panicky feeling
Minimal R, 0% CO <sub>2</sub>	0	
Moderate R, 0% CO <sub>2</sub>	5	
High R, 0% CO <sub>2</sub>	5	
Moderate R, 1% CO <sub>2</sub>	5	Nausea
Moderate R, 2% CO <sub>2</sub>	9	Nausea, two subjects Headache and vertigo headache and tunnel vision



# Contingency tables, hypercapnia and symptoms

Moderate R, 2% CO<sub>2</sub> in air

	$P_{ET}CO_2 \geq 50$ Torr	$P_{ET}CO_2 \geq 50$ Torr
Symptoms	3	0
No symptoms	4	4

Symptoms mean hypercapnia;  
lack of symptoms means nothing



# Summary 1

In air with moderate resistance and 2% inspired CO<sub>2</sub>

- More people had a reduction in endurance time to heavy exercise and some had a larger reduction than with either load alone.
- P<sub>ET</sub>CO<sub>2</sub> was higher than with either load alone.
  - Half the subjects reached P<sub>ET</sub>CO<sub>2</sub> > 51 Torr, and two exceeded 59 Torr.
- V<sub>E</sub> was unchanged from that with moderate resistance alone
  - much lower than with 2% inspired CO<sub>2</sub> alone.
- More people complained about difficulty breathing than with either load alone.



# Summary-- addendum

With O<sub>2</sub>, with moderate resistance and 2% inspired CO<sub>2</sub>

- The reduction of exercise endurance time was less marked than it was with an air background.
- Mean P<sub>ET</sub>CO<sub>2</sub> was similar to that with background air.
  - Seven of 12 subjects reached P<sub>ET</sub>CO<sub>2</sub> > 51 Torr.
- V<sub>E</sub> was similar to that with baseline air:
  - higher than that with resistance alone and
  - lower than that with 2% inspired CO<sub>2</sub> alone.
- Symptom did not differ from those with background air, except that fewer people noted difficulty breathing.



# Conclusions

- Reported symptoms tell you that a person has a problem; no symptoms indicate only that a person has no symptoms.
- At heavy exercise, although inspired  $\text{CO}_2$  alone increases breathing, resistance depresses breathing even with inspired  $\text{CO}_2$ .
- The combination of heavy exercise, moderate resistance and 2% inspired  $\text{CO}_2$  is dangerous.



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