Issues affecting the accuracy of Metabolic Carts

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Qualifications

Biophysics / Instrumentation

- Consultant Sport Technologist
- Athletics Coach

Background

- **Queen Victoria Medical Centre:** Biomedical Engineer intern.
- **Australian Institute of Sport**: Technical Officer intern.
- **Bionic Ear Institute:** Senior Technical Officer.
- **Victoria Uni. Human Perf. Lab:** Senior Technical Officer.
- **Uni. Of Limerick, Sports Institute**: Chief Technical officer.

Key Topics

- The most important issues affecting accuracy
- How metabolic sensors work and comparing them
- Accumulating errors! How to handle them?
- Mathematical error on your systems (LJMU)
- Mixing chamber versus Breath by Breath systems

Physical Measurements Needed

1. O2 – for both inspiratory & expiratory air
2. CO2 – for both inspiratory & expiratory air
3. Volume or Flow
4. Temperature – for BTPS and STPD correction
5. Pressure – for BTPS and STPD correction
6. Room Humidity – for BTPS and STPD correction
7. Time
8. Sample Humidity – metabolic gas displacement

Variables Affecting Accuracy

- O_2 Measurement error
- CO_2 Measurement error
- Volume Measurement error
- Calibration Gas errors
- Human Sample Humidity
- Breath by Breath issues
- Gas Sampling Time Delay
- Temperature Measurement
- Pressure Measurement
- Room Relative Humidity Measurement
- Subject Preparation
- Time Measurement
- Testing Environment
- Operator Initiated error

The sensor errors examined (what is important?)

+1% rel. error	% VO2
Oxygen* (0.17 % absolute)	-6.46
O2 Cal. gas	-6.46
Ventilation*	+1.00
Atmosph. Press.	+1.01
Carbon Dioxide*	-0.23
Room Temp.	-0.07
Room Humidity	-0.02
Sample water* vapour, 30%	+5.54

typ.% error
0.05 - 1.0
0.1 - 0.9
1-3
0.05
0.3
0.1
1.0
0 to 90%?

Christopher J. Gore, Rebecca K. Tanner, Kate L. Fuller and Tom Stanef (Australian Institute of Sport)

Reference values:

VO2 = 4.5495

VI STPD =136.10

VE STPD = 136.70

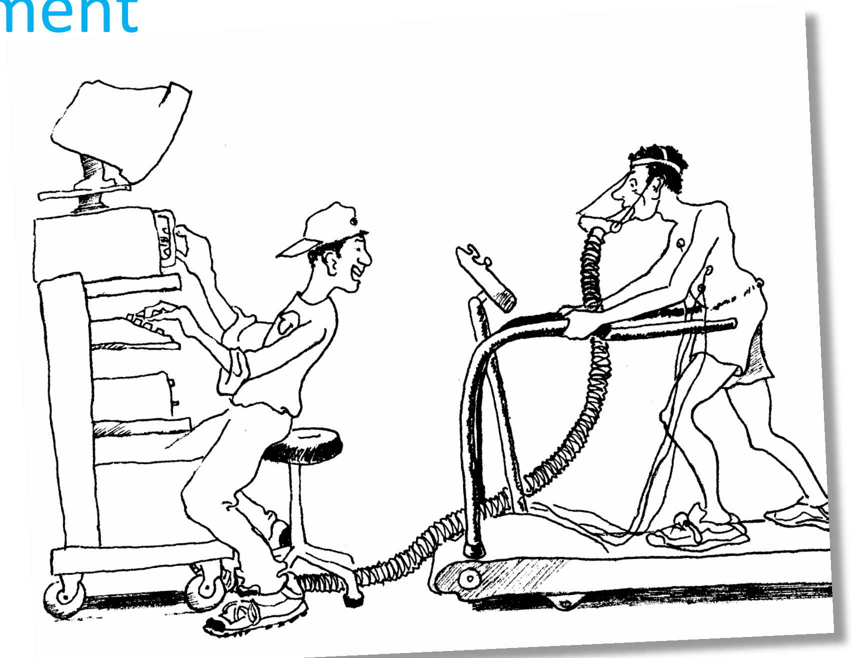
FIO2 = 0.1751%

O2 = 0.2093%

* Human sample

Most important factors

- O2 sensor
- Calibration gas
- Volume or Flow Measurement
- Gas Sample Humidity
- Breath by Breath issues
- Gas sampling delays



Room temperature, pressure, humidity and subject CO_2.

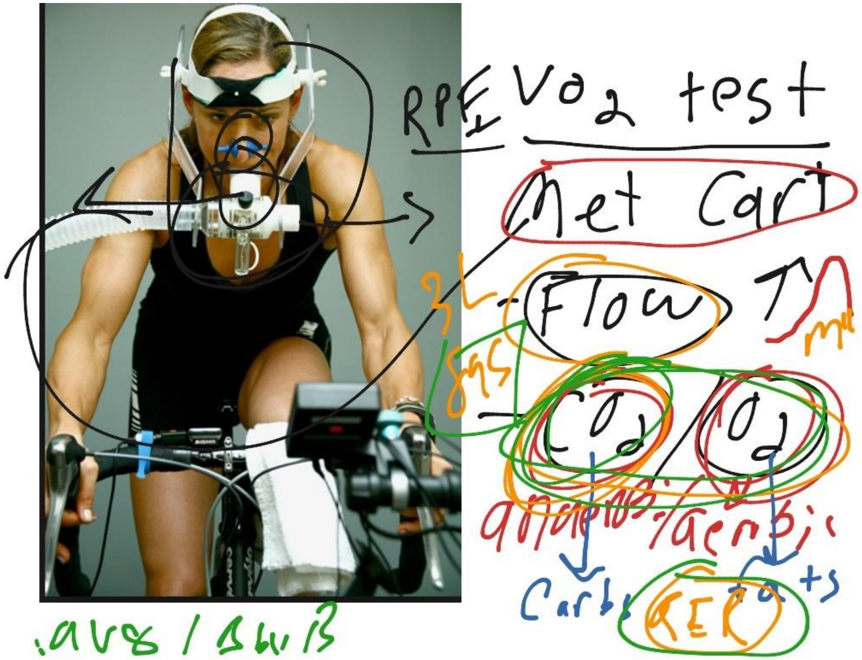
A 1% error I barometric pressure will result in a 1% error in VO_2 but the likely error is only 0.05%...so not really a contender as a problem.

Room temp, humidity and subject CO_2 even less...so relax about these!

O2 Measurement Errors

Oxygen Analyser:

accuracy errors – **we'll examine this only**
calibration errors
stability errors
response time errors



Gas Analyser Error Example
(next is cal gas error)

Utilise the textbook equations:

$$VO_2 = (Vi * fiO_2) - (Ve_{avg} * feO_2);$$

$$VCO_2 = (Ve * feCO_2) - (Vi_{avg} * fiCO_2);$$

Where $Ve = Vi * (100 - fiO_2 - fiCO_2) / (100 - feO_2 - feCO_2)$ [Haldane transform]

Or $$(Ve * feN_2) = (Vi * fiN_2)$$

Volume N2 expired = Volume N2 inspired

Assume all other errors are zero.

Error Example – Gas Analyser 1

Expected Values		Worst Case Values	
fiO2	20.93	fiO2	21.03
fiCO2	0.03	fiCO2	0.13
feO2	17.00	feO2	16.90
feCO2	4.00	feCO2	3.90
Haldane	1.00	Haldane	1.00
Vi (L/min)	150.00	Vi (L/min)	150.00
Ve	150.08	Ve	149.32
VO2	5.88	VO2	6.31
VCO2	5.96	VCO2	5.63
RER	1.01	RER	0.89

O2 Accuracy = 0.1% absolute
CO2 Accuracy = 0.1% absolute

Gas Analyser Error Contribution	
VO2 % Error	7.28
VCO2 % Error	-5.53
RER % Error	-11.94

Credit: Mr. Phil Loeb, CEO, AEI Technologies.

Error Example – Gas Analyser 2

Expected Values		Worst Case Values	
fiO2	20.93	fiO2	20.94
fiCO2	0.03	fiCO2	0.05
feO2	17.00	feO2	16.99
feCO2	4.00	feCO2	3.98
Haldane	1.00	Haldane	1.00
Vi (L/min)	150.00	Vi (L/min)	150.00
Ve	150.08	Ve	149.96
VO2	5.88	VO2	5.93
VCO2	5.96	VCO2	5.89
RER	1.01	RER	0.99

O2 Accuracy = 0.01% absolute
CO2 Accuracy = 0.02% absolute

Gas analyser Error Contribution	
VO2 % Error	0.84
VCO2 % Error	-1.08
RER % Error	-1.91

Credit: Mr. Phil Loeb, CEO, AEI Technologies.

Analysis & Conclusions – (Analysers)

Metabolic Carts utilising less accurate gas analysers may result in data far outside of acceptable limits.

A very small error in Oxygen sensor/analyser will result in a very large error in VO2.

Calibration Gas Error Examples

Utilise the textbook equations:

$$VO_2 = (V_i * fiO_2) - (V_e * f_eO_2);$$

$$VCO_2 = (V_e * f_eCO_2) - (V_i * f_iCO_2);$$

$$\text{Where } V_e = V_i * (100 - f_iO_2 - f_iCO_2) / (100 - f_eO_2 - f_eCO_2)$$

[Haldane transform]

Assume all other errors are zero.

Calibration Gas Error Example 2

Gases - Expected Values		Worst Case Values	
O2 (High)	20.93	O2 (High)	20.93
O2 (Low)	16.00	O2 (Low)	15.20
CO2 (High)	4.00	CO2 (High)	4.20
CO2 (Low)	0.03	CO2 (Low)	0.03
fiO2	20.93	fiO2	20.93
fiCO2	0.03	fiCO2	0.03
feO2	17.00	feO2	16.20
feCO2	4.00	feCO2	4.20
Haldane	1.00	Haldane	0.99
Vi (L/min)	150.00	Vi (L/min)	150.00
Ve	150.08	Ve	148.94
VO2	5.88	VO2	7.27
VCO2	5.96	VCO2	6.21
RER	1.01	RER	0.85

1 Cal Gases Utilised:
uncertainty = 5% relative

Cal Gas Error Contribution	
VO2 % Error	23.53
VCO2 % Error	4.24
RER % Error	-15.61

5% relative error
Eg.
= 17 O2 x 0.05
= 0.875 % absolute error.

Calibration Gas Error Example 1

Gases - Expected Values		Worst Case Values	
O2 (High)	21.00	O2 (High)	21.02
O2 (Low)	16.00	O2 (Low)	15.98
CO2 (High)	4.00	CO2 (High)	3.98
CO2 (Low)	0.03	CO2 (Low)	0.03
fiO2	20.93	fiO2	21.03
fiCO2	0.03	fiCO2	0.13
feO2	17.00	feO2	16.90
feCO2	4.00	feCO2	3.90
Haldane	1.00	Haldane	1.00
Vi (L/min)	150.00	Vi (L/min)	150.00
Ve	150.08	Ve	149.32
VO2	5.88	VO2	6.31
VCO2	5.96	VCO2	5.63
RER	1.01	RER	0.89

2 Cal Gases Utilised:
uncertainty = 0.02% absolute

Cal Gas Error Contribution	
VO2 % Error	1.35
VCO2 % Error	-0.58
RER % Error	-1.90

Credit: Mr. Phil Loeb,
CEO, AEI Technologies.

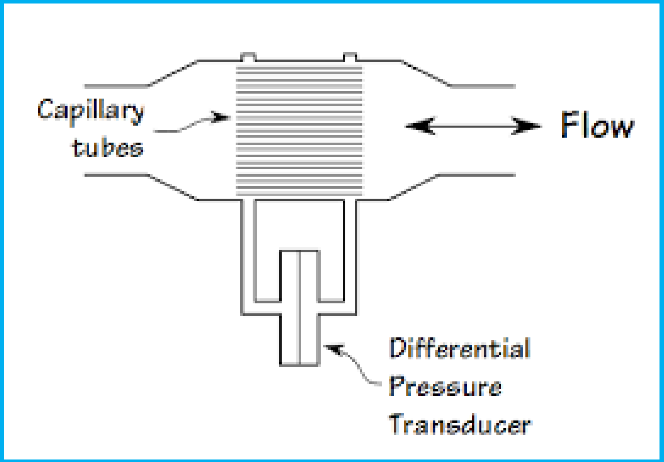
Analysis & Conclusions – (cal. Gas)

Metabolic Carts utilising less accurate calibration gas may result in data far outside of acceptable limits.

A very small error in Oxygen sensor/analyser will result in a very large error in VO2.

Flow or Ventilation Errors

Pneumotach



<1 - 2%

Very fast

Douglas Bag

Tissot tank

1% ?

Very slow

Turbine

1 - 3%

Inertial error

1% Ve or Vi error = 1% VO2 error

Analysis & Conclusions – (ventilation)

The error in ventilation in a metabolic system is directly translated into VO_2 error.

So a 1% error in Ve or Vi will result in a 1% error in VO_2.

2-3% ventilation error high for elite athletes or research.

Water Vapour / sample humidity
(Effects on the O_2 sensor)

An increase in sample water vapour displaces expired gases O_2, CO_2, N_2.

(less expired O_2…system thinks body metabolised this)

This artificially raises the VO_2 value.

30% water vapour raises VO_2 error to 5.54%.(Gore et.al)

We need an excellent drying system to handle this.

With multiple tests one after the other, drying systems don’t recover very quickly.

Water Vapour / sample humidity

(effects on the CO_2 sensor)... Credit: Ian Fairweather

Infra Red CO_2 sensors problems differentiating CO_2 and H20
- wavelength chosen to minimise: effects remain

Despite H_2O diluting the effect of CO_2 presence:
- analyser will report increased CO_2. VCO_2, RER, etc.

CO_2 analysers use a heated crystal window to minimise
- Condensation still occurs

Windows fogs or droplets form:
CO_2 level detected will change radically
- the IR may be virtually blocked
- giving impression very large amounts CO_2 re present

Water Vapour / sample humidity
(water droplets in the sample line)

- **Very wet gases in sample line:**
  Eventually condensation inside sample lines:
  - especially short nafion tubes:
  (not changed or dried well between tests)

- **If water droplets form (can be serious):**
  Some O2 cells operate extreme temperatures:
- -destroy sensor

- **More likely water droplets occlude gas flow**

- **All gas analysers sensitive to flow**
  - their calibration can vary wildly if the flow changes

- **Most have "flow controls" which regulate**
  (however not all effective)
  - especially if flows not constant
  - cant respond to sudden flow changes

Water Vapour / sample humidity (Solutions)

- Peltier device (cooling)
- Nafion tubing
- Drying crystals
- Drying Crystals cause huge varied phase delays
  - Drying crystals surrounding Nafion do not.

<u>All the above leaves us with uncertainty so:</u>

- Humidity sensors before gas sensors – would solve issues. (these cost a few Euros each)

Nafion Tubing Issues

- Nafion absorbs 22% by weight of water
- Absorbs 13 molecules H_2O for every sulfonic acid group
- Cant absorb more humidity than external tubing (use Peltier to cresate 0% RH)
- Sulphuric acid may corrupt gas samples (Nafion = Teflon + Sulphuric acid)
- O2 and N2 also pass but lower %.
- Issues with long tests (Sulphuric acid saturated) (50% capacity at 25 min, 10% capacity at 45min)

Analysis & Conclusions – (H20 vapour)

It a bugger !

- Use Dryer (Peltier or crystals)
- Use nafion
- Change nafion every 3-6 months and between many tests.
- Use Humidity sensor and compensate O2/CO2 sensor values.
  (almost no commercial systems do)

Breathing valve shape

Hans Rosdahl et. al. 2017

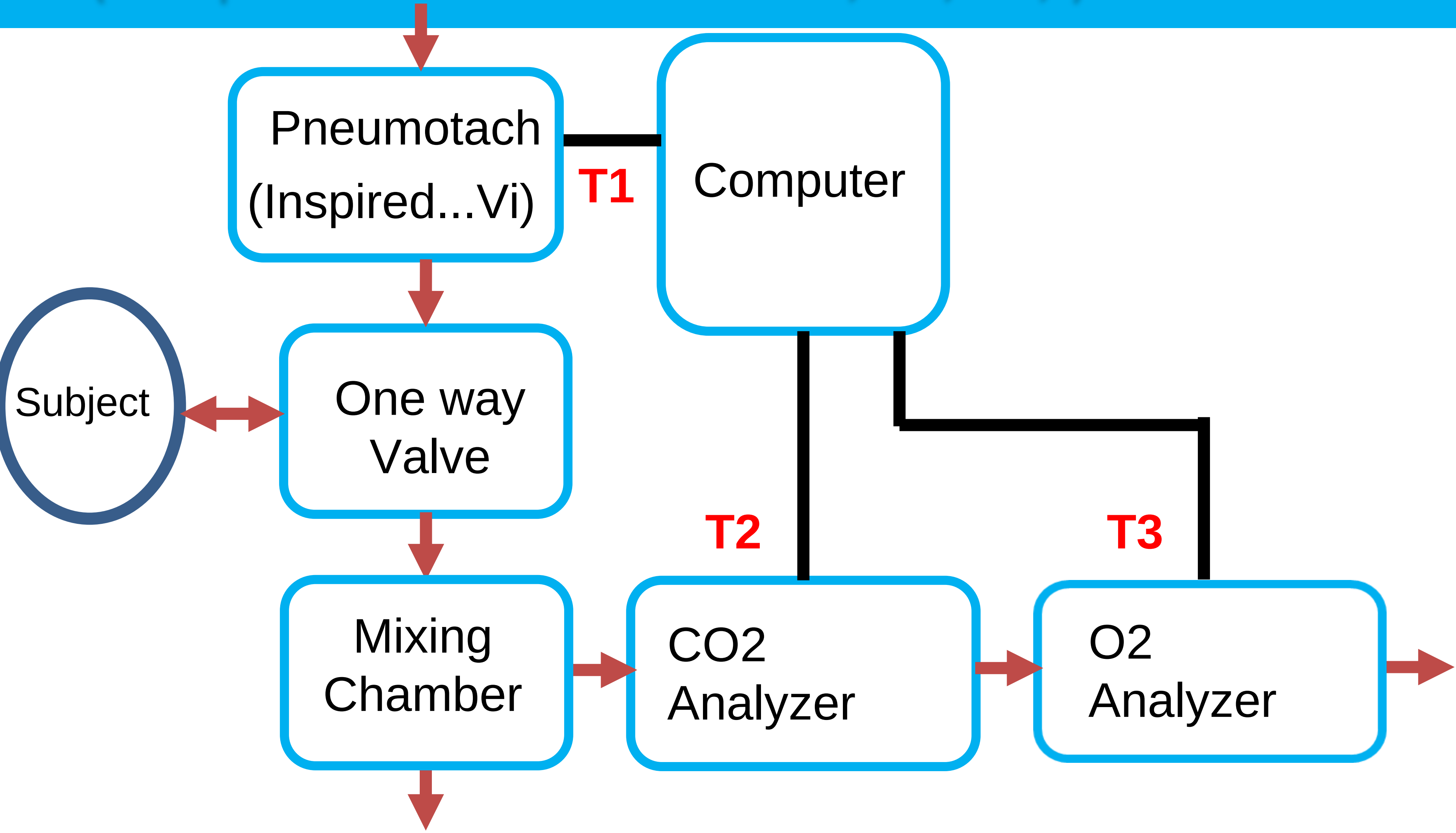
(Ian Fairweather 1990's)

- T shaped (typical) breathing valve create non laminar flow (increase errors)

- Use Y shaped breathing valve

Phase delays

(sample time differences...T1, T2, T3,)



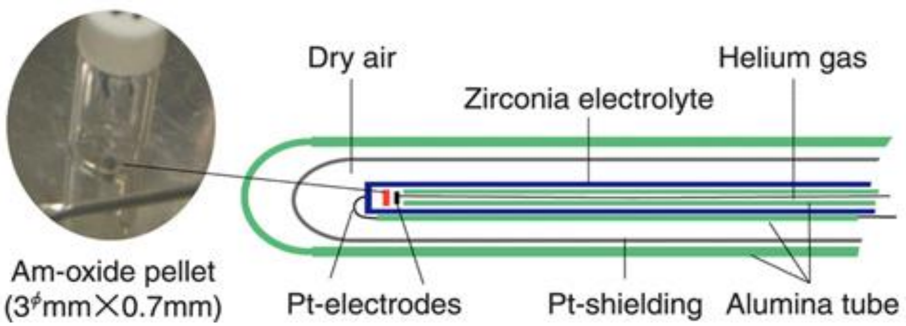
O2 Sensors
(most critical sensor!)

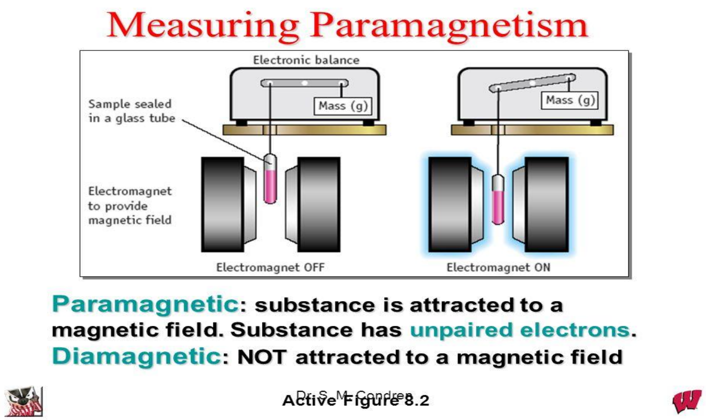
Zirconia

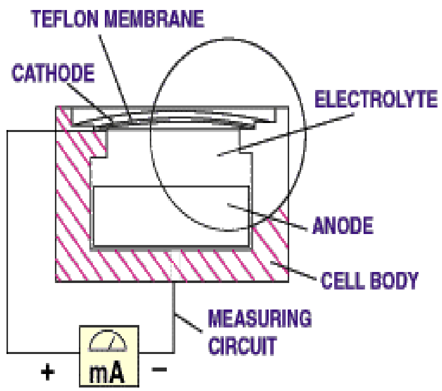
Paramagnetic

Galvanic

others (not used)



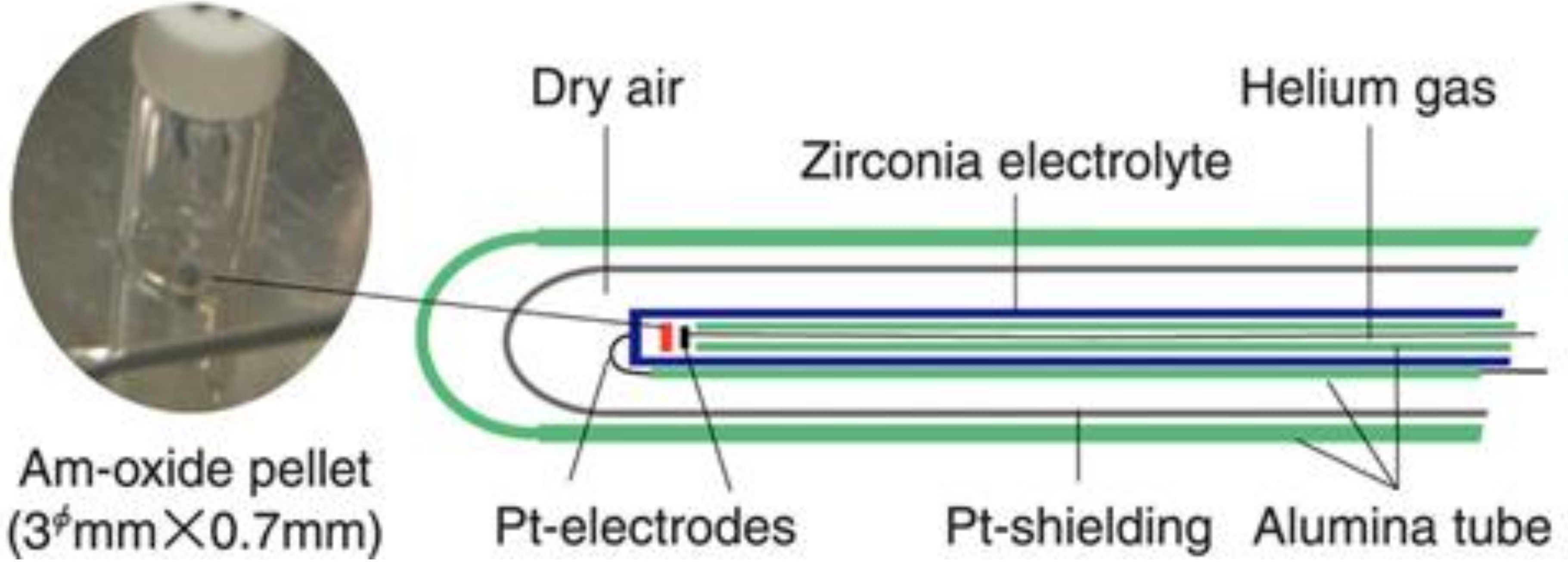




Zirconia

The most accurate (+/- 0.01%)
Most sensitive (+/- 0.001%)
(Photosynthesis experiment)

Zirconia



zirconia ceramic is a solid electrolyte.

conductive only to oxygen ions at 700+DegC.

zirconia element with a porous platinum electrode

Zirconia

Electrodes exposed to oxygen gas

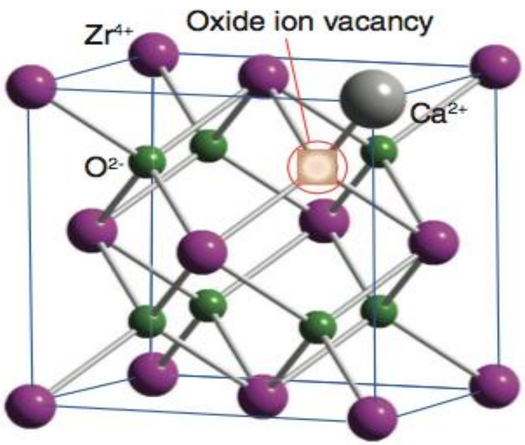
Following reactions occur between the electrodes

Zirconia element serving as a separator

Zirconia Oxide can only react to Oxygen

P1 side (cathode): O2 + 4e --> 2O2

P2 side (anode): 2O2- --> O2 + 4e



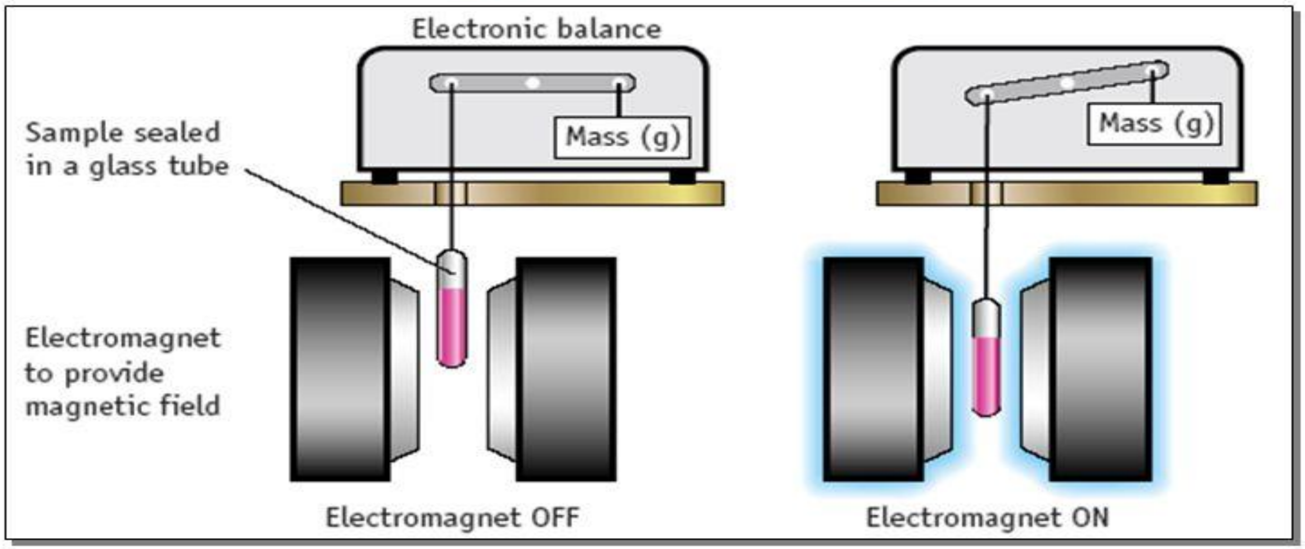
Photosynthesis Experiment (O_2)

Our Zirconia system is the only metabolic system that is sensitive and accurate enough to be used to sense O_2 coming from leaves in Photosynthesis. Since Bjorkman and Gauhl, 1970, many similar papers have been published every decade using our technology. A small sample is below.

Bjorkman and Gauhl, 1970
John P. Krall, 1993 (Maize plant)
Vello Oja 2011 (Sunflower leaves)
Agu Laisk, 2015 (cell cultrures in vitro)

Paramagnetic O2 sensors

Measuring Paramagnetism



Paramagnetic: substance is attracted to a magnetic field. Substance has unpaired electrons.
Diamagnetic: NOT attracted to a magnetic field

Active Figure 8.2

Paramagnetic O2 sensors

- Uses the paramagnetic property of oxygen

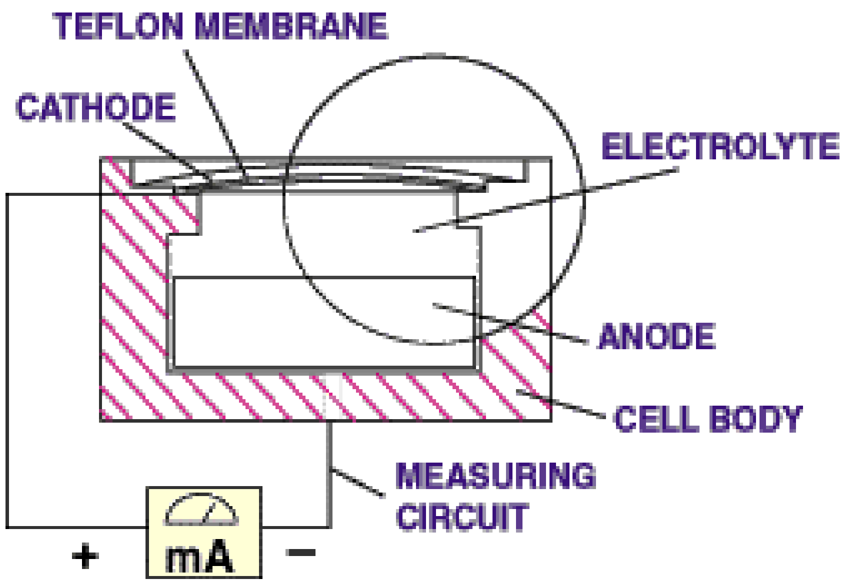
  (ability to be magnetized by applied magnetic field)

- Measures oxygen with high precision

- Other gases in sample also paramagnetic ! (but less)

  - Accuracy = 0.05%
  - Drift = 0.01% O2 /hr

Galvanic Cell O2 sensors



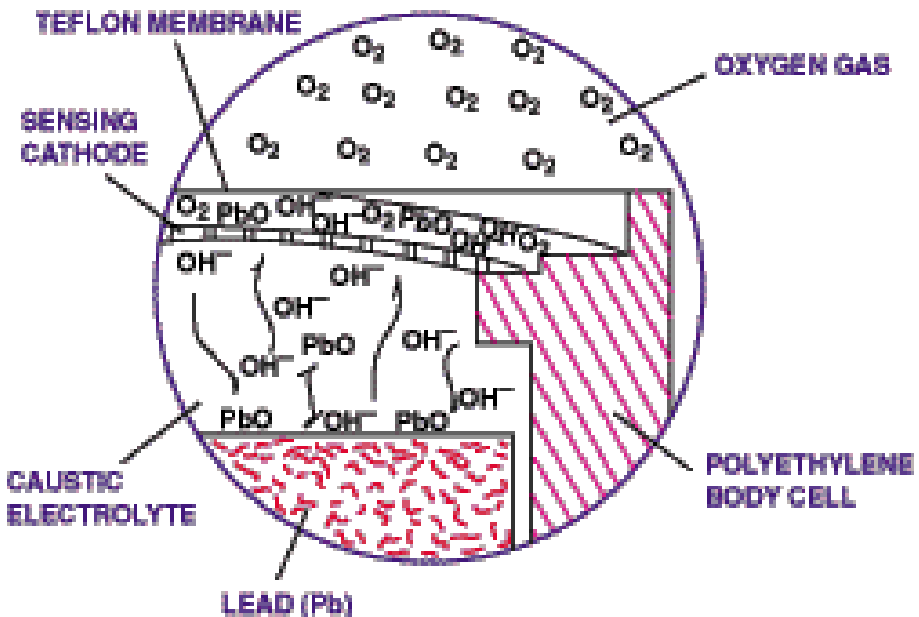
Jelly electrolyte applied to gold cathode & silver anode

Teflon membrane that is only permeable to oxygen

Galvanic Cell O2 sensors

voltage applied between electrodes

current proportional to O2 detected



Galvanic Cell O2 sensors

- Sensor cell time limited

  (in contact with air even when not used)

  so periodic replacement is required.

- High drift occurs if operated continuously

  not suitable for continuous measurements

- Compact & low cost

O2 cell comparison

Zirconia	Paramagnetic	Galvanic Fuel Cell
• Average 20 year cell life • solid ceramic electrolyte • conductive only to oxygen ions at 700+DegC. • Most sensitive +/- 0.001% • Most accurate +/- 0.01% • Response 0.1sec to 90% • Low drift 0.01% in 24 hrs	• 5-10 year cell life • O2 paramagnetics • Good sensitivity +/- 0.05% • Good accuracy +/- 0.05% • good response: 0.1 sec to 90% • Drift: 0.2% in 24 hrs	• 12 month cell life • Jelly electrolyte b/w anode/cathode • O2 permeable membrane • Good sensitivity +/- 0.04% • Good accuracy +/- 0.04% • Good response: 0.1 sec to 90% • High drift

How to handle all this error
(cant simply add and subtract error)

$$(VO_2\ \text{error})^2 = (\text{error } 1)^2 + (\text{error } 2)^2 + \ldots\ldots (\text{error } N)^2$$

The following errors are included:

1 = VO2 error from calibration gas

2 = VO2 error from O2 sensor error

3 = VO2 error from CO2 sensor error

4 = VO2 error from Ve (ventilation error)

…

N = all the sensors (Temp, Humidity, Barr press, sample humidity, etc)

Enter MS Excel Macro

Accumulate O2, CO2 and Flow errors only

* Taken from manufacturers specs.

System	Sensor (O2,Ve)	Resp. time	O2	CO2	Flow	VO2
AEI Moxus systems	Zi, Pneumo.	0.10s	0.01	0.01	1.0	1.07
Cortex Metalyzer 3B	Gal, Turbine	??	0.1	0.1	2.0	4.37
Cortex MetMax units 3B	Gal, Turbine	??	0.1	0.1	2.0	4.37
Jaeger Oxycon Pro	Para, Turbine	0.04s	0.05	0.05	3.0	3.57
Medgraphics Ultima	Gal, Pitot tube	0.20	0.2	0.1	3.0	8.20
Servomex 5200 high flow	Para, ??	12.00s	0.05	2.0	??	??
Servoflex MiniHF	Para, ??	15.00s	0.05	2.0	??	??
GEM Indirect Calorimeter	Para, Thermal	??	0.1	1.0	1.0	8.87

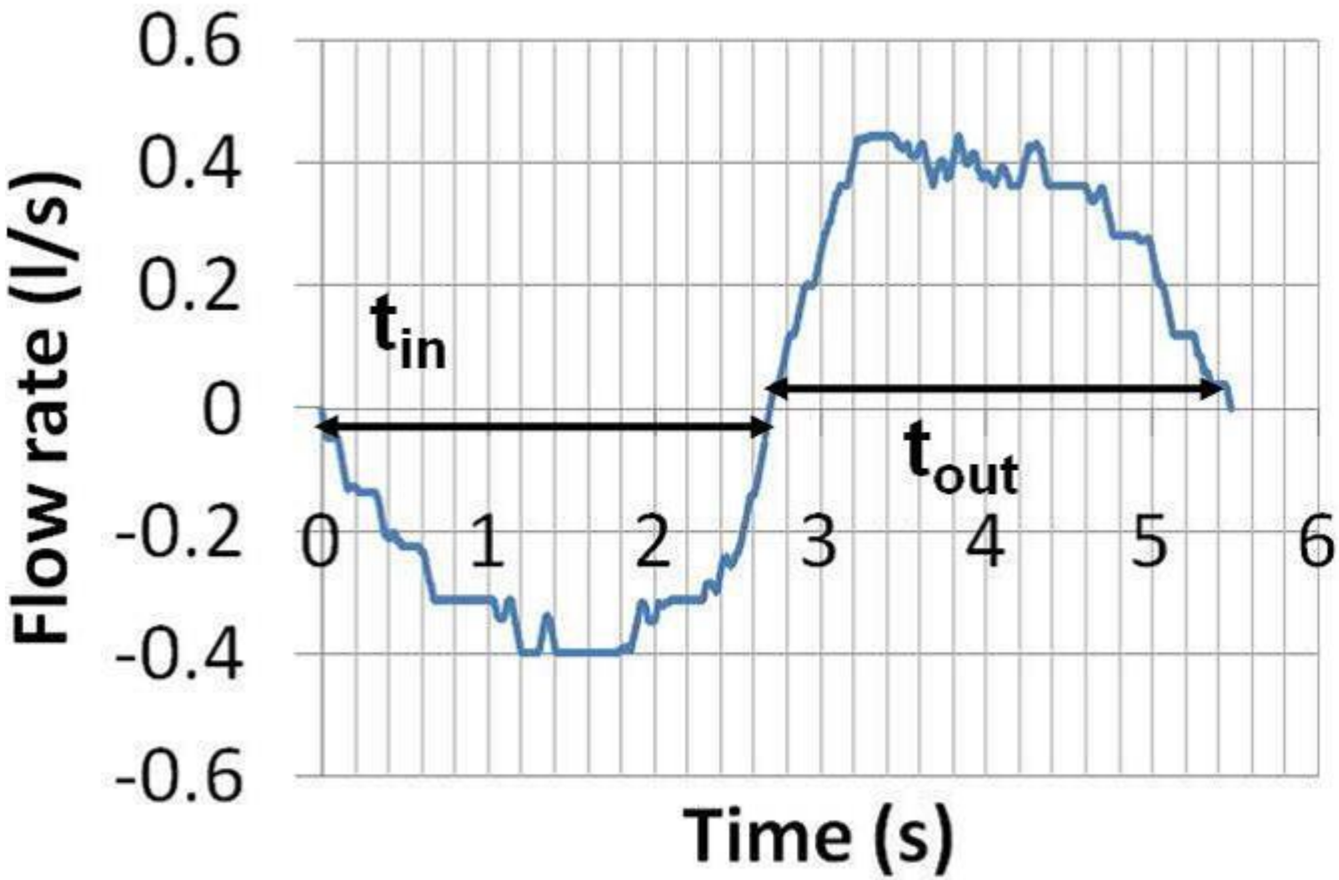
Mixing chamber versus BxB

- In reality VO2 very hard to do correctly.
- Many factors can conspire against a diligent scientist.
- BxB makes things neat for scientist and subject.

- But at a significant price.

BxB issues – 1. noisy real signals

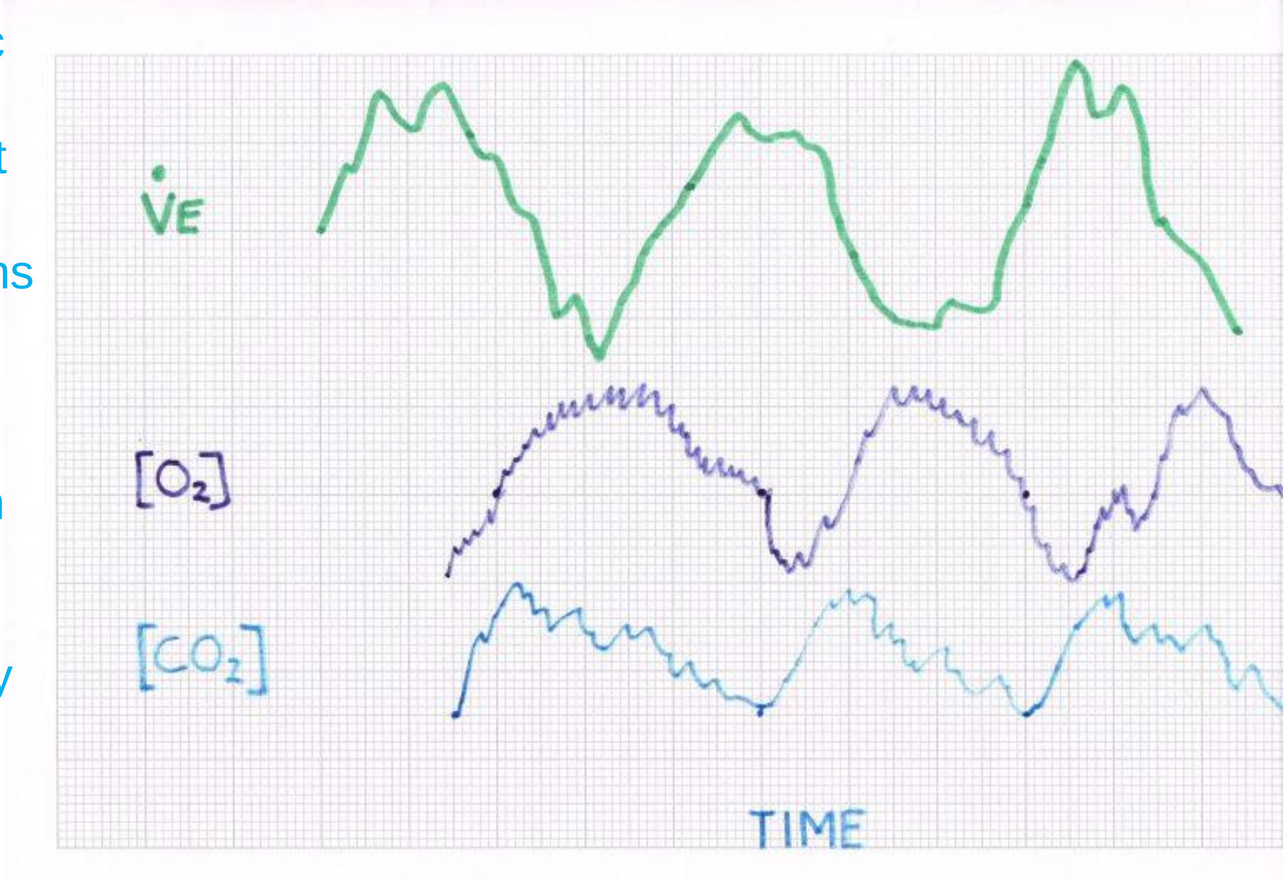
- This is a typical resting flow versus time graph
- Exercising graph has more noise and more variation



BxB issues – 2. misaligned signals

Typical Ve, O2 and CO2 graphs.

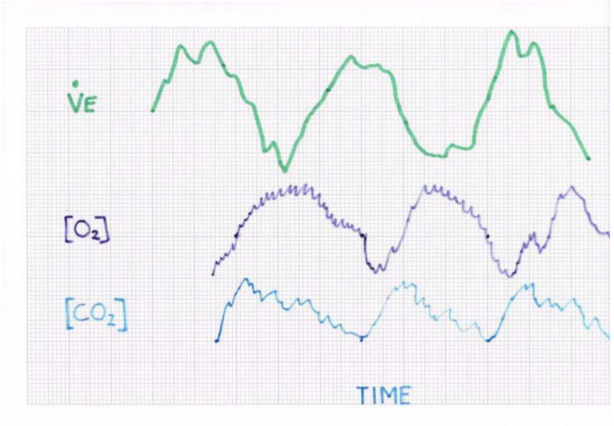
- Sample 200 times / sec
- Note time misalignment
- Note variability of graphs
- Difficult to time align
- If not time aligned, then creating false data
- In mixing chamber, only one sample per breath
- If slightly out no major issue



BxB issues – 3. Multiplying noisy signals

Noise here is 5-15% - lets see 5% noise

So with reference values set at say:
FiO2=21%, FeO2=17.5%, FiCO2=0.04, FeCO2=3.8, Ve=137L/min.



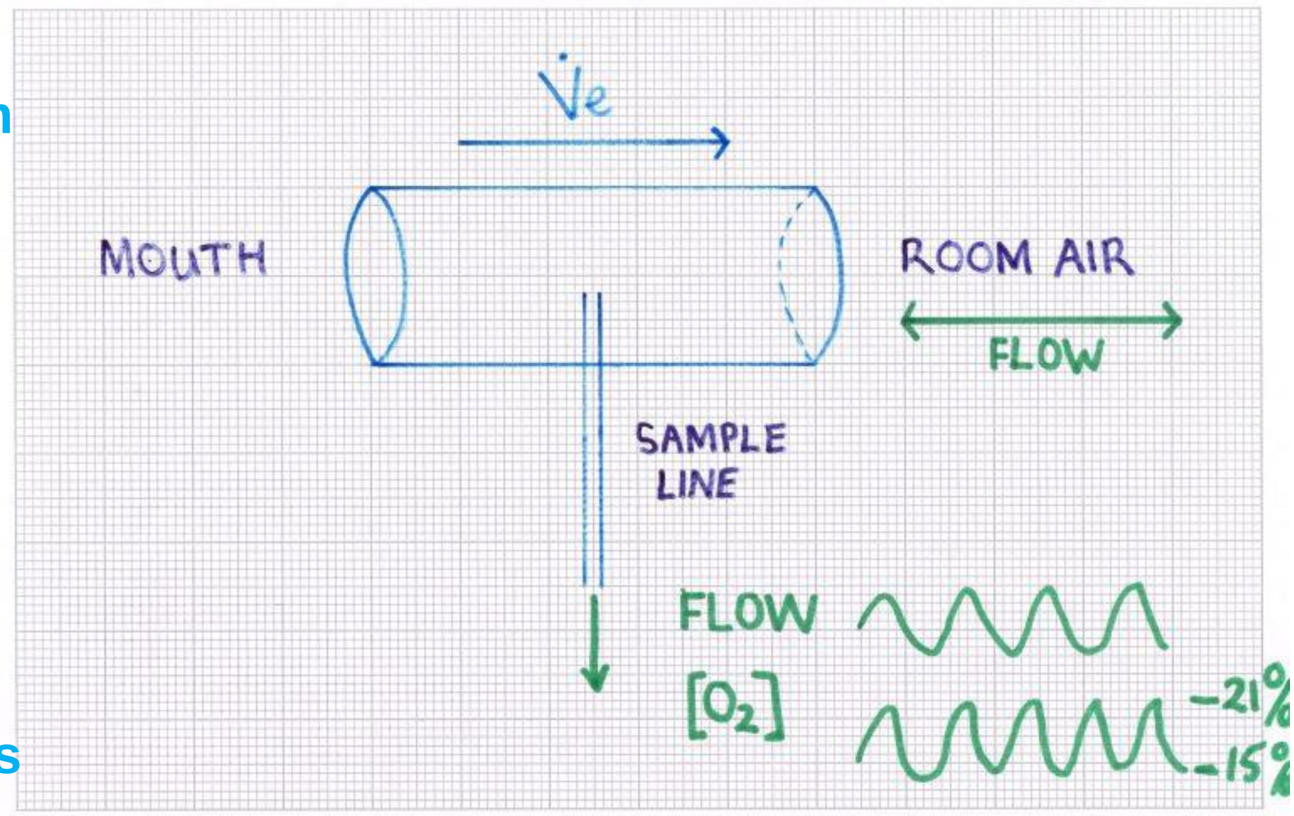
Now lets add the 5% relative error to **FeO2 and Ve** .
This would change these values to:
FeO2= 18.3% , Ve=143.8L/min

Its not looking too drastic at all at this stage. However using our error algorithm above, this amounts to a VO2 error = 33.9% …try it yourself.

Keep in mind we have not added any error to CO2 or any other sensors.
In mixing chamber, all this variation just fills the chamber as one bolus of expired air.

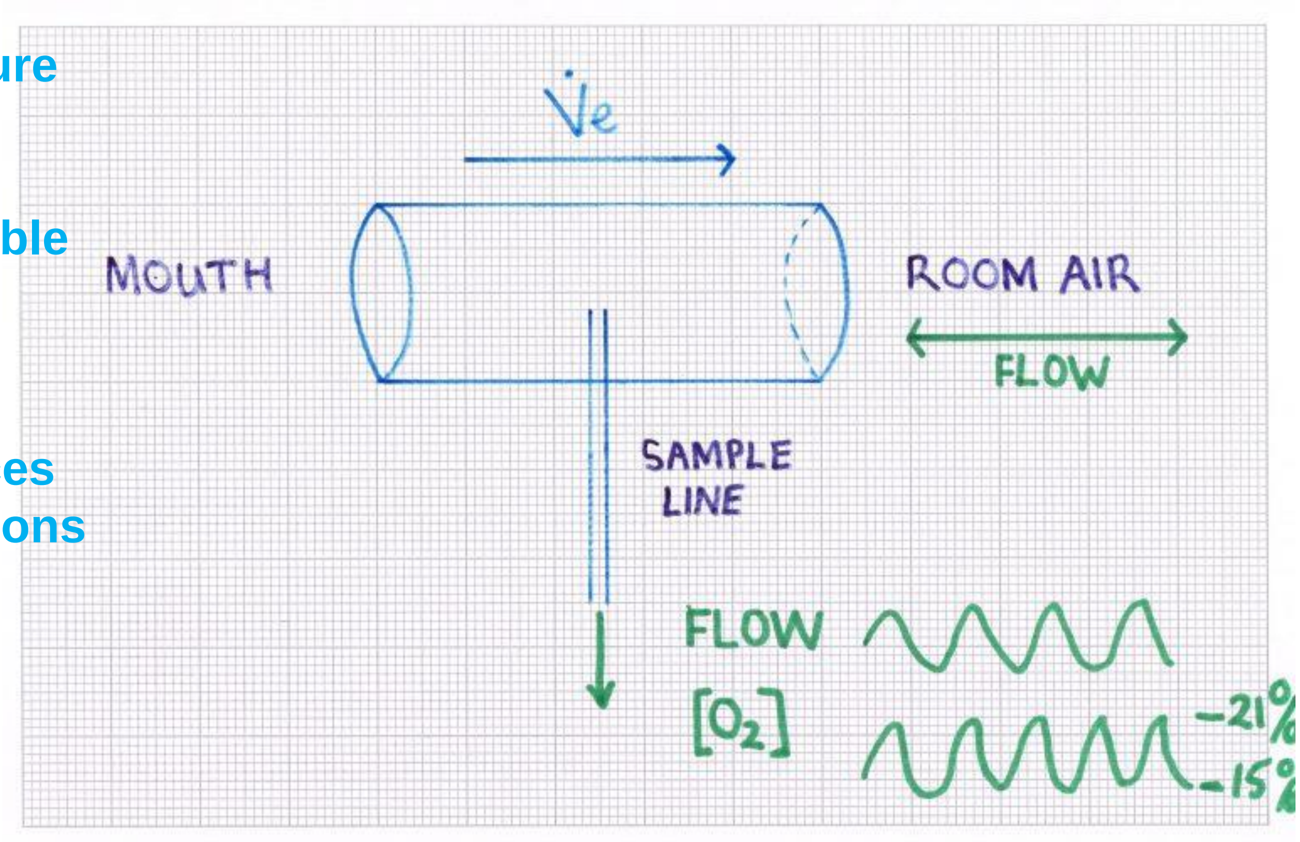
BxB issues – 4. Sensors hate Flow variations

- Sensors exposed to expired air and room air simultaneously
- Causes large variations swings
- Sensors constantly trying to adjust
- Mixing chamber No issues: sample goes from small tube to large chamber, dampening any pressure variations.



BxB issues – 5. Mouthpiece sampling issue

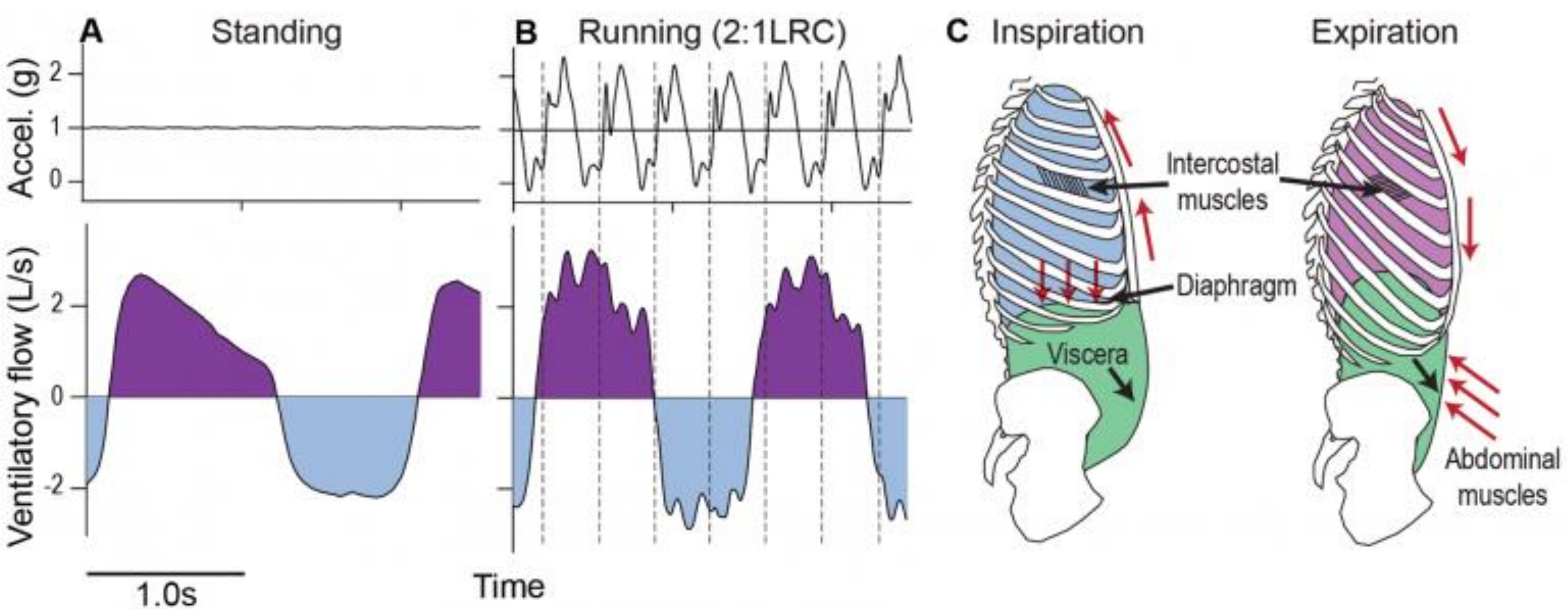
- Sensors do not measure %, only quantity.
- Flow must be very stable to calculate % O2 and CO2.
- Sample line experiences significant flow variations
- Almost impossible to eliminate these flow issues.
- Mixing chamber dampens any flow variations to almost zero.



BxB issues – 6. Running mechanics issues

Daley MA, (2013) Impact Loading and Locomotor-Respiratory Coordination Significantly Influence Breathing Dynamics in Running Humans.

Running (most movements probably) create Ve variations and unhappy sensors – more VO2 errors



Summary of BxB issues

- 1. BxB use very noisy (real) instantaneous O2, CO2, flow signals.
- 2. Time misalignment of O2, CO2 and flow difficult to correct.
- 3. Instantaneous multiplication of these signals to VO2 create incredibly noisy and erroneous VO2 signals.
- 4. Gas sampling with large flow variations means flow to sensors is unstable.
- 5. Mouthpiece sampling means very large swings in gas concentrations from room air to sample. Difficult on sensors.
- 6. If running, then noisy flow resulting from lung vibrations adds to the noise in BxB systems.

Summary

- Most important VO2 error factors: O2 sensor, Cal gas, Flow, sample humidity and BxB issues.
- The O2 sensor mathematically 50 times more important than next sensor, Ventilation. So O2 accuracy is paramount. Especially in sport.
- Sample humidity, its treatment, measurement and compensation very important
- O2 sensors not equal. Accuracy, sensitivity & drift important. Low cost sensors not always best..

Thanks for their help.

Mr. Ian Fairweather. Former Chief Technologist, Victoria University.

Dr. Hans Rosdahl, GIH, Sweden. (former first student of Astrand)

Dr. Thomas Steiner, BASPO, Switzerland. Head of Science.

Mr. Phil Loeb, AEI Technologies, USA.

Dr. Chris Gore, AIS. Head of Laboratory Standards.

Dr. Jens Westergren, Dalarna Sports Academy, Sweden.

Mr. Jamie Plowman, AIS. Chief Technologist

Mr. Tom Stanef. Technology Specialist, University of Adelaide.

Thank You

Danny Rutar

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