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…accuracy, stability.
- Extremely high oxygen sensor accuracy needed for athletes & research (0.01% absolute = 1% VO2).
- Human sample humidity causes havoc to systems.
- Mathematical error on your systems
- Breath by Breath issues – not fit for purpose?

Measurement Error 101

Systematic Error

(offset, scale…manageable)

Alinear system

(20,30,40,50 = 15,35,45,48)

Repeatability

(precise not accurate)

*Random Error

(all else manageable)

(+/- 0.5mm , what is your met cart +/-   ?? ml/kg/min?)

Calculating Random Error

(met cart validation)

- Douglas Bag comparison
  - Not a validation, just comparison.
  - Unknown input
- Industrial calibrator
  - Not accurate enough, single piston
  - No humidity
- AIS Max II calibrator
  - 0.8% error
  - Humidity input possible
- Accumulated Error using manufacturer sensor specs.

Variables Affecting Accuracy
(all with random errors that accumulate)

- O2 Measurement error
- CO2 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

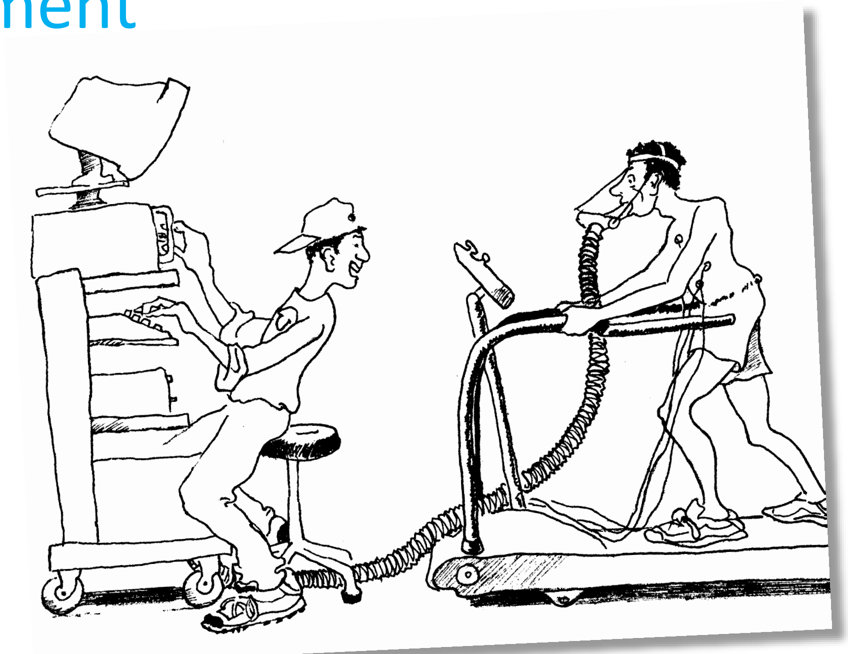
FIO2 = 0.1751%

O2 = 0.2093%

* Human sample

Most important factors

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



O2 Measurement Errors

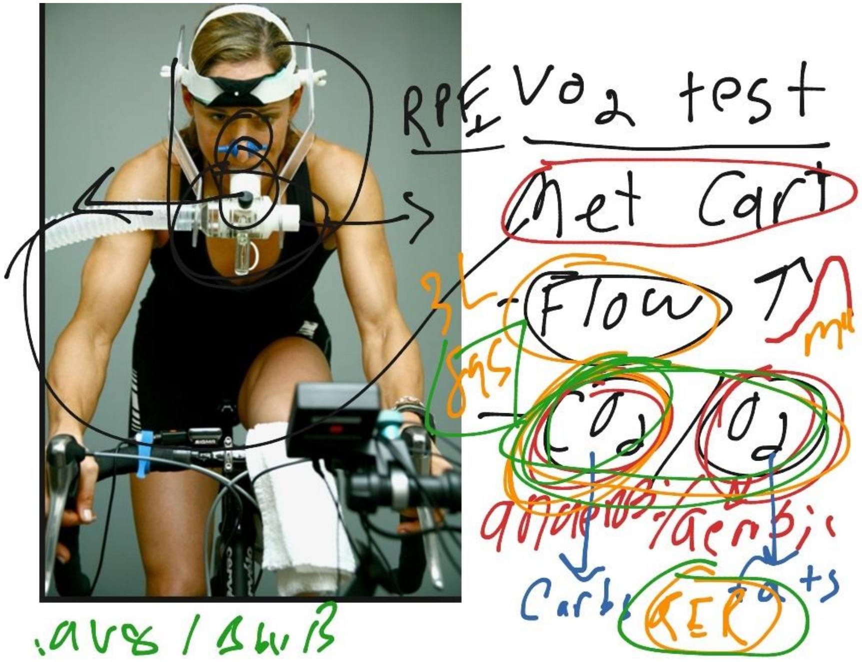
Oxygen Analyser:

accuracy errors – **we'll examine this only**

calibration errors

stability errors

response time errors



Gas Analyser Error Example

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

O_2 Accuracy = 0.1% absolute
CO_2 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.

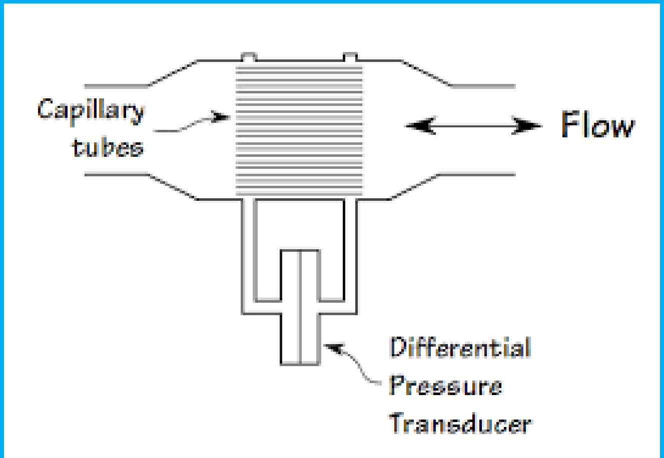
Analysis & Conclusions – (cal. Gas)

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



Douglas Bag
Tissot tank

Turbine

<1 - 2%
Very fast

1% ?
Very slow

1 - 3%
Inertial error

1% Ve or Vi error = 1% VO2 error

Analysis & Conclusions – (ventilation)

So a 1% error in Ve will result in a 1% error in VO2.

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

Inspired side no issues

Expired side debris with saliva

Mechanical parts change calibration with debris

Water Vapour / sample humidity

Water displaces gases..this artificially raises the VO2 value

30% water vapour raises VO2 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.

CO2 sensor (IR) sees water as increased CO2

Water Vapour / sample humidity (Solutions)

- Peltier device (cooling)
  - drop water from sample
  - sample needs to be reheated

- Nafion tubing
  - drys to room humidity only
  - 50% effective after 25min
  - 10% effective after 45 min
  - shelf life 6 months
  - dry cal gas between tests, replace often

Breathing valve shape

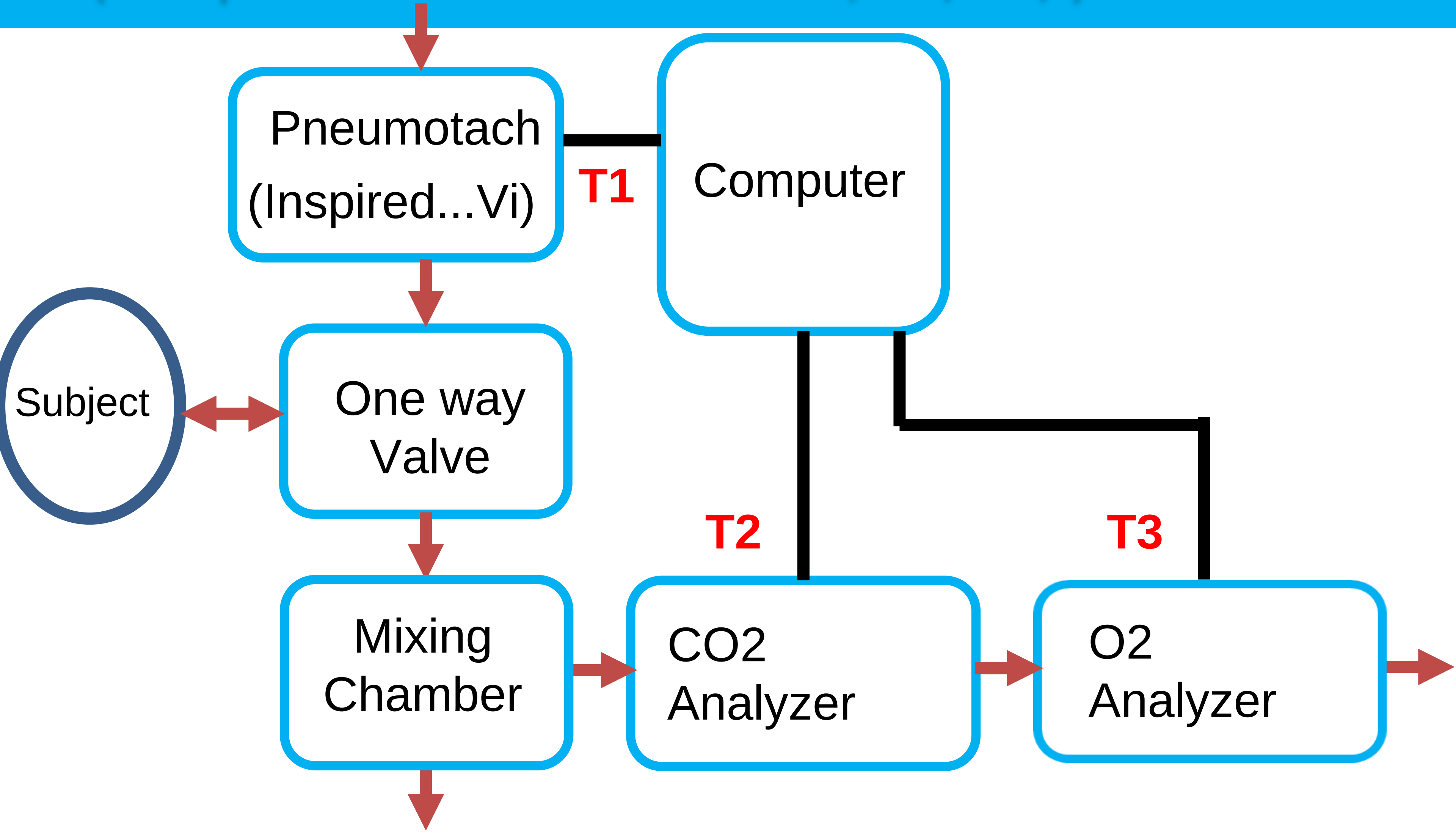
Hans Rosdahl et. al. 2017
(Ian Fairweather 1990's)

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

- Use Y shaped breathing valve

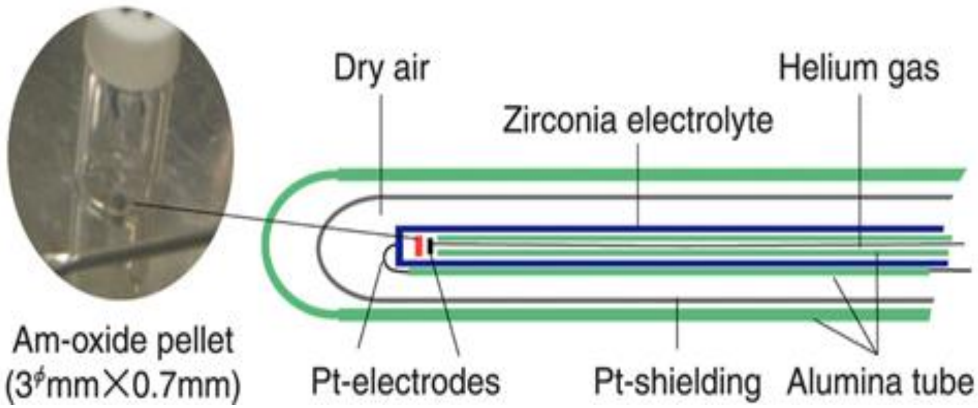
Phase delays

(sample time differences…T1, T2, T3,)

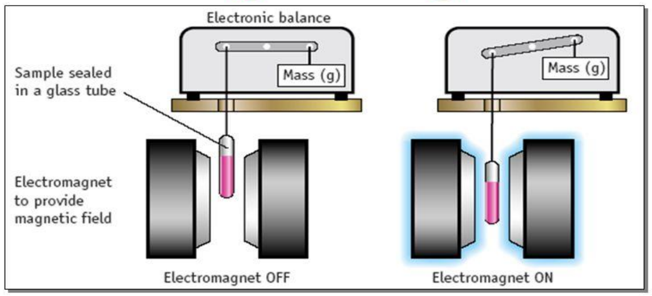


O2 Sensors
(most critical sensor!)

- Zirconia
- Paramagnetic
- Galvanic

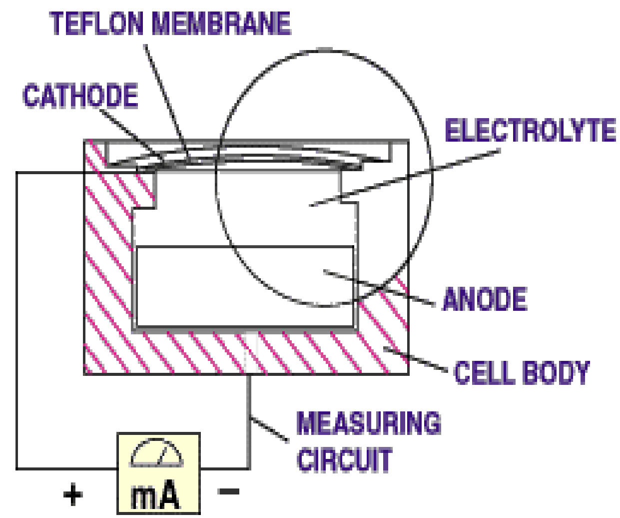


Measuring Paramagnetism



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

Active Figure 8.2



Zirconia

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

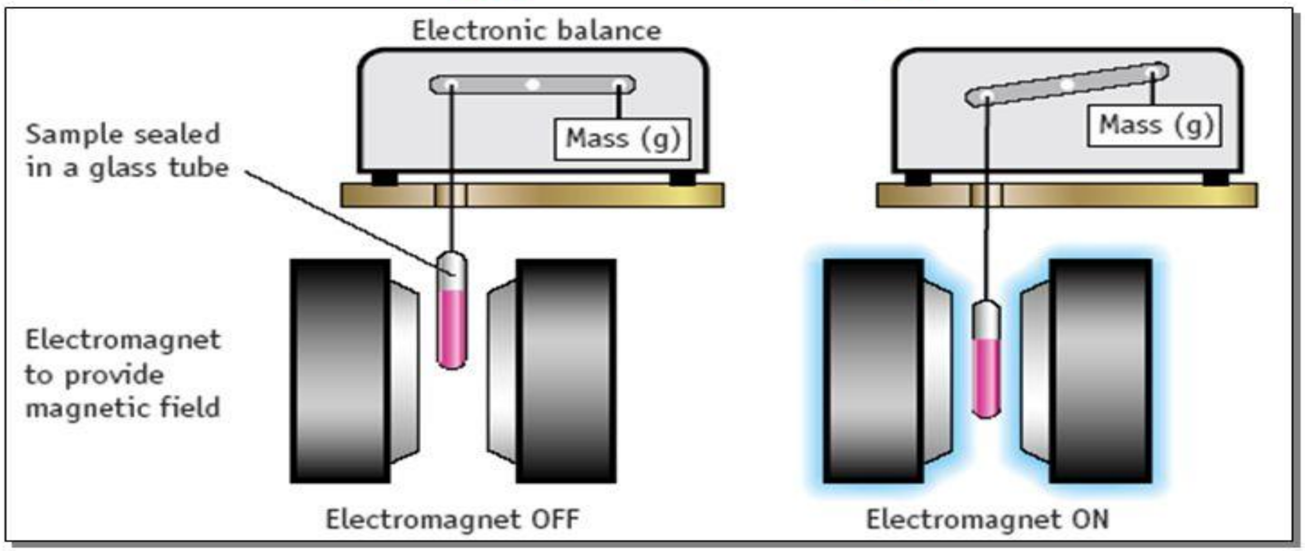
Photosynthesis Experiment (O_2)

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

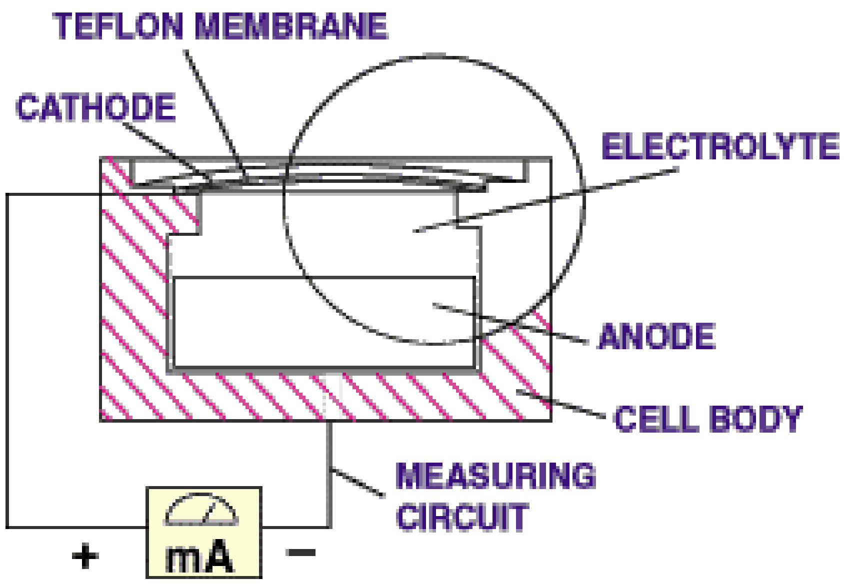
Measuring Paramagnetism



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

Active Figure 8.2

Galvanic Cell O2 sensors



Jelly electrolyte applied to gold cathode & silver anode

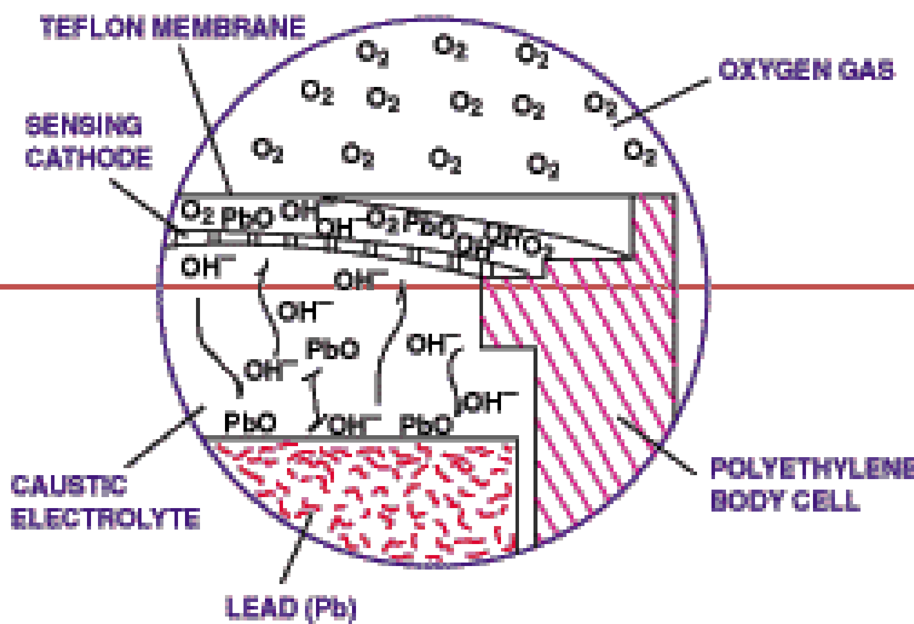
Teflon membrane that is only permeable to oxygen

Galvanic Cell O2 sensors

voltage applied between electrodes

current proportional to O2 detected

(note O2 must take time to get through membrane)



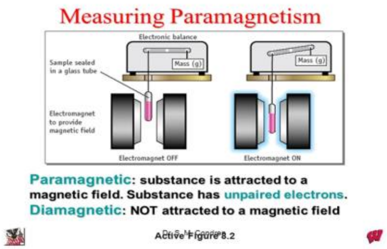
O2 cell comparison

Zirconia

- 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

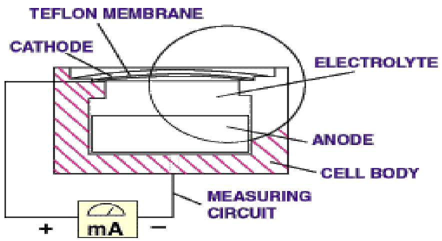
Paramagnetic

- 5-10 year cell life
- O2 paramagnetics
- N2 and CO2 paramagnetic also.
- Good sensitivity +/- 0.05%
- Good accuracy +/- 0.05%
- good response: 0.1 sec to 90%
- Drift: 0.2% in 24 hrs



Galvanic Fuel Cell

- 12 month cell life
- Jelly electrolyte b/w anode/cathode
- O2 permeable membrane
- Good sensitivity +/- 0.04%
- Good accuracy +/- 0.04%
- Response: 0.1 sec ???? to 90%
- High drift



VO2 error calculator

- Lets examine some individual parameters
- Use VO2 error calculator

Very best case error.

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
Cosmed Quark	Gal, Turbine	0.12s	0.1	0.02	2.0	4.30
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

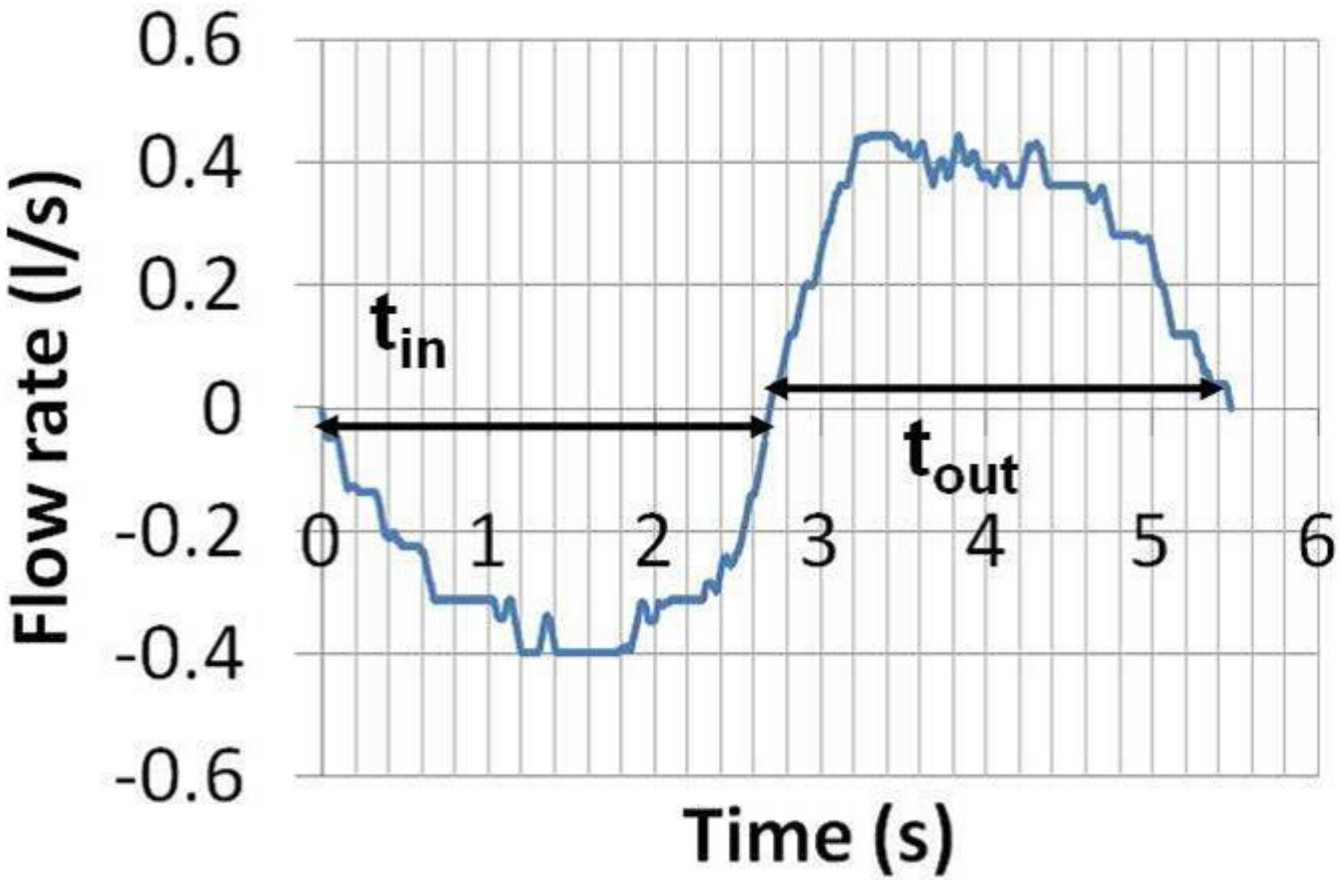
Mixing chamber versus BxB

- 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

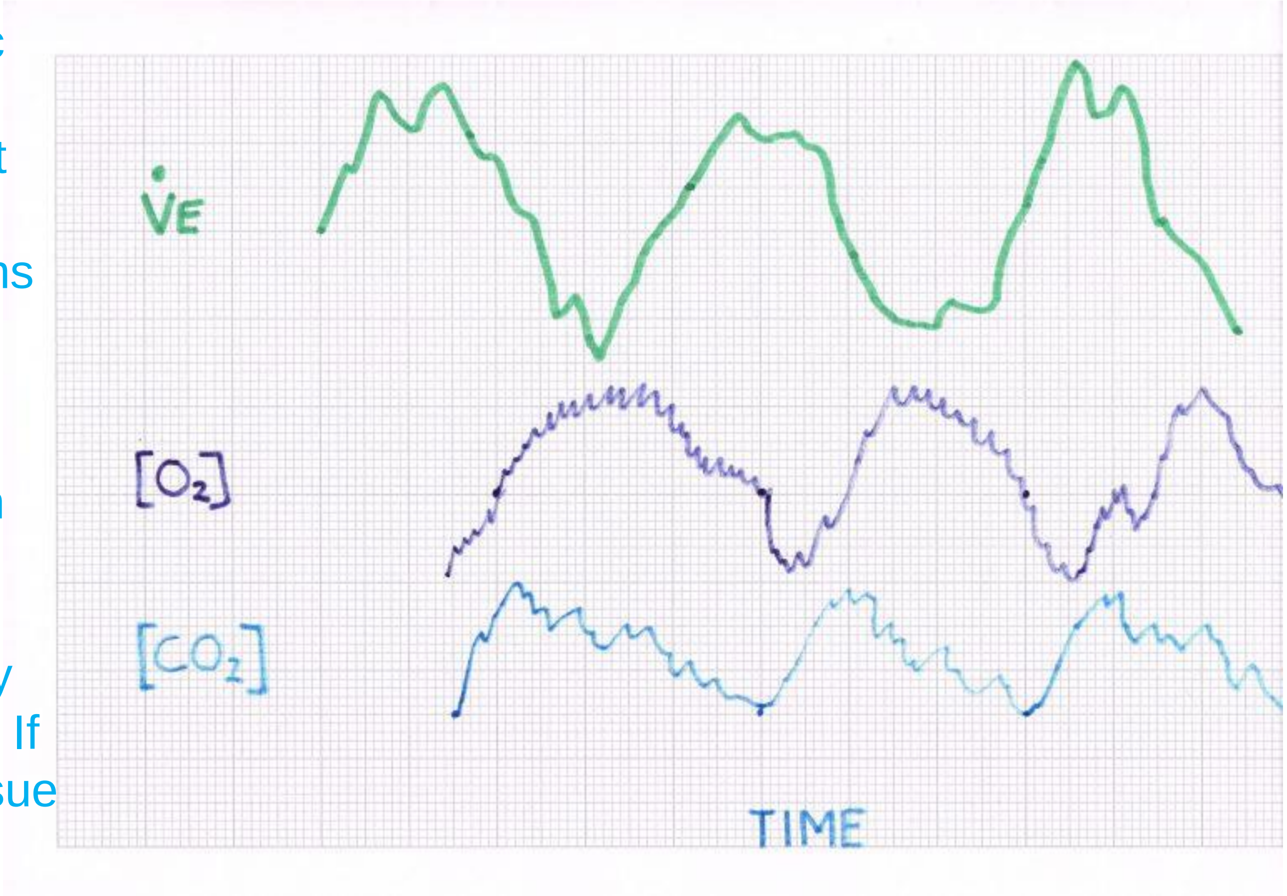
- This is a typical resting flow versus time graph
- Exercising graph has more noise and more variation



BxB issues – 2. misaligned signals

Typical Ve, O2 and CO2 graphs.

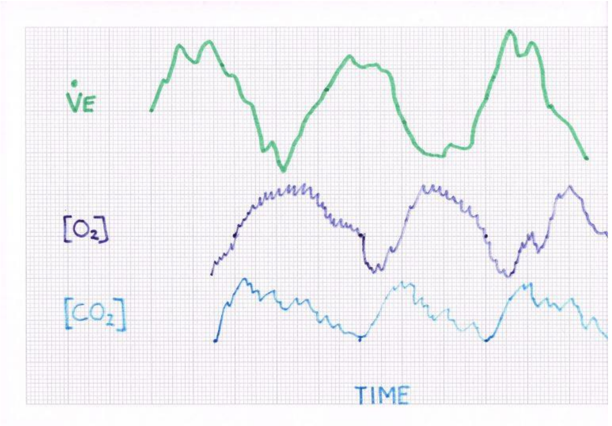
- Sample 200 times / sec
- Note time misalignment
- Note variability of graphs
- Difficult to time align
- If not time aligned, then creating false data
- In mixing chamber, only one sample per breath. If slightly out no major issue



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.



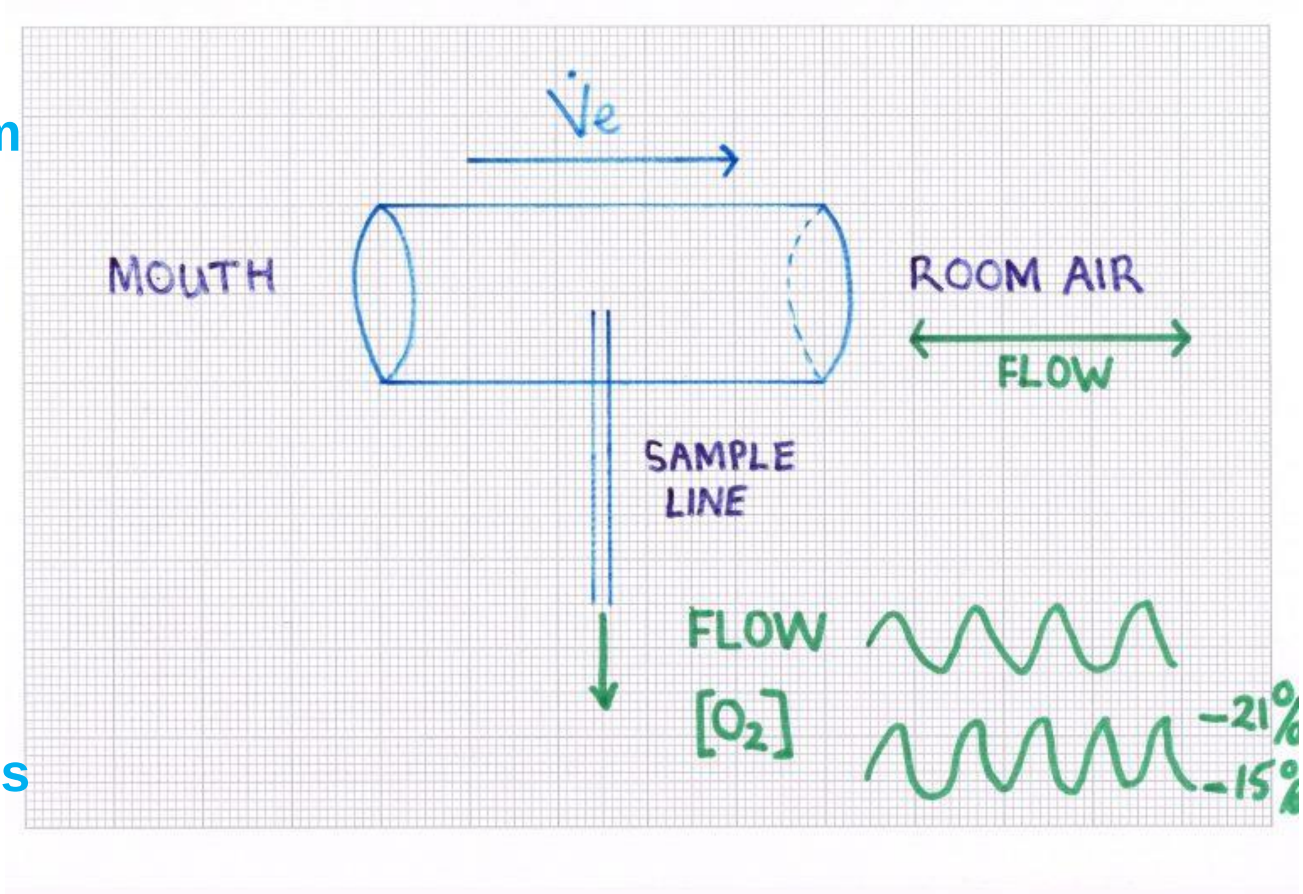
Now lets add the 5% relative error to **<u>FeO2 and Ve </u>**.
This would change these values to:
FeO2= 18.3% , Ve=143.8L/min

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.

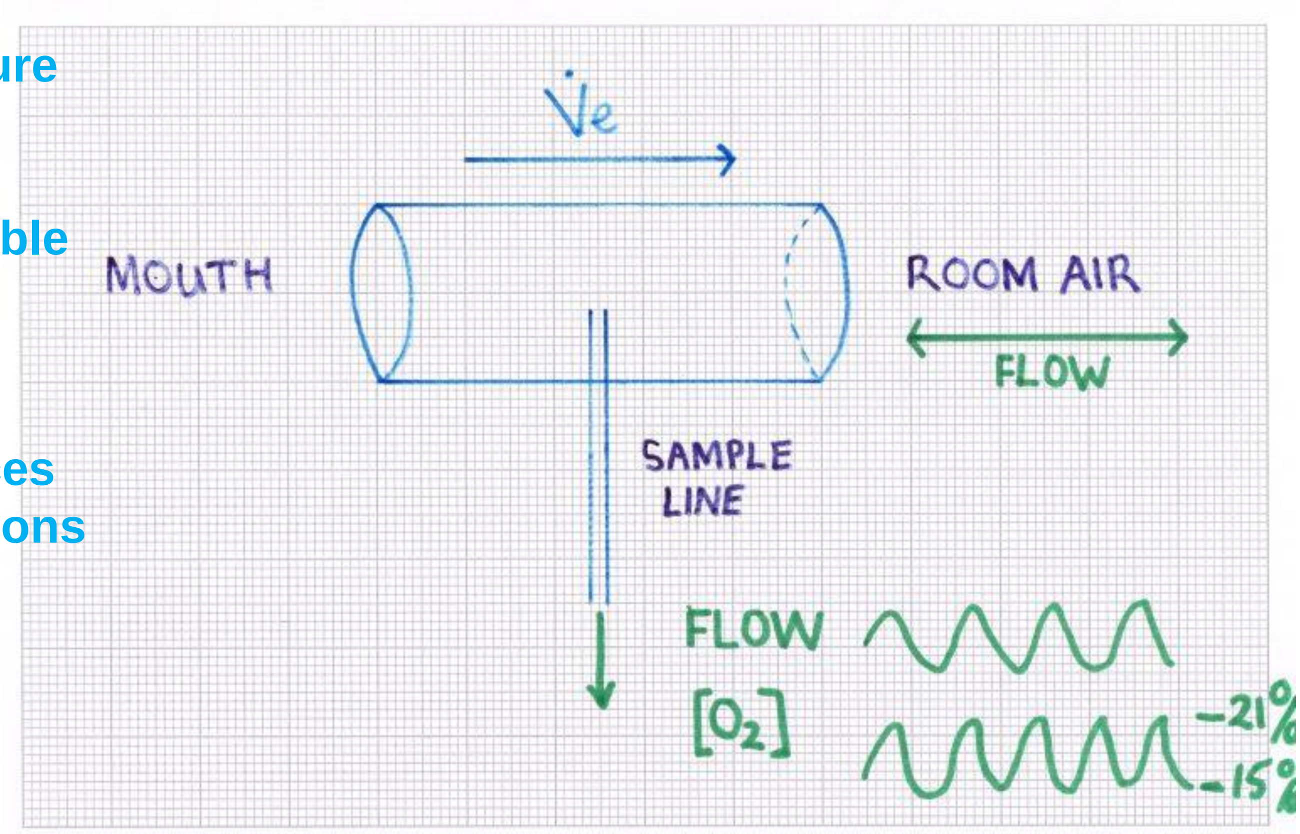
BxB issues – 4. Sensors hate Flow variations

- 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

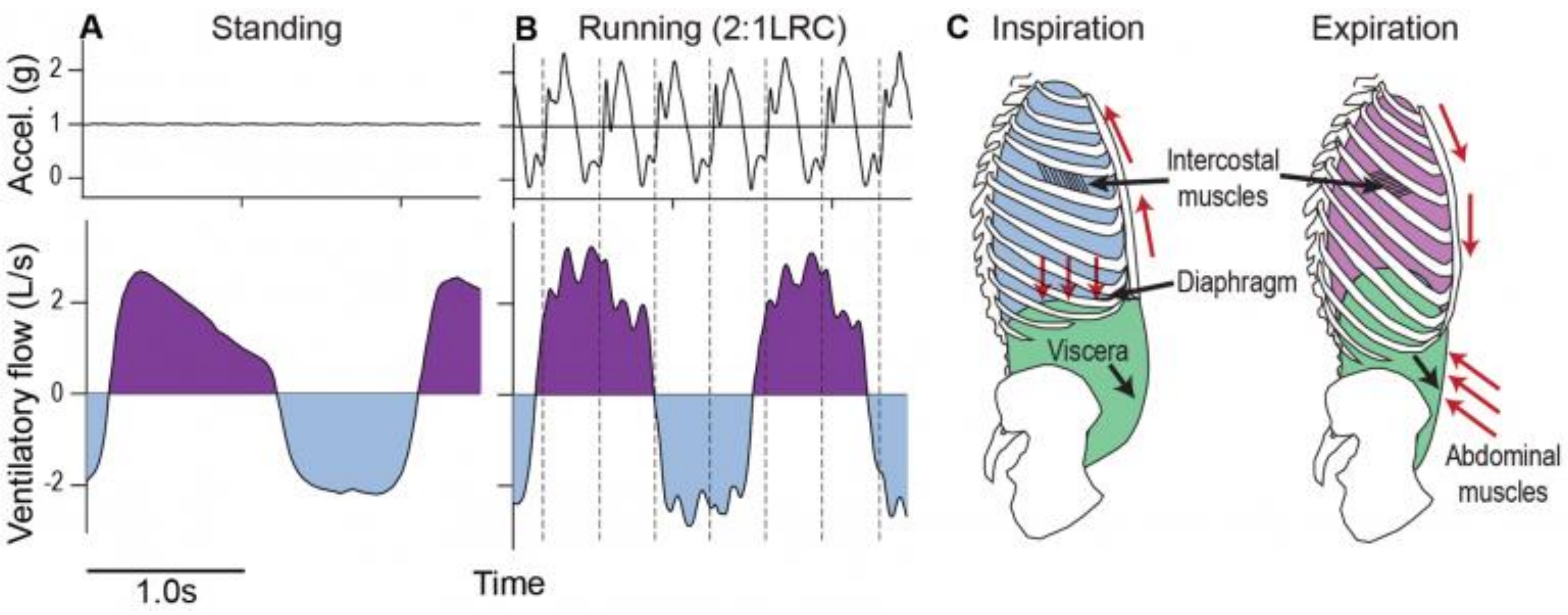
- **Sensors do not measure %, only quantity.**
- **Flow must be very stable to calculate % O2 and CO2.**
- **Sample line experiences significant flow variations**
- **Almost impossible to eliminate these flow issues.**
- **Mixing chamber dampens any flow variations to almost zero.**



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 O_2, CO_2, flow signals.
- 2. Time misalignment of O_2, CO_2 and flow difficult to correct.
- 3. Instantaneous multiplication of these signals to VO_2 create incredibly noisy and erroneous VO_2 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 is very important
- O2 sensors not equal. Accuracy, sensitivity & drift important. Low cost sensors not always best.
- Breath by Breath not for athletes or research.

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

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