RMIT UNIVERSITY

VICTORIA UNIVERSITY MELBOURNE AUSTRALIA

HESTA 2017

Issues affecting the accuracy of Metabolic Carts

Danny Rutar

redback biotek

Danny Rutar

Managing Director, Redback Biotek

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.

Why did I want to know?

- Selling the AEI Moxus system
  - Declare vested interest.
- Marketing strategy
  - Most accurate system.
- Had to learn more
  - About why most accurate.

- Ended up learning about how many problems exist with metabolic systems in general.

Key Topics

- Physical measurements & Variables affecting accuracy
- The most important issues affecting accuracy
- How metabolic sensors work and comparing them
- Accumulating errors! How to handle them?

Physical Measurements

1. O_2 – for both inspiratory & expiratory air
2. CO_2 – 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

1. Calibration of system physical measurement components
2. Calibration Gas
3. Testing Environment
4. Subject Preparation
5. Metabolic Cart setup and maintenance
6. Time delays of gas sampling
7. Operator Initiated errors
8. Humidity of Gas Sample

Common Types of Errors

- Operator Initiated
- O2 Measurement
- CO2 Measurement
- Gas Calibration
- Volume or Flow Measurement
- Gas Sample Humidity
- Testing Environment
- Subject Preparation
- Temperature Measurement
- Pressure Measurement
- Relative Humidity Measurement
- Metabolic Cart Setup/Maintenance
- Gas Sampling Time Delay
- Time Measurement
- Cumulative

The sensor errors examined (In order of importance)

+1% rel. error	% VO2
Oxygen*	-6.46
O2 Cal. gas	-12.92
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

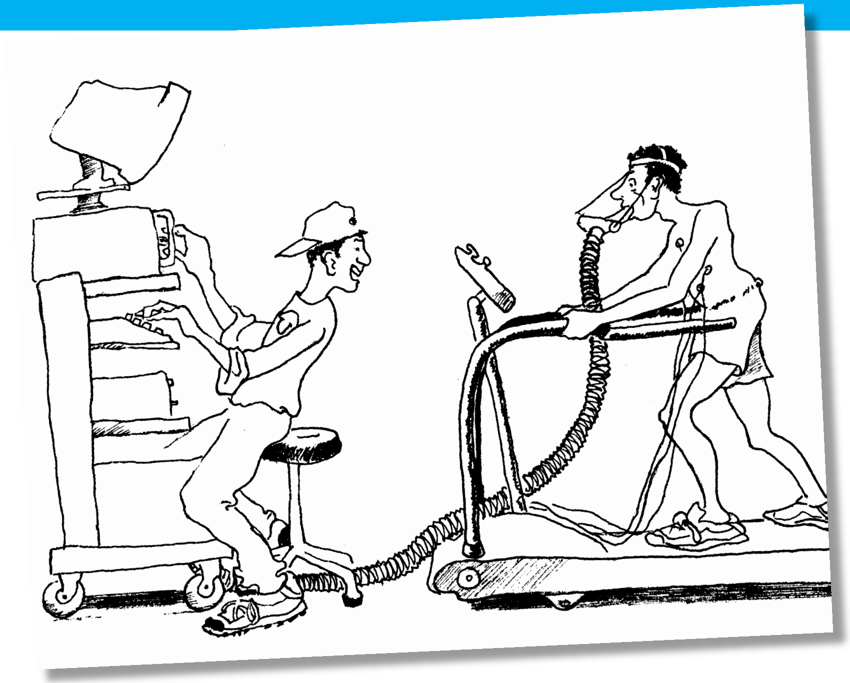
VE STPD = 136.70

FIO2 = 0.1751%

O2 = 0.2093%

* Human sample

Most important factors



- O2 sensor
- Calibration gas
- Volume or Flow Measurement
- Gas Sample Humidity
- Human Error ? (Basic setup errors)
- Testing environment ? (20.85, air conditioning & small rooms.)
- Breathing Valves (T or Y piece)
- Phase delay between gas and ventilation (Time O2/ Time Ve)

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:

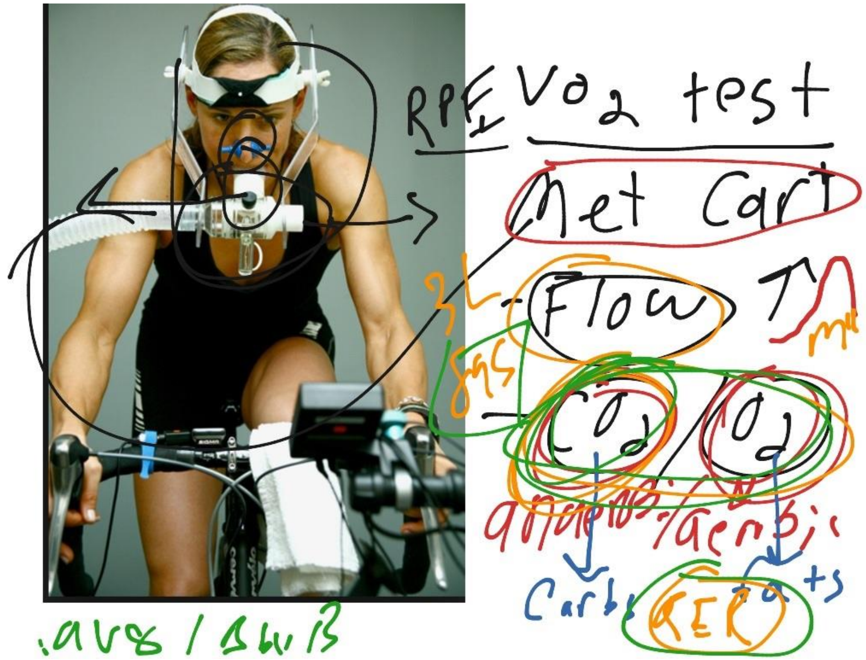
accuracy errors

- the greatest source of equipment error!

calibration errors

stability errors

response time errors



Gas Analyser Error Example

Utilise the textbook equations for Exercise:

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

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

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

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 for Exercise:

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

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

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	
O_2 (High)	20.93	O_2 (High)	20.93
O_2 (Low)	16.00	O_2 (Low)	15.20
CO_2 (High)	4.00	CO_2 (High)	4.20
CO_2 (Low)	0.03	CO_2 (Low)	0.03
fiO_2	20.93	fiO_2	20.93
$fiCO_2$	0.03	$fiCO_2$	0.03
feO_2	17.00	feO_2	16.20
$feCO_2$	4.00	$feCO_2$	4.20
Haldane	1.00	Haldane	0.99
Vi (L/min)	150.00	Vi (L/min)	150.00
Ve	150.08	Ve	148.94
VO_2	5.88	VO_2	7.27
VCO_2	5.96	VCO_2	6.21
RER	1.01	RER	0.85

1 Cal Gases Utilised:
uncertainty = 5% relative

Cal Gas Error Contribution	
VO_2 % Error	23.53
VCO_2 % Error	4.24
RER % Error	-15.61

5% relative error
Eg.
= 17 O_2 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.

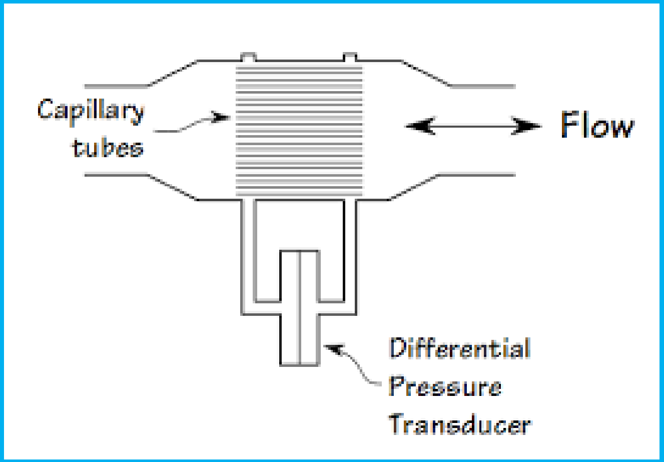
Analysis & Conclusions – (cal. Gas)

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%

Douglas Bag
Tissot tank

1% ?

Turbine

1 - 3%

1% Ve or Vi error = 1% VO2 error

Analysis & Conclusions – (ventilation)

The error in ventilation in a metabolic system is directly translated into VO2 error.

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

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 6 months and between many tests.
- Use Humidity sensor and compensate O2/CO2 sensor values.
  (almost no commercial systems do)

Breathing valve shape

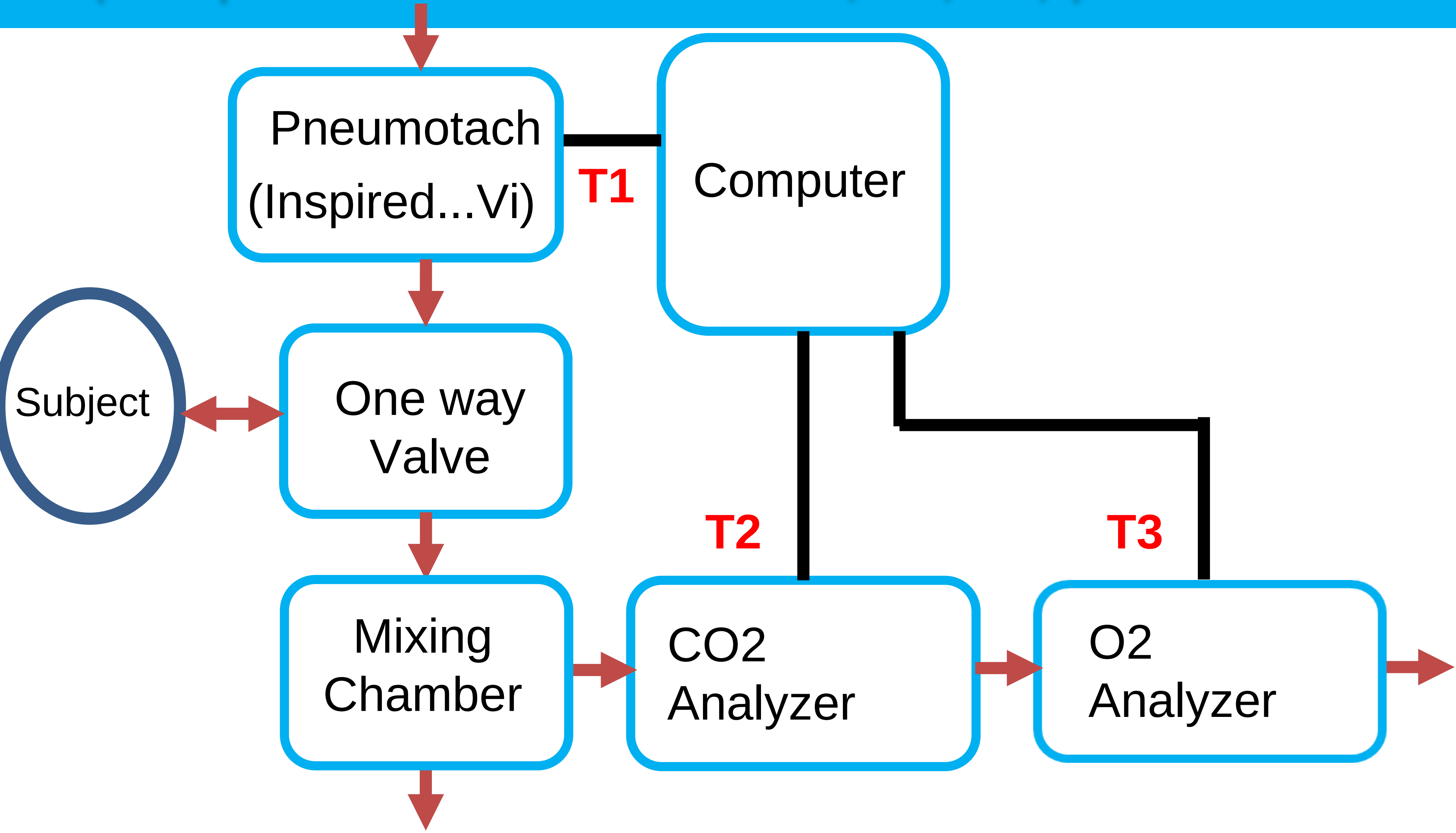
Hans Rosdahl et. al. 2017

(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,)



How to handle all this error
(cant simply add and subtract error – as per Gore et. al.)

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

The following errors are included:

1 = VO2 error from cal gas 1

2 = VO2 error from cal gas 2

3 = VO2 error from Fe (O2 sensor error)

4 = VO2 error from Fi (O2 sensor error)

5 = VO2 error from Fe (CO2 sensor error)

6 = VO2 error from Fe (CO2 sensor error)

7 = VO2 error from Ve (ventilation error)

…

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

VO2 error: A worked example
(only the critical errors examined – not sample H2O)

From AEI Moxus system: (all values absolute)

O2 error = 0.01 > VO2 error = 0.38%

Cal gas 1,2 = 0.02 > VO2 error = 0.76%

Vi = 1.0%

$$(VO_2 \text{ error})^2 = (0.38)^2 + 2(0.76)^2 + (1.0)^2$$

$$VO_2 \text{ error} = 1.5\%$$

Reference values:

VO2 = 4.5495

VI STPD =136.10

VE STPD = 136.70

FIO2 = 0.1751%

O2 = 0.2093%

Enter MS Excel Macro

Open VO2 error Macro

Projected VO2 Error for various metabolic systems

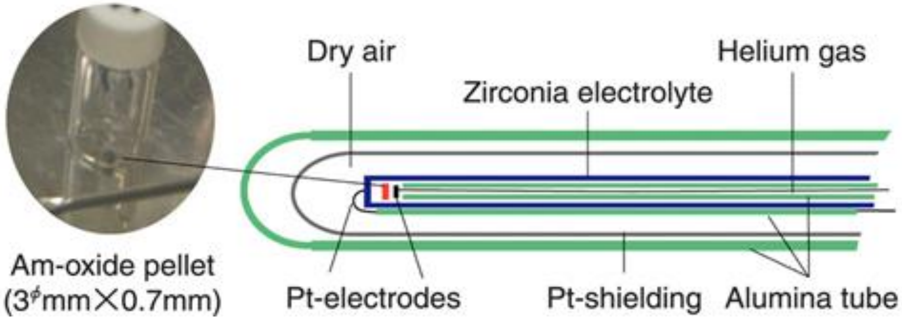
(Based on manufacturer specifications – absolute values)

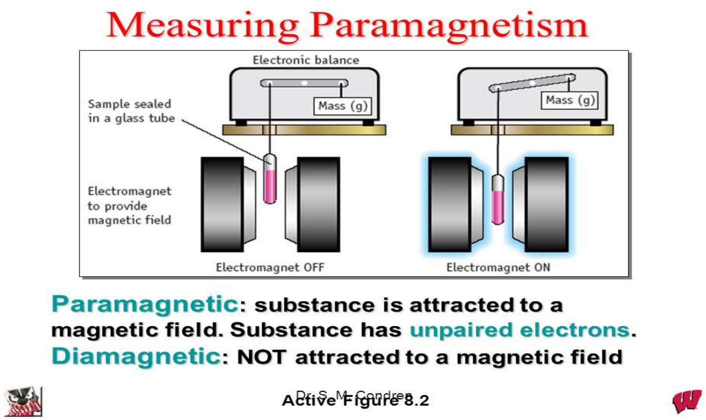
MANUFACTURER & MODEL	O_2 SENSOR TYPE	O_2 CELL LIFESPAN	O_2 ACCURACY % ABSOLUTE	CO_2 ACCURACY % ABSOLUTE	VENTILATION ACCURACY % ABSOLUTE	VO_2 ERROR
AEI Tech.	**Zirconia**	**20-30 years**	**0.01**	**0.02**	**1**	**1.16**
Other 1	Galvanic fuel cell	12-18 months	0.04	0.04	2	2.96
Other 2	Paramagnetic	5-10 years	0.1	0.02	2	5.73
Other 3	Paramagnetic	5-10 years	0.1	0.1	2	5.85
Other 4	Galvanic fuel cell	12-18 months	0.1	0.1	3	6.25

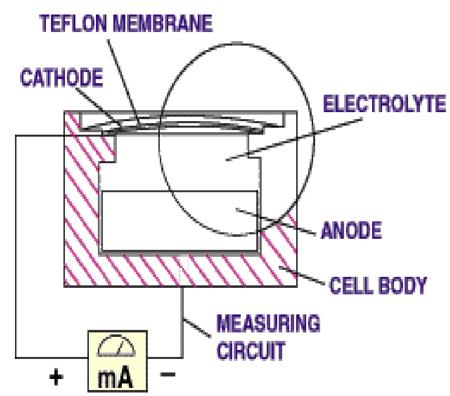
Note that our systems provide the highest accuracy for both Oxygen and Ventilation on the market, giving rise to much superior metabolic accuracy.

O2 Sensors
(most critical sensor!)

- Zirconia
- Paramagnetic
- Galvanic
- others (not used)



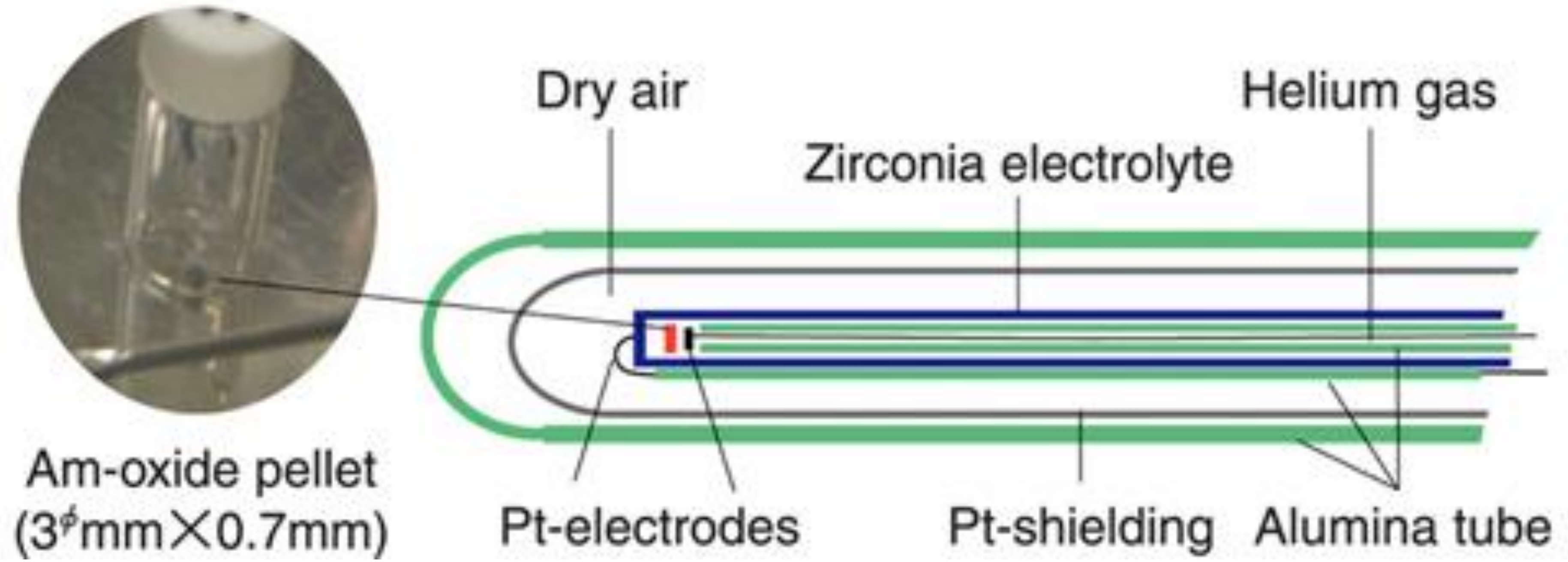




Zirconia

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

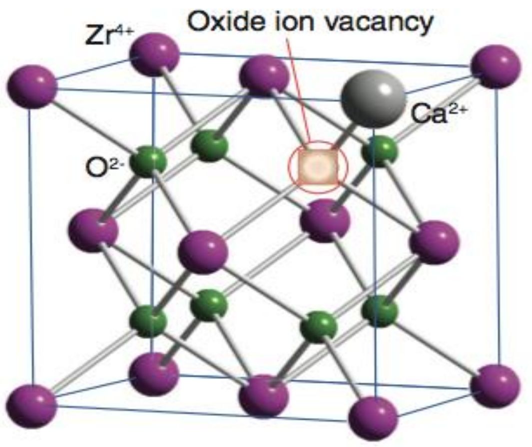
Following reactions occur between the electrodes

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



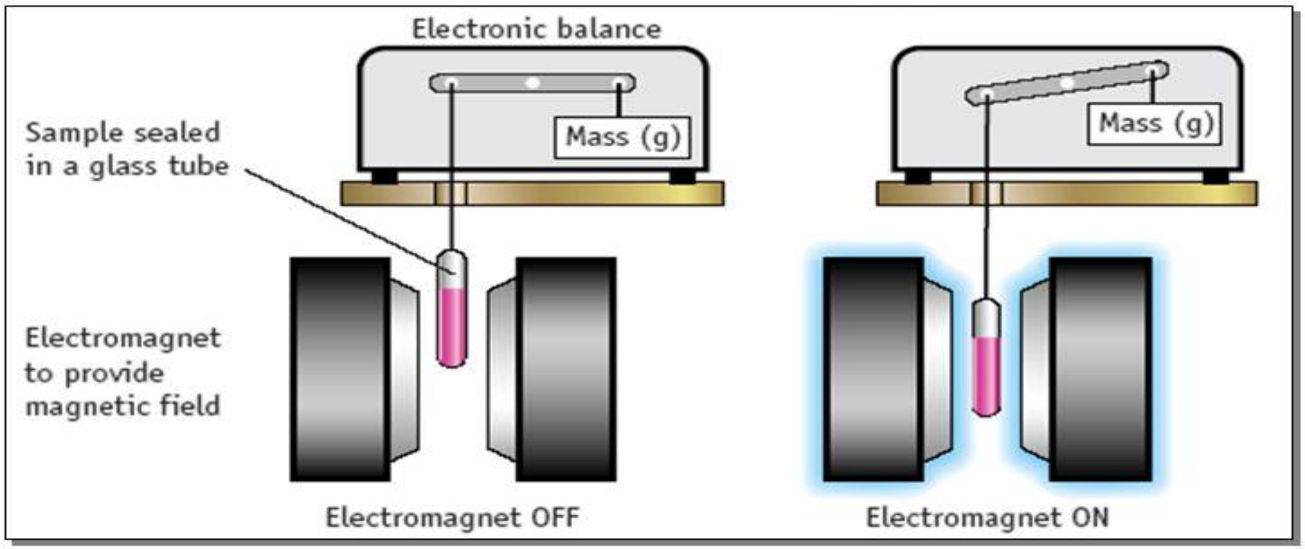
Photosynthesis Experiment (O_2)

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 O_2 sensors

- **Uses the paramagnetic property of oxygen**

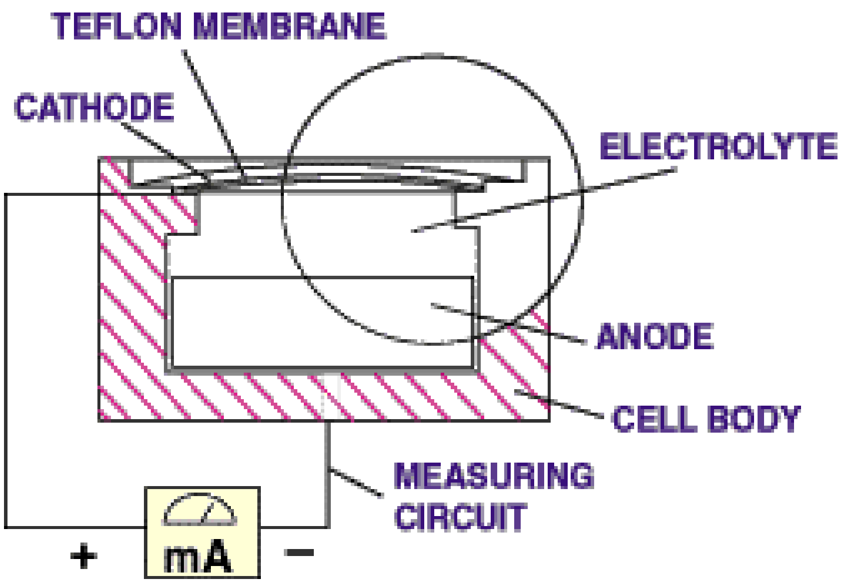
  (ability to be magnetized by applied magnetic field)

- **Measures oxygen with high precision**

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

  - **Accuracy = 0.05%**
  - **Drift = 0.01% O_2 /hr**

Galvanic Cell O2 sensors



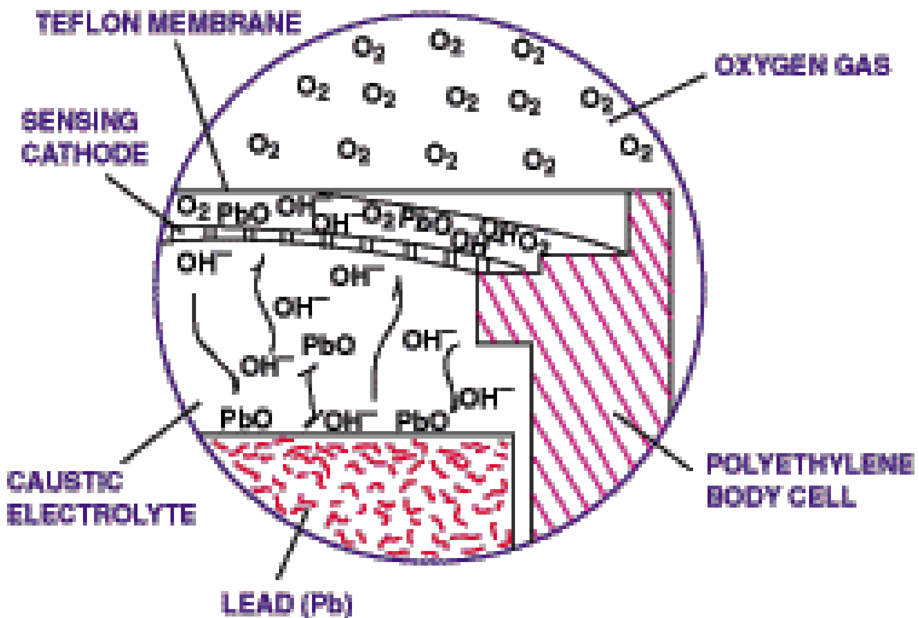
Jelly electrolyte applied to gold cathode & silver anode

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

Summary

- Most important VO2 error factors: O2 sensor, Cal gas, Flow and sample humidity
- Other important factors probably: Sample phase delays, & valve setups (T vs Y)
- The O2 sensor mathematically 50 times more important than next sensor, Ventilation. So O2 accuracy
- Sample humidity, its treatment, measurement and compensation for VO2 QC. Replace Nafion regularly (6 months) & and b/w tests (Or a Peltier device).
- Add VO2 errors use sum of squares. Examine met carts for accumulated errors. Specs with 0.1% O2 error seems low but actually very high VO2 error. 2-3% Ventilation is high.
- O2 sensors not equal. Accuracy, sensitivity & drift important. Low cost sensors not always best..

Thanks for their help.

Ian Fairweather.

Dr. Hans Rosdahl, GIH, Sweden.

Dr. Thomas Steiner, BASPO, Switzerland.

Phil Loeb, AEI Technologies, USA.

Dr. Chris Gore, AIS.

Dr. Jens Westergren, Dalarna Sports Academy, Sweden.

Jamie Plowman, AIS.

Tom Stanef.

References

Physiological Tests for Elite Athletes, Second Edition, Australian Institute of Sport, Chapter 7.

Principles of Exercise Testing and Interpretation, Fourth Edition, Wasserman et.al.

Design Control Guidance for Medical Manufactures, US Food and Drug Administration.

American Thoracic Society & American College of Chest Physicians Joint Statement on Cardiopulmonary Exercise Testing, 2003.

MOXUS Instruction Manual, AEI Technologies.

Where to next?

The facts behind

- Mixing chamber
- Breath by Breath
- Douglas Bags
- Metabolic calibrators
  – water vapour

Dedication

Tom Harvey

13 November 2017

R.I.P.

RMIT UNIVERSITY

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

HESTA 2017

Thank You

Danny Rutar

redback biotek