Errors in VO2 Testing

First presented at the 12th Asian Federation Sports Medicine Congress in Amritsar, India

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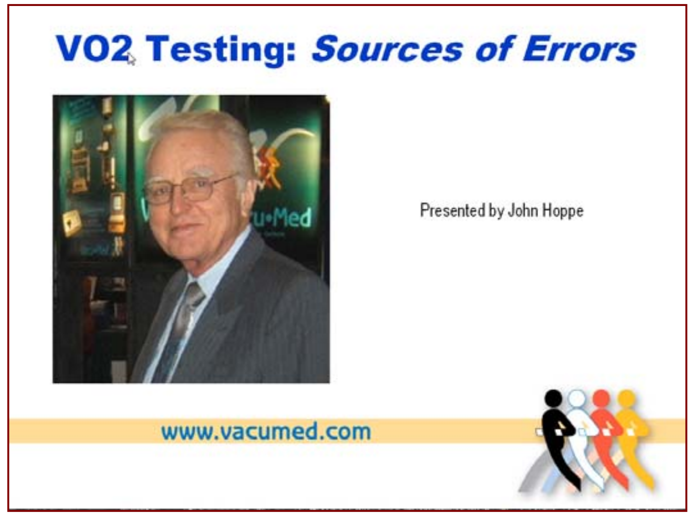


After calibrating the gas analyzers, calibrating the flow sensor and entering ambient parameters (pressure, temperature, humidity) it is assumed that the instrument will produce accurate results. Really?

Well, I am here to tell you there is potential for error from many other sources.
Many assumptions are made,
Basic questions:
Are gas analyzers and flow sensor linear?
Are there software errors?
Are there issues with technique or method of testing?

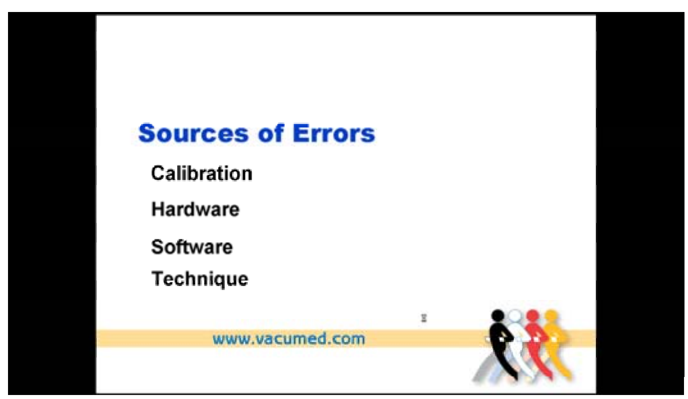
Why is accuracy important?

For example: VO2max testing is used prior to heart or lung transplantation. Peak VO2 of 14ml/kg/min has been used as a cut-point for risk stratification of patients on a transplant list, although there remains considerable debate about this.

VO2 testing is used to determine degree of disability, but problem here is that test subject is NOT motivated to make maximal effort.

In Rehab, VO2 testing is used to measure the progress and outcome of rehabilitation.

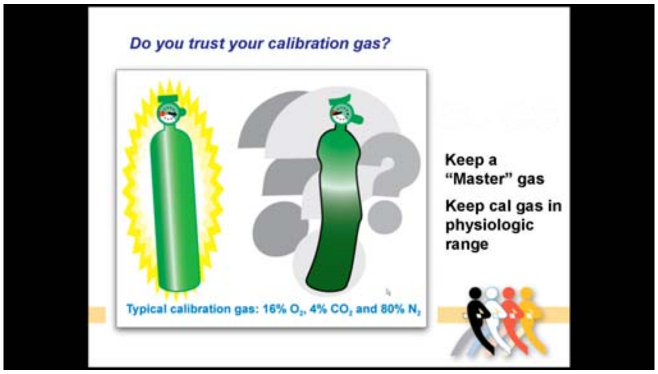
In athletics, VO2 testing is used to measure the progress of training programs, to compare athletes to each other and also to determine their anaerobic or lactate threshold, which is often used by athletic trainers as a training guidepost.



Note: It should be understood that mentioning VO2 in the following document also includes VCO2.

CALIBRATION related errors:

Improper calibration seems to be the most common problem in VO2 testing.



Calibration gas – questionable local source:

An extreme case was a Latin American country. The order was to buy a gas containing 16% O2, 4% CO2, balance N2. It was delivered 4% O2 – 16% CO2.

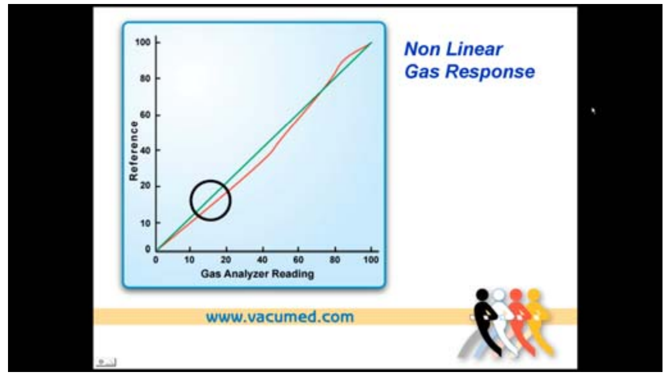
In a European country we had 3 tanks all labeled 5% CO2, but all measured different.

In an Asian country we had a tank from the most "reputable" supplier. The tank said 16.5% O2 but it was more than 17%.

We suggest buying 1 quality gas from reputable company and using that to calibrate other vendor gas. What is the point of research if the calibration gas is unreliable?

Who is reputable? Ok, we are.

Gas Analyzer Linearity



No gas analyzer is perfectly linear, CO_2 is never.

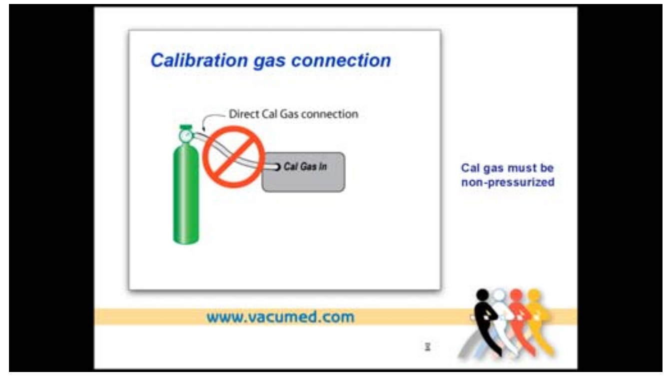
The green line above represents a perfectly linear gas sensor, the orange line an imaginary (and exaggerated) non-linear response. The intent here is to show that calibrating an O_2 sensor with a 100% or zero O_2 gas would not detect a non-linearity in the physiologic range of 14 to 21% O_2.

Using a calibration gas in the physiologic range, such as 15 to 16% and 21% O_2, minimizes the effect of a non-linear O_2 sensor.

Remember, every VO_2 measurement system has an O_2 analyzer. Using ambient air to calibrate it to 20.9% O_2, you can then MEASURE and verify the accuracy of the O_2 content of your unknown calibration gas, if you first establish O_2 ZERO, such as ZERO verification with 100% N_2 gas.

CO_2 is more difficult to verify, ask us about the dilution method.

Note that the typical calibration gas tank contains enough gas for 5 years, but failure to close the tank valve often causes the gas to leak out much sooner. Keeping a spare tank on hand to minimize unforeseen downtime is recommended.



Improper Calibration Gas Connection

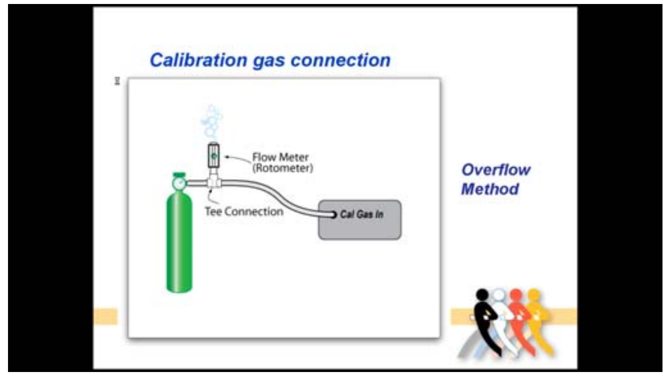
We have seen even experienced users make this mistake.

Never connect the calibration gas under unknown pressure, e.g. in a pressurized bag or direct from a tank without pressure relief. Filling a rubber bag from a tank and then connecting the bag to a gas sensor will also cause miss-calibration for 2 reasons: A bag is never totally empty, so the calibration gas will be diluted with any residual gas in the bag, and also if the bag is even slightly pressurized, the calibration will be wrong.

ALL gas sensors are sensitive to pressure.

Cal Gas must be delivered at atmospheric pressure, but how to make sure ?

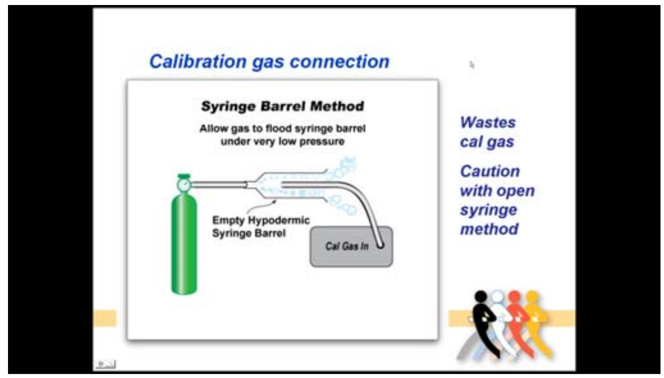
Recommended Calibration Gas Connection



We use and recommend the overflow method. Top of flow meter is open to room air

Adjust pressure regulator so that the small ball within the flow meter floats.

This guarantees that gas is at near-atmospheric pressure.



Open syringe method but beware of problems there also:

If pressure from tank is too high, gas is wasted and may suck in air via venturi-like fashion.

If gas flow is too low, tube to gas sensor may mix with air.
Proper method: hold partially close,
Hold to lips to verify outflow

Volume Calibration Issues?

- **Could be leaky calibration syringe**
- **Failure to push full stroke**
- **Out of calibration**

Some flow sensors are very sensitive to flow rate, they must be calibrated at different stroke rates. Moreover, some of those are also sensitive to gas composition.

Check accuracy against other syringes, this is not foolproof but it's unlikely that 2 or more syringes are equally bad.

Sticky syringe? Spray silicone oil lightly into barrel.

Best to total 10 strokes. This averages small variations.

Problems with Ambient Gas Concentrations

Lack of Ventilation:
The room is too small
Too many people in the room

Big Problem, especially for resting metabolism measurements.

But also causes inaccurate calibration if room air used for calibration.

Then ambient (inhaled) gas is not as expected, or changes during the test.
(CO_2 >0.04, O_2 <20.94)

We have had customers complain that the CO_2 analyzer drifts, but they had 20 students in small room. Analyzer was MEASURING CO_2 accumulation, not drifting.

These problems are often more visible in closed environments, such as closed off rooms in winter or air-conditioned rooms in summer where air is recirculated.

Gases flowing from calibration gas tanks and gas mixtures from metabolic simulator will affect ambient gas.

Inaccurate Ambient Inputs:

Gas sensors, as previously mentioned, can cause hardware and software problems.

Temperature, barometric pressure, humidity sensors are often used as delivered by the manufacturer. If they are software integrated with the VO2 measurement system, then these sensors may need to be recalibrated after installing software upgrades.

Sampling sites in BBB or Mixing chamber systems. For example, if the gas sampling port is located at the exit of the mixing chamber, care must be taken that during inhalation, when there is no outflow, ambient air cannot backflow and mix with the exhaled gas.

Flow sensor:
None is perfect, but some are better

In general, turbine is best

Look in contrast Pitot, Variable Orifice and Ultrasonic

Ventilation Measurement Devices

Properties	Linearity	Temperature	Noise*	Thermal Conductivity	Position	Barometric Pressure	Humidity	Viscosity	Gas Density	Response Time	Cost
Transducer Type											
Pneumotachometer	😐	☺	☹	☺	☺	☺	☺	☹	☺	☺	$$
Turbine	😐	☺	☺	☺	☺	☺	☺	☺	☺	😐	$
Pitot**	☹☹	☹	☹	☺	☺	😐	😐	☺	☹☹	☺	$$$
Variable Orifice	☹☹	☹	☹	☺	☹	😐	😐	😐	☹	☺	$$
Hot Wire (Mass Flow)	😐	☺	☺	☹☹	☹	😐	😐	☺	☹	😐	$
Ultrasonic	☺	😐	☺	☺	☺	☺	😐	☹	☹☹	☺	$$$
* = Mechanical & Acoustic											
** = Some of the disadvantages may be software-correctable with gas sensors											

Non-Rebreathing Valve

First of all: the name. Breathing valve, non-rebreathing valve T- or Y-valve is fairly clear, but other names can lead to confusion.
It contains 2 one-way valves, so it is not a one-way valve. Note also that each breathing valve adds some dead space, which will be rebreathed.

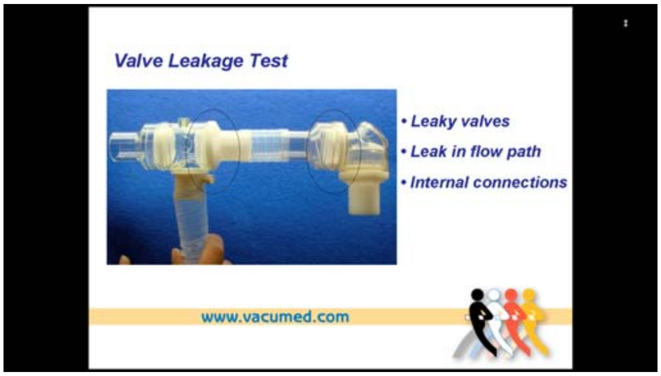
Rubber strings holding silicone valve diaphragm repeatedly get stretched to max

Result: Leaks

Replace valve diaphragm every 6 month or at least test for leakage.

And disassemble, sterilize and clean the valve components after each test. If the last person tested had TB, do you want to be next?

How to Leak-test a Valve:



Push 10 strokes of a 3-liter syringe into the mouth port of the valve under test. Note the total accumulated volume in you metabolic measurement system software, it should be around 30 liters.

Now add a 2nd one-way valve in series with the valve under test, as shown. This 2nd valve can be just a portion of another non-rebreating valve.

Repeat the 10-stroke maneuver. If the volume is now higher, you know the size of your leak.

Programming Errors or “Bugs”

Just because it’s from a computer does not mean it’s accurate. Software (programming) errors occur for a variety of reasons, but willful "Adjustments" by programmers to correct some unknown cause of inaccuracy are not uncommon. We call it “Fudging”.

Barometric pressure, temperature and humidity sensors, examples:

Humidity error of 10% = ½% error in VO2
Temperature = error?
Baro = error

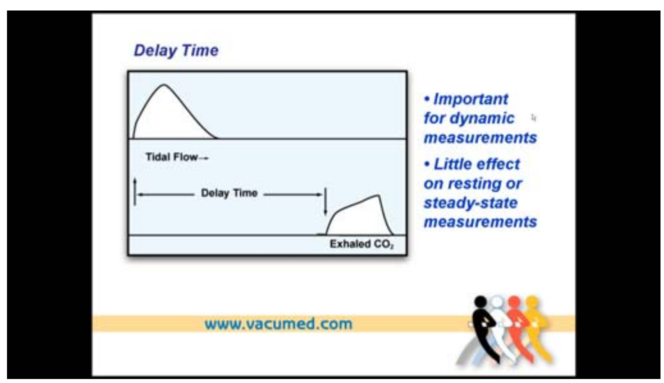
Exhaled gas temperature has to be measured at the site of the flow sensor because volume of gas changes with temperature.

Where the flow sensor is located near the mouth, it would be easy to assume that the temperature is 37°C.

But publications we saw had it measured at 33°C or 34°C two inches away from mouth.

Time Delay

Another software issue is the delay time between the tidal flow measurement (Vt) and the arrival of the gas belonging to that breath at the gas sensor.

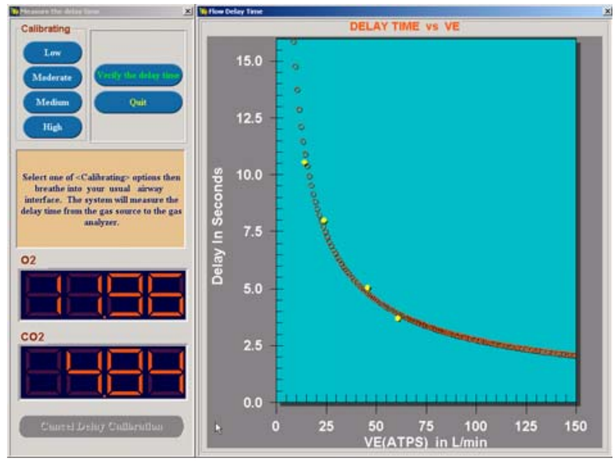


Delay Time affects dynamic measurement (Changing workloads)

We simply measure the time lag from start of Vt to start of CO2 rise.

How do you check?

Screen shot from VacuMed's Turbofit© software



(Mixing chamber version)

Delay time varies with length and diameter of tube.

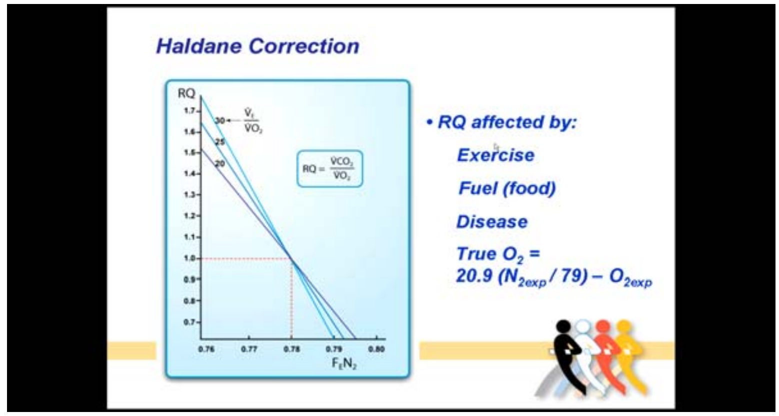
So what if you change length of tube?
How long can it be?

We measure time from first turbine spin to rise of CO_2 (Or fall of O_2) at four ventilation rates, from slow resting breathing to near panting to simulate maximal exercise breathing.

Our software then plots Delay Time vs. Minute Ventilation.

The breath-gas concentration alignment is then dynamically implemented during a real test.

Haldane Correction



The Haldane correction (Transformation) is used to compute True O2

True O2 varies with RQ.
Typically, at rest the avg. RQ = 0.85.
This means that for every liter of O2 consumed, we exhale 0.85 L of CO2.

Near maximal effort our RQ might be 1.1, then for every liter of O2 consumed, we exhale 1.1 L of CO2.

So this deficit or excess of CO2 has to by made up by N2. N2 acts as a shrinking or expanding buffer.

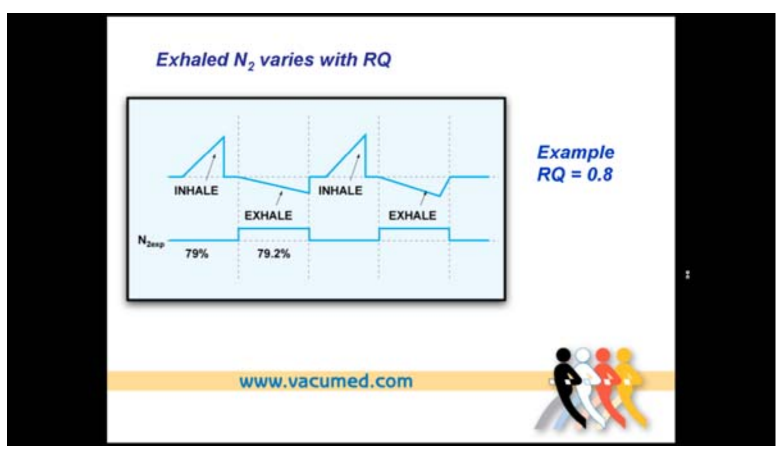
RQ also depends on the fuel (food) we eat. Fats lower RQ, carbohydrates increase RQ, with a typical range of 0.7 to 1.0.

During exercise anaerobic processes increase CO2 output so that RQ can increase above 1, to 1.3 or even higher post-exercise.
(CO2 wash-out)

True O2 = Haldane equation

Beware of errors caused by the Haldane Transformation if FiO2 is larger then 40%.

If one were to show a strip chart recording of Tidal Breathing vs., N2%, it might look like this



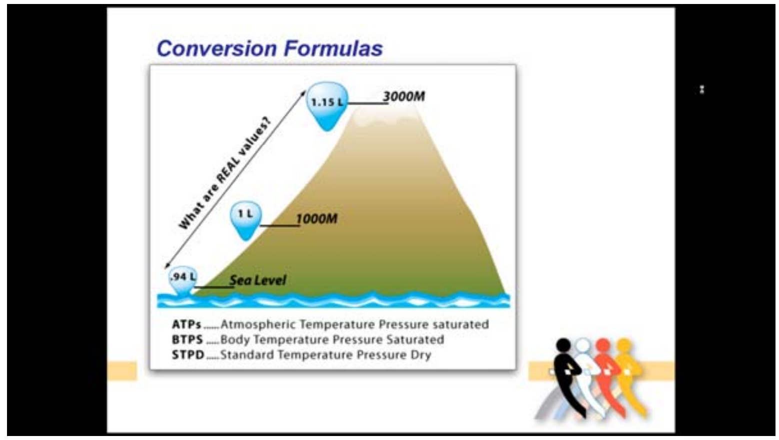
But if RQ = 1, then no change in N2

If RQ = higher than 1, then opposite

(N2 + Ar = 79)

Standardization of Data

Fill a bag with 1 liter gas at 1000 meter altitude, close the bag, then take it up or down and the volume changes.
In order to standardize, volume is typically reported in STPD.

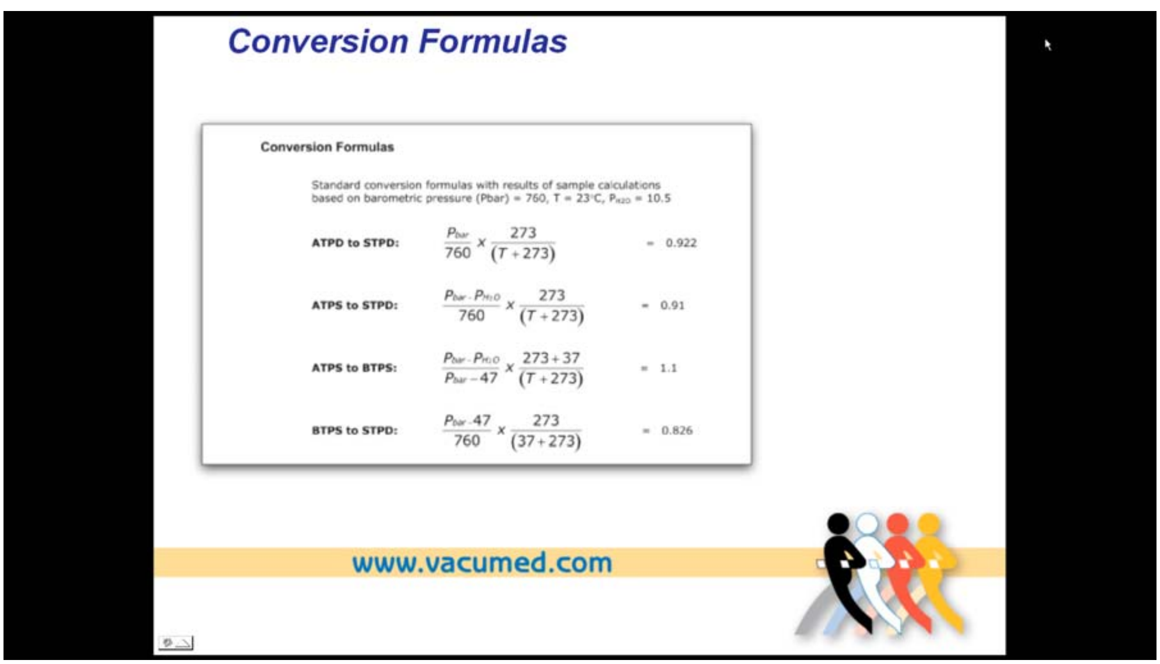


ATPs - BTPS - STPD

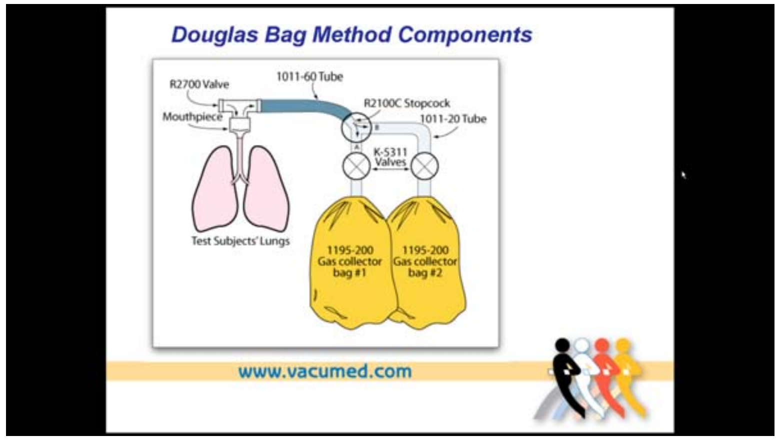
STPD = Standard Temp (0ºC)
Pressure = sea level (760 mmHg)
Dry = zero humidity

Don't underestimate the possibility of error.

Conversions – remember, a Mars mission failed because improper conversion between the metric and American system.



Validation: What is it?



A potential customer asks about validation, or asks to see some publication how the system was validated.

Here is an example of "validation":

You buy a pound of meat, you suspect you were cheated, so you go across the street and ask another vendor to weigh it for you.
It also shows 1 pound. Are you happy?
Does it prove the first scale was correct?
What if all vendors on that street are cheating?
Maybe both scales are correct, maybe both are wrong!

Commonly, they "validate" one metabolic measurement system against another.
They call it SCIENCE?

The point here is that comparison to another instrument only proves that both could be wrong, both could be right or one or the other is wrong.

In other words, it proves nothing!

The other "Validation" method:

The Douglas Bag Method, some still call it the Gold Standard but it is impossible to verify its accuracy because it has no known input.

Then there is manual calculation to verify computer calculation, but the system manufacturer must be willing to give you the formula used to calculate VO2 in their software.

Dr. Astrand laboratory in Sweden

This is how actual Douglas bag setup looks, 1 bag per minute.

So how do we validate?

The Metabolic Simulator

Australia is the only country to require official certification.

They use a simulator similar in principle to the one shown here to produce known VO2s and VCO2s with 1% accuracy.

More information on this web site:

http://www.vacumed.com/274.html

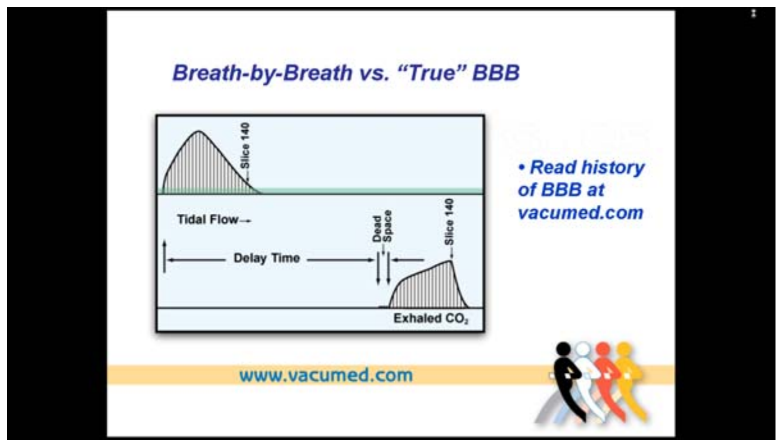
BBB vs. "True" BBB

Basically, there are 2 types of VO2 measurement systems:
Mixing chamber and True Breath-By-Breath.

With a mixing chamber system all the expired breath is routed via a non-rebreathing valve into a mixing chamber where the gas is mixed, or averaged. No need or advantage for fast response gas analyzers here. All VO2 data may be reported after each breath, so it is BBB.

More details as well as the History of BBB on our web site: http://www.vacumed.com/274.html.

The "True" BBB system does not use a mixing chamber; it uses fast response gas sensors to digitize the fast changing flow and gas concentrations as shown in the slices on the right.



Two major problems with "True" BBB: You can clearly see that just a little change in delay time could seriously affect the sampling alignment, thus accuracy.

Second, over-sampling. The thin green band above the Tidal Flow line represents the continuous sample pump demand, typically ½ LPM. At the end of exhalation, especially resting ventilation, the test subject breathes less than that, so ambient air is mixed in and dilutes the sample. A problem in both human and animal (rodent) studies.

Australia so far is the only country in the world that requires all VO2 systems to be tested by the Australian Institute of Sport.

Fact:

There is not a single advantage to "True" BBB!

Not a single "True" BBB system has passed the Australian Institute of Sport accuracy testing.

Failure to get resting data, wrong RQ.
Some one says RQ does not look right.
Can't tell if start at 100W

Leaks in valve, face mask, breathing circuit

Calibration: Gases, flow sensors, ambient conditions.

So how to make sure all is ok?
At min, Know yourself! Test yourself to know your own VO2 in steady state condition

Improper (or none) calibration of ergometer
You work at 100W and expect a VO2 of ~ 1.5 L for a 60kg subject, now what?

Treadmill handrail holding reduces measured VO2 by up to 15%.

Checking Zero-offset: Another way to check correct VO2 is to breathe into the flow sensor (or mixing chamber) but disconnect the gas sampling tube so that the tube samples ambient air instead of exhaled breath. This should result in 0.00% VO2 and VCO2. Typically, a slight offset may be seen. Let's say we see a +0.030 VO2. This suggests that an exercise generated VO2 of 3.000 includes that offset and if the offset were eliminated that the actual VO2 would be 2.970. Only a 1% error, not a serious issue. But deduct this offset from a 0.300 resting VO2 and you have a 10% error!
We know of one company that prevents its software from reporting any VO2 below a certain value, making the offset check impossible.
Now why would they do that?