Carbon Dioxide
&
Diving Apparatus

Testing for Re-Inspired Carbon Dioxide

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GLOSSARY OF ABBREVIATIONS

ALPM	Actual Liters Per Minute
ATA	Atmospheres Absolute - 1 ATA=14.7 psig
BAR	Bar - one bar = 14.5 psig
BPM	Breaths Per Minute
CE	Symbol for European Conformance
ET	End Tidal - the end of exhalation where gas flow stops
ET CO2	End Tidal Carbon Dioxide **-** the level of CO2 in exhaled gas at the very end of exhalation
EU	European Union
FSW	Feet Sea Water
J/L	Joules Per Liter
LPM	Liters Per Minute
MBR	MILLIBARS - pressure measurement often used for atmospheric pressure readings and partial pressure reading of gases within a mixture of gases
MSW	Meter Sea Water
PSI	Pounds Per Square Inch
PSIG	Pounds Per Square Inch Gauge
RMV	Respiratory Minute Volume - the volume of gas moved in and out of the lungs in one minute. Volume in liters multiplied by the number of breaths per minute equals the RMV
SLPM	Standard Liters Per Minute
WOB	Work Of Breathing - measurement of breathing effort

1.0 Understanding CO_2 & Diving

The main intension of this article is to explain in detail how Dive Lab measures re-inspired CO2 when testing Diving Helmets and Full-Face Masks based on our interpretation of the current standards and practices required by industry standards and others. Dive Lab does not claim to be the authority on this subject however, we have been doing this type of testing for many years, and we do it regularly on diving helmets full face masks and wide variety of other breathing apparatus. We are always looking for ways to improve our test procedures. When Dive Lab tests equipment, the testing is done in accordance with the requirements of the standard being used. In some cases, Dive Lab also performs tests that are not in accordance with specific standards. This is often done an effort to draw a parallel with established test standards and procedures. We welcome all positive and negative criticism

The first few pages of this paper reviews the basics of CO2 as it effects the diver, as well as a basic explanation of terms. This paper has been written in a style for persons having more than just a casual understanding of the effects of CO2 and testing process for measuring Re-Inspired CO2.

1.1 Understanding the Effects of CO_2

Understanding the effects of CO2 on the diver the diver, is of great importance. For most new divers entering the world of commercial diving or even sport diving, very little focus is placed on the importance minimizing CO2 retention in diving apparatus and body. Excessive blood levels of CO2 can be dangerous. The sneaky insidious effects of CO2 can often go unrecognized by divers that are not doing things right or paying attention. Early symptoms range from labored breathing, irritability, headache, confusion, not necessarily in any particular order. As the CO2 level increases a total lack of judgment from the narcotic effect of CO2 can occur. In addition, deep air diving that results in nitrogen narcosis, will be further influenced by the narcotic effects of elevated CO2, and people breathing high partial pressure of oxygen (PPO2) are also at a much greater risk of oxygen toxicity. Understanding the signs and symptoms of high CO2, and what to do to counter it extremely important. But first, a review of the basics.

1.2 CO_2 Production

CO2 is produced by the body as a product of metabolism. Normal atmospheric air is made up of approximately 20.95% oxygen, 78.09% nitrogen, 0.93% argon, and 0.04% (.004) of carbon dioxide. With most healthy people, the amount of CO2 produced during the respiratory process is fairly close to the amount of oxygen metabolized. The higher the work rate the greater the oxygen consumed, and CO2 produced. Besides the breathing work rate, CO2 production is influenced by individual fitness and diet as well as individual physiology. It is important to understand some persons have a dulled response to increased blood level CO2, what is called CO2 retainers, while others may be very sensitive to elevated blood CO2. The normal accepted ratio for oxygen consumption and CO2 production is for each liter of oxygen consumed, 0.9 liters of CO2 is produced. With most people, the ratio is probably more like 0.75-0.85 liters of CO2 for every liter

1.2 CO_2 Production - continued

of oxygen consumed. Persons that have a diet high animal protein will produce slightly more CO2 than those on a plant-based diet. Physiologist as well as other professionals specializing in respiratory studies have made breathing rate categories for different activities. For diving, the U.S. Navy as well as others, uses a number of different breathing rates to evaluate diving helmets, full face masks, and other man worn breathing equipment. The blood level CO2 can be significantly affected by the breathing apparatus used so understanding how to use the equipment properly and understanding how to keep CO2 levels below dangerous levels is the main intent of this article. This article will primarily focus on work rates established for diving equipment which is different than rates used for firefighting equipment or other equipment intended for use in non-hyperbaric environments. In addition, this article deals with testing using a mechanical breathing simulator.

1.3 Breathing Rate/ Work Rate

To accurately measure breathing performance and CO2 retention in man worn diving equipment, a mechanical non-compliant volume breathing machine is used that can mimic human breathing volume and breaths per minute and breathe the equipment at known tidal volumes (TV) and number of breaths per minute (BPM) the tidal volume multiplied by the breaths per minute make up the respiratory minute volume (RMV). Internationally for diving apparatus there are a number of RMV's used, ranging from 10 to 90 RMV. As an example, the U.S. Navy respiratory rates start at the low RMV rate of 10 RMV. Ten RMV is made up of a 1 liter TV, and 10 (BPM) and represents what a diver at rest on a stage during decompression would do. Light to moderate work is regarded as 22.5 RMV and is made up of a 1.5 TV by 15 BPM which might represent a diver slowly walking on the bottom, doing light work such as performing an inspection, photographing, or performing a simple light rigging task. Next is heavy work, and for most starts around 38-40 RMV, so we use a 2.0 liter TV, by 20 BPM, and this would be equivalent to swimming at one knot or running at 7 miles per hour. Next, 50 RMV, (2.5 TV X 20 BPM) this is now approaching the extreme range of what many can do for more than a few minutes. Then the extreme rate of 62.5 RMV (2.5 TV X 25 BPM), and finally 75 to 90 RMV which is considered severe work. 75 RMV is made up of a 3.0 TV X 25 BPM and 90 RMV (3.0 TV x 30 bpm). Keep in mind 75 and 90 RMV can easily be done at one ATA but as depth increases so too does the density of the gas increasing overall breathing effort. Add to this the restriction of the divers' exposure suit and work becomes much more difficult

1.4 Re-inspired CO_2

Simply put, re-inspired CO2 is the amount of CO2 that is re-inhaled during each breath. Even with nothing covering the mouth or nasal area, there will still be a small amount of CO2 re-inhaled from the area in front of the mouth. Covering the mouth and nose, or completely encasing the head such as when using a diving helmet, adds what is called dead space, which greatly increases

1.4 Re-inspired CO_2 - continued

the amount of re-inspired CO2. With helmets and full-face masks, the "Dead Space" is the physical volume inside the equipment that encompasses the oral nasal cavity. There is always a portion of previously exhaled breath re-inhaled due to this space. A good example of re-inspired CO2 is a simple diving snorkel. When breathing from a snorkel, as the user reaches the end of exhalation, the tube is filled with an air mixture containing approximately, 4.0-to 4.5% % CO2 with most people. The very last portion of the exhalation thru the snorkel will have the highest percent of exhaled CO2. At the beginning of the next inhalation, the entire volume of the snorkel is re-inhaled into the lungs first, before any fresh air makes its way in. The larger the physical volume of the snorkel, the greater the amount of re-inspired CO2.

The snorkel is a good example because of its smooth cylindrical shape allow all the gas to transfer similar to liquid in a syringe, even when a small breath is taken. Now picture breathing from an irregular shape such as an oral nasal mask, full face mask, or diving helmet, the exchange of gas eddies, tumbles, and does not exchange smoothly like the snorkel. For this reason, a snorkel having the same physical volume as an irregular shaped item like an oral nasal mask will show more re-inspired CO2 due to eddying, swirling within the irregular cavities of the mask and breathing components.

1.5 Primary Factors Influencing Re-inspired CO_2

There are three primary factors that influence the amount re-inspired CO2. "Physical Dead Space Volume", "Gas Flow Path", "Breathing Resistance" and lastly proper ventilation. Proper ventilation does not apply to a breathing simulator but does to a human. Persons "Skip- Breathing" or controlling inhalation and exhalation in an effort to conserve air is the best example.

1.6 Dead Space

The dead space is the volume within the item being breathed thru, however it can also be linked to the space within a full-face mask or helmet. With a simple SCUBA regulator or snorkel, the physical volume is very small, (less than 200 ml) and generally the potential for significant re-inspired CO2 is minimal. However, if you take the same regulator or snorkel and attach it to a full-face mask with an oral nasal that does not seal well to the face, both inhalation and exhalation gas may escape from the oral nasal mask interior to the interior space of the full face mask or diving helmet. Add to this, that CO2 is 50% heavier than air and has a tendency to collect. The collection of dead space CO2 this is why all helmets and full- face masks should be lightly purged at least every few minutes.

1.6 Dead Space - continued

Examples of Items with Dead Space

1.7 Gas Flow Path

The gas flow path is simply how smooth and how well the gas can move through and exchange the gas within the space. Gas flow path is important because even though the actual dead space volume may be small, if the gas swirls and eddies, the CO2 level will show a higher value.

1.8 Breathing Resistance

Breathing resistance and compliant volume are directly linked when using a full-face mask or diving helmet. The compliant volume of the system is the expansion and contraction of the physical breathable volume within the helmet or full-face mask due to the face seal or neck dam volume change. If the inhalation effort is high, the neck dam and compliant spaces will contract allowing the user to breath this gas which may contain trapped CO2. The volume change acts much like an accordion or bellows, this is especially true with diving helmets that have excessively large neck dam expansion and contraction compliance. Even full-face masks can have significant expansion and contraction of the face seal if breathing resistance is high. Keeping the helmet or mask in tune and adjusted for least amount of cracking pressure helps reduce the compliant volume exchange effect. Additionally, venting the mask or helmet every two to three minutes will help keep CO2 levels low.

1.9 Improper Ventilation

Most commonly known as Improper Breathing or "Skip Breathing". For divers it is important to breathe long and deep in a comfortable manner. Never take short shallow breaths. And never skip breath as some SCUBA Divers do in an effort to conserve air. The diver should not work at a level so high that the diver cannot carry on a simple conversation with topside. When breathing at low ventilation rates such as performing light work, or during decompression, the surface supply diver should crack open the steady flow slightly, or set up a slight hiss on the demand regulator just enough to keep a very small, almost unnoticeable flow of gas into the helmet or full face mask.

1.10 Symptoms of CO_2 Exposure

The symptoms of elevated CO2 will generally be more pronounced when diving, as compared to the surface due to elevated gas density and increased breathing resistance. One of the most common symptoms is loss of concentration others include those listed below and may appear in any order.

- Irritability
- Increased breathing rate
- Shortness of breath
- Narcosis
- Euphoria
- Confusion/disorientation
- Headache
- Panic

1.11 Minimizing CO_2 for the Diver

- For helmets and full-face masks, Insure the oral nasal fit is good. This means making sure the headliner of the helmet is packed so the helmet is snug and forces a good comfortable fit into the oral nasal mask so that when the head moves the helmet moves with it. "*Pre-Dive Preparation*"

- "Insure", the oral nasal one-way valve, seals properly in the oral nasal mask, and the microphone is properly installed in its space. "*Proper Pre-Dive Inspection*"

- "Insure", the supply pressure is adequate for the diving depth and demand regulator bias device (Dial-a-Breath) is adjusted for lowest inhalation resistance and should be readjusted after depth changes and whenever the divers physical attitude is changed. *"Diver staying on top of things"*

- Breath deep, and normal never skip breath. When at rest or very light work rates, set up a very slight free flow to help keep the back ground CO2 low.

- During moderate to heavy work rates, the diver should take at least a 5 second vent every two to three minutes by cracking open the steady flow valve a 1/8-1/4 turn. *Note: You do not need to blast a lot of gas into the helmet, simply flowing light flow by opening the the steady flow open 1/8 to ¼ turn for 5 seconds is all it takes to completely flush out the helmet.*

1.11 Minimizing CO_2 for the Diver - continued

- During periods where the RMV is very low such as during decompression or sitting idol, the diver should crack open the steady flow slightly or set up a slight hiss on the demand regulator just enough to keep a very small, almost unnoticeable flow of gas into the helmet or full-face mask.

1.12 Summary

Summary: All divers must be aware of the symptoms of elevated CO2. Whenever in doubt, "Take a Vent".

2.0 Measuring Re-inspired CO_2 Concept

The concept of measuring Re-Inspired CO2 is relatively simple however, to accurately measure re-inspired takes a good understanding of breathing equipment. Re-Inspired CO2, also known as re-inhaled CO2 or breath by breath washout, is simply the amount (volume) of CO2 that is re-inhaled after exhalation. This becomes important when breathing from anything covering the nose and mouth, as compared to breathing thru nothing. Examples are firefighting and diving full face masks, diving helmets, dust respirators, gas masks to name a few. Persons researching this topic will find there are limits that have been established by the European Union under personal protective device standards such as EN-250, EN15333 and others. The US Navy also has set limits for diving equipment. Finding information on how to actually test and measure re-inspired CO2 can be difficult, and to date we have not found any information that clearly explains in detail the theories and procedures for measuring re-inspired CO2. The intension of this article is to explain in detail how Dive Lab measures re-inspired CO2 based on our interpretation of the current standards. Dive Lab does not claim to be the authority on this subject however, we have been doing this type of testing for many years, and we do it regularly on diving helmets, full face masks, and wide variety of breathing apparatus. We are always looking for ways to improve our equipment, techniques, and procedures.

When Dive Lab tests equipment to particular standards or requirements, the testing is done in accordance with the standard being used. In some cases, Dive Lab also performs tests that are not in accordance with specific standards, this is done in an effort to draw a parallel with established test standards and procedures.

To accurately measure the amount of re-inspired CO2 in breathing equipment requires the use of a mechanical breathing simulator, high speed CO2 analyzer, and a data acquisition system that can record, analyze, and store measurements. The CO2 analyzer and data recording system needs to process at least 1000 samples per second or greater to 95% of the sample reading step change in 150 milliseconds or less. In addition, the mechanical breathing simulator system in use needs to be capable of breathing both tidal volumes (TV) and breaths per minute (BPM) accurately at the required TV and BPM that make up each test RMV. Measuring the CO2 content at surface conditions (1ata) is far easier than measuring at depth. Measuring at depth requires not only a fast analyzer system, but a good data acquisition system capable of displaying proper resolution and scaling due to the partial pressure of CO2 at depth. Getting reliable, accurate data on re-inspired CO2 is generally limited to depths of 60 msw (200 fsw) or less due to the analyzer speed, accuracy, and scaling for depth.

2.1 Breathing Rate/Work Rate

Physiologist as well as other professionals specializing in respiratory studies have made breathing rate categories for different activities. For diving, the U.S. Navy as well as others, uses a number of different breathing rates to evaluate diving helmets, full face masks, and other man worn

2.1 Breathing Rate/Work Rate - continued

breathing equipment. The blood level CO_2 can be significantly affected by the type breathing apparatus used, so understanding how to use the equipment properly and understanding how to keep CO_2 levels below dangerous levels is important. This article will primarily focus on work rates established for diving equipment which is different than rates used for firefighting equipment or other equipment intended for use in non-hyperbaric environments.

To accurately measure breathing performance and CO_2 retention in man worn diving equipment, a non-compliant volume breathing machine is used that can mimic human breathing volume and breaths per minute and breathe the equipment at known tidal volumes (TV) and number of breaths per minute (BPM) known properly, as respiratory minute volume (RMV). Internationally there are a number of RMV's used as pertaining to diving equipment ranging from 10 to 90 RMV. As an example, the U.S. Navy respiratory rates start at the low RMV rate, or resting rate of 10 RMV. Ten RMV is made up of a one (1) liter TV, and 10 breaths per minute (BPM) and represents what a diver at rest on a stage during decompression would do. Light to moderate work is regarded as 22.5 RMV and is made up of a 1.5 TV by 15 BPM which might represent a diver kneeling on the bottom doing work light work such as performing an inspection, photography, or performing a simple light rigging task. Next is heavy work and starts around 38-40 RMV for this, a 2.0 liter TV by 20 BPM is used. 40 RMV would be equivalent to swimming at one knot or running at 7 miles per hour. Next would be 50 RMV, (2.5 TV X 20 bpm) this is now getting into in the extreme range as far as a work rate that could be maintained for by fit persons minutes, up through 62.5 RMV (2.5 TV X 25 BPM), and finally 75 to 90 RMV which is considered severe work 75 RMV is made up of a 3.0 TV X 25 BPM and 90 RMV (3.0 TV x 30 BPM). The EU surface supply standards for breathing are fairly close to the US Navy requirements.

2.2 Primary Factors Influencing Re-inspired CO_2 using a Breathing Simulator

There are three primary factors that influence the amount re-inspired CO_2. "Physical Dead Space Volume", "Gas Flow Path", "Breathing Resistance".

2.3 Dead Space

The dead space is the volume within the item being breathed thru, however it can also be linked to the space within a full-face mask or helmet. With a simple SCUBA regulator or snorkel, the physical volume is very small, (less than 200 ml) and generally the potential for significant re-inspired CO_2 is minimal. However, if you take the same regulator or snorkel and attach it to a full-face mask with an oral nasal that does not seal well to the face, both inhalation and exhalation gas may escape from the oral nasal mask interior to the interior space of the full face mask or diving helmet. Add to this, that CO_2 is 50% heavier than air and has a tendency to collect.

2.3 Dead Space - continued

The collection dead space CO2 this is why all helmets and full- face masks used for open circuit diving should be lightly purged at least every few minutes especially when breathing at very low and very high RMV's.

2.4 Gas Flow Path

The gas flow path is simply how smooth, and how well the gas can move through and exchange within the space. Gas flow path is important because even though the actual dead space volume may be relatively small, if the gas swirls and eddies, the CO2 level will show a higher value.

2.5 Breathing Resistance

Breathing resistance and compliant volume are directly linked when using a Full-Face mask or Diving Helmet. The compliant volume of the system is the expansion and contraction of the physical breathable volume within the Helmet or Full-Face mask due to the face seal or neck dam expansion and contraction. This volume change acts much like an accordion / bellows and is especially true with Diving Helmets that have excessively large neck dam compliance. Some Full-Face masks can also have significant compliance of the face seal. Keeping inhalation and exhalation effort as low as possible helps reduce the compliant volume exchange effect.

3.0 Basic Test Configuration

Test Head Form - Dive Lab has a number of test heads of various sizes primarily for testing full face masks with various size mask skirts. For diving helmet tests for re-inspired CO2 tests, only the larger CE test head is normally used, or other large test heads are used, and the helmet fit of the oral nasal mask is obtained by varying the head cushion padding in the same manner the wearer would do. Testing of full-face masks can be more challenging due to leakage around the oral nasal mask which are often a one size fits all.

With any mask or helmet the measured re-inspired CO2 will always be higher than that of an actual human because the test head mouth does not have lips and flesh which takes up volume and reduces dead space. It is estimated a human face planted comfortably in the oral nasal mask could account for a dead space as much as 25 to 40 % less volume than a rigid test head due to not only the reduced volume, but also the pathway of breathing gas.

3.1 CO2 Sampling

Sampling is done at the center of mouth, 3-4 mm inward from the leading edge. For surface testing, and very shallow depths, we use a single sample catheter having an inside diameter of 0.050 that is approximately 2.0 meters long. The sample is drawn into the sample cell of the CO2 analyzer using a high-speed vacuum pump. For testing to depths of 20 to 60 msw, we use two different size catheters joined together. These are a .010 sample line from the test head thru the top the test chamber approximately one meter long. At the topki of the test chamber the .010 sample line mates to the 0.050 surface catheter which delivers the sample to the analyzer. This set up is critical in order to get a good solid sample wave form when testing at depth. The gas sample traveling from the test mannequin head to the special interface fitting at the lid of the chamber is under pressure, so it travels much quicker than using the 0.050 catheter tube used for surface testing. The special fitting has a vent port which allows excess pressure to escape and allowing the vacuum pump to maintain a steady and uniform sample draw. The sample delay time of two catheters are adjusted by trimming back the surface 0.050 catheter 1 inch at a time until the delay time of the start of inhalation matches that of the surface head only tests. This configuration has shown to be extremely accurate and repeatable works well with Dive Labs ANSTI test system because the sample system is physically located very close to the test chamber (< 1 meter). Systems using long sample catheter runs in excess of 3 meters in length can become distorted due to sample gas mixing in route to the analyzer. The longer the sample line, the greater the gas mixing and possible reduction in accuracy.

Sample Point

3.2 System Calibration

Accurate calibration of the CO_2 analyzer alone is critical. Then calibration of the "test head alone" with the CO_2 flow rates for each test RMV's to be used with the equipment being tested. In general, the test head alone, will show a re-inspired CO_2 value of between .70 to 1.4 mbr depending on the RMV. Normally at a breathing rate of 10 RMV, with the head alone, the CO_2 value will be highest, and as the RMV increases the re-inspired CO_2 value will drop due to the velocity of the sample at the mouth of the test head, room temperature, and number of people in the room that may raise background CO_2 levels. The .70-1.5 mbr re-inspired CO_2 is considered the starting point for the head alone. This value represents the atmospheric background CO_2 in combination with the small residual CO_2 in front of the head. On average the typical back ground CO_2 in air at 1 ATA is .004% (400 PPM, 0.4 mbr) add to this the small amount exhaled by the test head only and you will be in the neighborhood of 0.070 - 0.140 percent CO_2 which if expressed as mbr, would be .70 – 1.40 mbr. European testing (CE) also requires a check using calibration tube having a volume of 110 milliliters. Testing using the tube at 62.5 RMV is supposed to be end tidal (ET) range of 4.0 - 4.2 mbr.

Going from testing the head alone, to anything that adds space around the oral nasal cavity such as a full-face mask, diving rebreather dive surface valve (DSV), or full diving helmet, even just a plain dust mask, the re-inspired volume of CO_2 will always be substantially higher than the head alone. Normally, items such as a SCUBA regulator, simple snorkel, or rebreather DSV with a floodable volume of less than 200 milliliters will show low levels, within the US Navy and European CE standards requirements. The US Navy uses 2% SEV (20 mbr) as the limit for re-inspired CO_2 regardless of the RMV while European Union CE Diving Standards allow for a surface equivalent value (SEV) up to a maximum of 20 mbr (2.0 % SEV) re-inspired CO_2 at breathing rates from 10, 15,22.5 RMV. At 40 RMV and above, the limit is cut to a maximum of 10 mbr, (1.0% SEV) CO_2.

3.3 CO_2 Expression

The data test sheets Dive Lab produces during re-inspired CO2 testing reads in millibar (mbr) as the partial pressure measurement. The measurement can also be expressed as "Percent PCO2" by simply moving the decimal point two places to the left. The data sheets are scaled based on the depth of the testing.

3.4 CO_2 Injection

The US Navy injects CO2 into the system based on 4% of whatever the testing ventilation rate is. The EU CE testing bases the injection rate on what is required to achieve a steady 5% end tidal value (E.T.) for each RMV test rate. Using a straight 5% E.T. results in a slightly higher than actual average E.T. CO2 value as compared to that of a healthy human which has an E.T. CO2 between 4.2, to 4.6%. However, it must be noted that these methods are intended to give worst case for any given RMV, based on the assumption that for every liter of oxygen consumed, 0.90 liters of CO2 is produced. The actual number may be as low 0.75 liters of CO2 produced for each liter of oxygen consumed, so it is understandable why there can be a disparity in how much CO2 the average human produces, and what value is used for test purposes with a breathing simulator system when measuring the re-inspired CO2 in diving masks and helmets. The EU standards are intended to error against the equipment being tested by using a slightly higher % to the ultimate benefit of the user which makes the testing slightly more conservative than using the US Navy system of 4% ventilation. US Navy testing generally will generally show 20-25% less CO2 at RMV'S greater than 40 RMV than the CE test method.

3.5 Stabilizing End Tidal

Dive Lab injects CO2 into the breathing simulator just after the test head one-way valve on the suction side of the breathing simulator. The CO2 is injected into the breathing simulator via a six-foot long 1.1/8" I.D. suction hose. The amount of time required for the end tidal CO2 to stabilize is mainly dependent on the respiratory rate. At the low rate of 10 RMV it can usually take 5 to 8 minutes to fully stabilize depending on the overall volume of the item being tested. The greater the RMV, the quicker the stabilization and at high work rates of 40 RMV or greater, stabilization takes only is 1-2 minutes. Using the 4% of ventilation as a starting point and then adjusting the CO2 mass flow controller until the end tidal CO2 reading at the mouth is steady at 5% is what is used for Dive Lab when testing to the EU standards involving diving apparatus. When testing at each RMV, once it appears the end tidal has maximized and stabilized, we take and record at least at least 5 consecutive loops which are then automatically recorded, averaged, and presented on two separate printouts. One print out represents the breathing volume, the other is based on time. The time loop is used to adjust for the sample delay time between the sample at the mouth and the time it takes to get a peak reading at the sample cell of the analyzer.

3.6 Sample Delay

A vacuum pump within the CO2 analyzer draws a suction on the sample line and draws the sample from the sample point at the test head to the sample cell within the CO2 analyzer. The sample delay time is simply the time it takes for the gas to travel from the test head mouth, thru the sample tube to the analyzer sample cell to give a reading. The sample delay is then coordinated with the breathing machine breathing pressure loop so that the start point of inhalation can be determined. The start of inhalation is determined by adding or subtracting time in milliseconds until the time line lines up with the start of inhalation on the test loop. Note: At Dive Lab, the determination of the delay is done starting at the at the highest ventilation rate first, and that delay time is then used for all the other RMV test rates. We do it this way because at the higher ventilation rates the sample actually travels slightly quicker (20-30 ms). The head alone is tested at each test rmv, see test loops pages below which show the head alone and then with the 110 milliliter CE test tube.

3.7 Understanding the Test Loop

The test sheet marked A1 shows the wave form for the test head only, for 10 rmv, on the surface, at 1ATA. With Dive Labs ANSTI system, the wave form moves clockwise. At the top right of the test loop is where exhalation stops, and inhalation starts, this loop shows the test stroke. This loop is then expanded using a second print out "A2" that shows "time", so that the sample delay can be determined. The shaded area as marked between the time line 3, to approximately 3.65 represents the re-inspired CO2 Volume of the test head alone. For this low breathing rate, the re-inspired CO2 was 1.40 mbr. Test sheet A3 shows the test head re-inspired CO2 when the head is equipped with a 110 ml CE test tube. Note: At the very low breathing rates of 15 RMV or less, the gas is traveling so slow that the head alone CO2 will show slightly higher re-inspired CO2 than that of moderate to heavy work rates where the gas is moving at much higher velocities, allowing for a, more consistent test loop. At 40 RMV with the head only we generally see re-inspired values of less than 1 mbr At 10 RMV, 1.0 to 1.40 is normal.

Carbon Dioxide & Diving Apparatus

ANSTI TEST SYSTEMS - Dive Lab

File	LSTF-0615_20191226_144755.co2m
Date: 12/26/2019	Time: 2:47:55 PM
Run Time (s)	30.028
Equipment	
Serial Number	CEW TUBE CHECK
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.96
Remarks	HEAD ONLY BROOKS 358

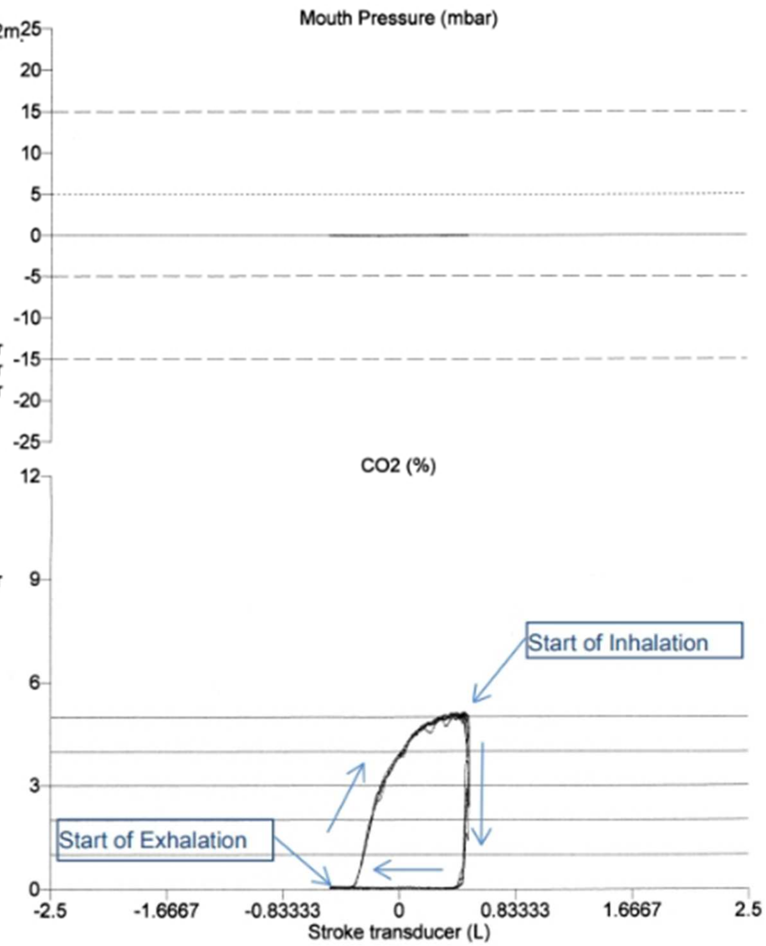
Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.11 mbar	0.10 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.09 mbar	0.08 mbar	0.10 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	660 ms		
VWA PCO2	1.40 mbar	1.05 mbar	1.77 mbar
Equivalent Deadspace at 5% CO2	27.63 ml	20.59 ml	34.76 ml
Time average CO2	0.36 %	0.27 %	0.44 %

Head Only 10 RMV



A1

Carbon Dioxide & Diving Apparatus

ANSTI TEST SYSTEMS - Dive Lab

File	LSTF-0615_20191226_144755.co2m
Date: 12/26/2019	Time: 2:47:55 PM
Run Time (s)	30.028
Equipment	
Serial Number	CEW TUBE CHECK
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.96
Remarks	HEAD ONLY BROOKS 358

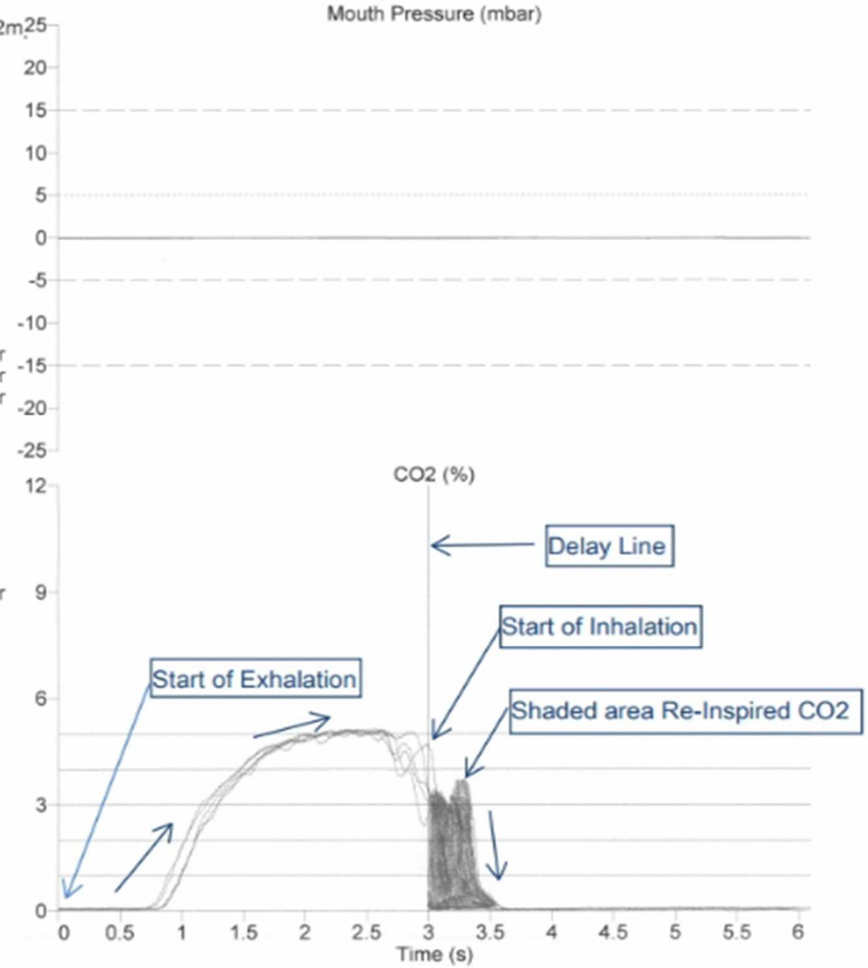
Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.11 mbar	0.10 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.09 mbar	0.08 mbar	0.10 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	660 ms		
VWA PCO2	1.40 mbar	1.05 mbar	1.77 mbar
Equivalent Deadspace at 5% CO2	27.63 ml	20.59 ml	34.76 ml
Time average CO2	0.36 %	0.27 %	0.44 %

Head Only 10 RMV



A2

ANSTI TEST SYSTEMS - Dive Lab

File	LSTF-0615_20200223_131655.co2m
Date: 2/23/2020	Time: 1:16:55 PM
Run Time (s)	12.014
Equipment	
Serial Number	CO2 BASE LINE
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	2.50
Breathing rate (BPM)	24.97
Ventilation (l/min)	62.46
Remarks	HEAD AND CE TUBE 62.5 RMV BROOKS 2801 =2.80 ALPM CO2

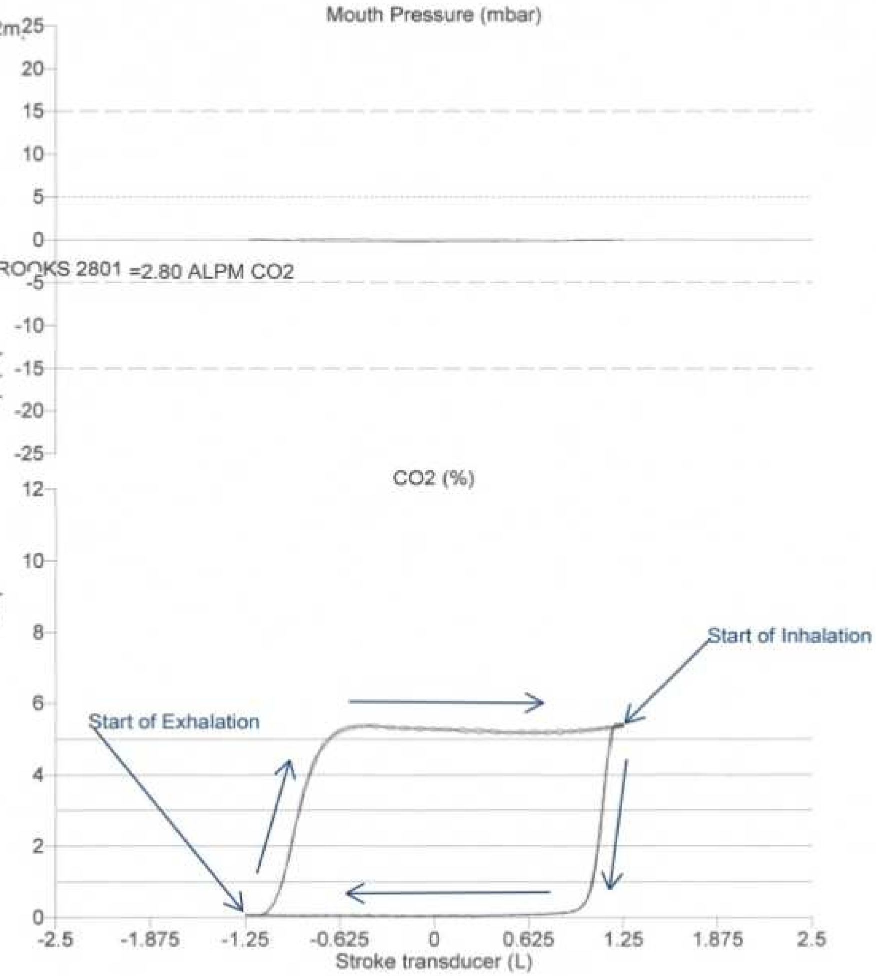
Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.24 mbar	0.23 mbar	0.24 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.01 mbar
Exhale Pressure	0.05 mbar	0.05 mbar	0.05 mbar
Ext Work of Breathing	0.02 J/l	0.02 J/l	0.02 J/l
Ext Inhale Work	0.02 J/l	0.02 J/l	0.02 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	650 ms		
VWA PCO2	4.04 mbar	3.88 mbar	4.13 mbar
Equivalent Deadspace at 5% CO2	199.25 ml	191.65 ml	204.02 ml
Time average CO2	0.88 %	0.85 %	0.89 %

HEAD & CE Tube



B1

Carbon Dioxide & Diving Apparatus

ANSTI TEST SYSTEMS - Dive Lab

File	LSTF-0615_20200223_131655.co2m
Date: 2/23/2020	Time: 1:16:55 PM
Run Time (s)	12.014
Equipment	
Serial Number	CO2 BASE LINE
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	2.50
Breathing rate (BPM)	24.97
Ventilation (l/min)	62.46
Remarks	HEAD AND CE TUBE 62.5 RMV BROOKS 2801=2.80 ALPM CO2

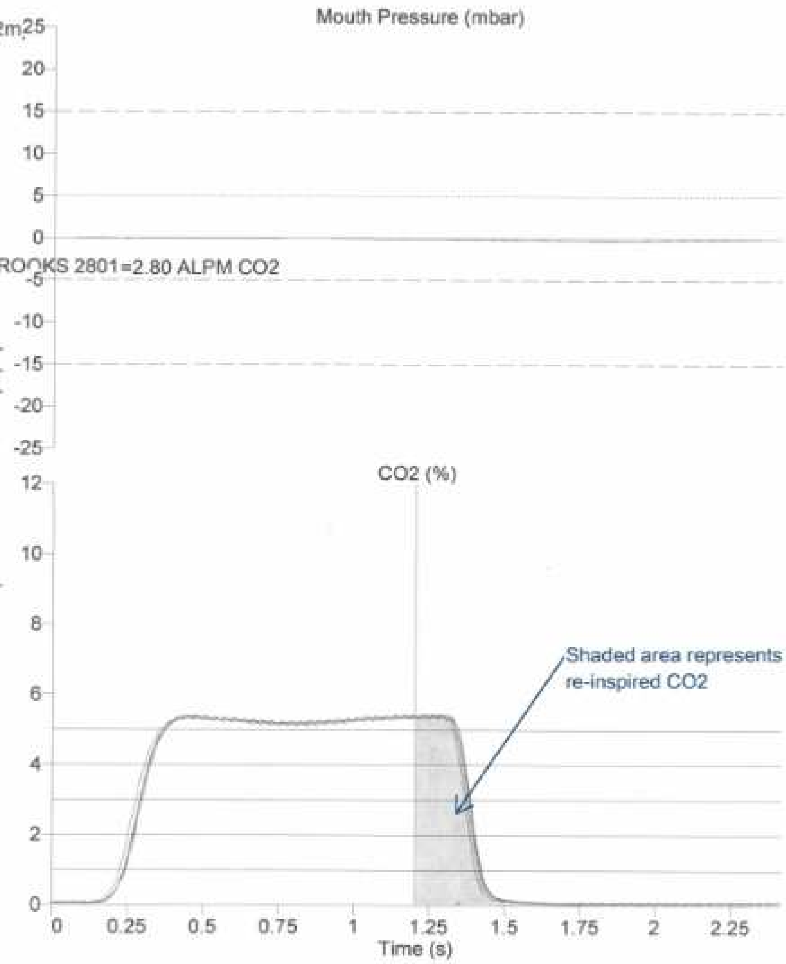
Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.24 mbar	0.23 mbar	0.24 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.01 mbar
Exhale Pressure	0.05 mbar	0.05 mbar	0.05 mbar
Ext Work of Breathing	0.02 J/l	0.02 J/l	0.02 J/l
Ext Inhale Work	0.02 J/l	0.02 J/l	0.02 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO_2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	650 ms		
VWA PCO2	4.04 mbar	3.88 mbar	4.13 mbar
Equivalent Deadspace at 5% CO2	199.25 ml	191.65 ml	204.02 ml
Time average CO2	0.88 %	0.85 %	0.89 %

Head & CE Tube



B2

Carbon Dioxide & Diving Apparatus

ANSTI TEST SYSTEMS - Dive Lab

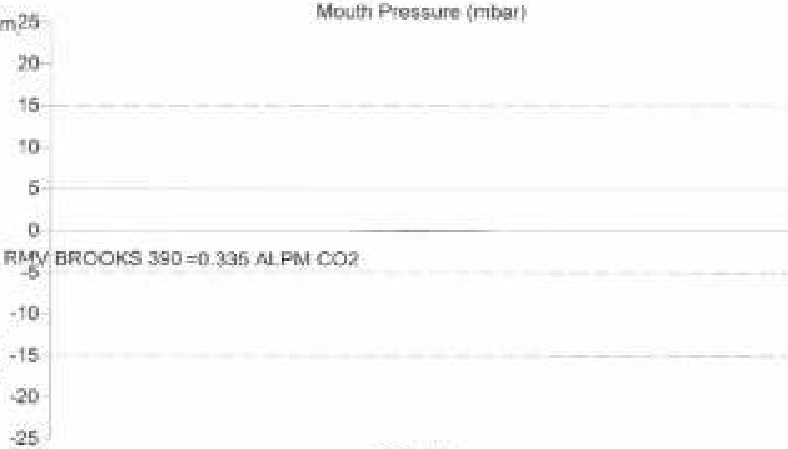
File	LSTF-0615_20200223_134914.co2m
Date: 2/23/2020	Time: 1:49:14 PM
Run Time (s)	30.035
Equipment	
Serial Number	CO2 BASE LINE
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.97
Remarks	3 M MODEL 5200 DUST MASK 10 RMV BROOKS 390=0.335 ALPM CO2

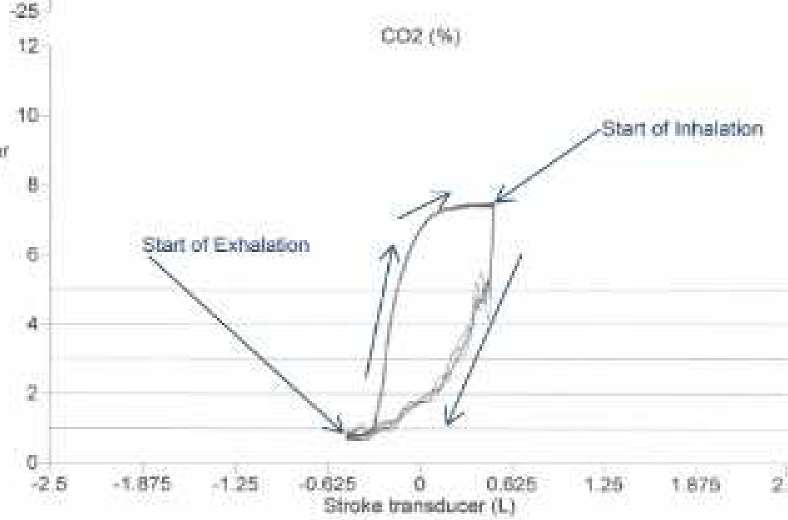
Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.13 mbar	0.13 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.08 mbar	0.08 mbar	0.08 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	650 ms		
VWA PCO2	22.80 mbar	22.54 mbar	23.14 mbar
Equivalent Deadspace at 5% CO2	449.14 ml	444.08 ml	455.74 ml
Time average CO2	2.56 %	2.47 %	2.63 %





3 M Model 5200 Dust Mask

C1

Carbon Dioxide & Diving Apparatus

ANSTI TEST SYSTEMS - Dive Lab

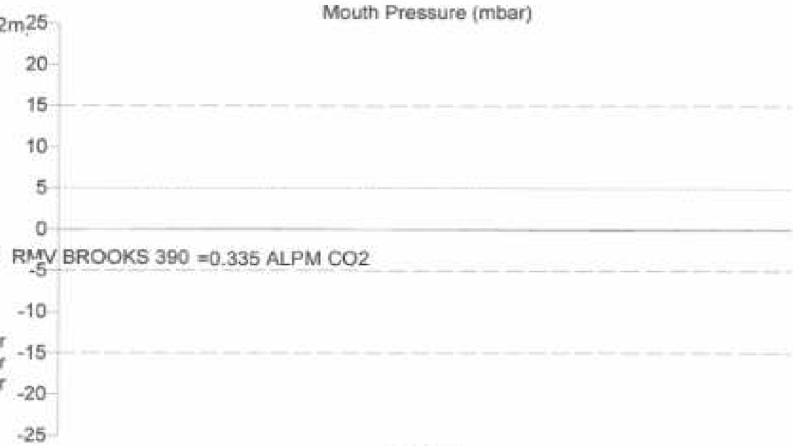
File	LSTF-0615_20200223_134914.co2m
Date: 2/23/2020	Time: 1:49:14 PM
Run Time (s)	30.035
Equipment	
Serial Number	CO2 BASE LINE
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.97
Remarks	3 M MODEL 5200 DUST MASK 10 RMV BROOKS 390 =0.335 ALPM CO2

Mouth Pressure Results (5 loops)

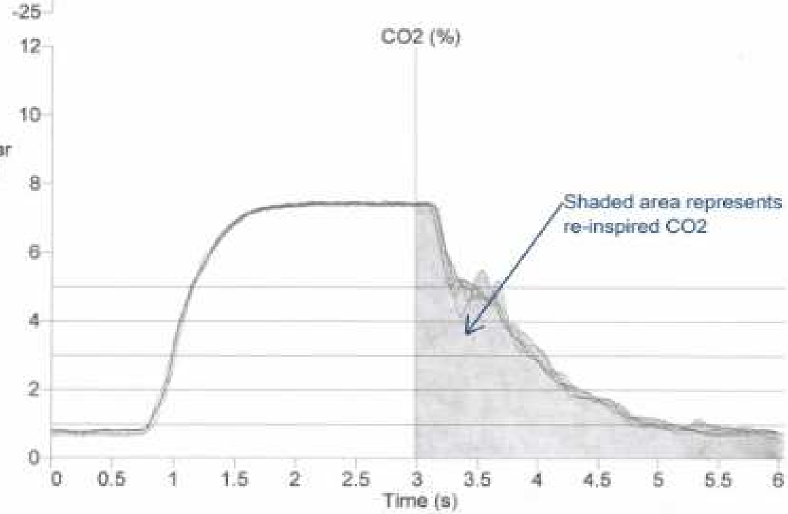
	Mean	Min	Max
Inhale Pressure	0.13 mbar	0.13 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.08 mbar	0.08 mbar	0.08 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	650 ms		
VWA PCO2	22.80 mbar	22.54 mbar	23.14 mbar
Equivalent Deadspace at 5% CO2	449.14 ml	444.08 ml	455.74 ml
Time average CO2	2.56 %	2.47 %	2.63 %



3 M Model 5200 Dust Mask



C2

Rev. February 25, 2020

3.9 Sample Catheter

The sample catheter Dive Lab uses for surface testing has a I.D. of .050 and is approximately 65" inches long from the mouth of the mannequin to the inlet of the inlet of the analyzer. The sample catheter we use for sampling at 50 msw (165 fsw) or deeper is made up of two different sample lines joined together. The first line has an I.D. of 0.010 is 52" long and goes from the mouth of the test head up through the lid of the ANSTI chamber thru a specially machined fitting that allows it to interface with a second surface sample catheter. The interface fitting is designed to allow excess pressure to vent, so the sample speed does not get changed. The sample delay time at depth is usually less than that of the surface catheter because the pressure makes the sample flow much faster even though the entire sample line is longer.

4.0 European CE Breath by Breath Washout Testing

The European standards do not give specific step by step written guidelines on exactly how re-inspired testing is to be done. The way Dive Lab has been testing re-inspired CO2 is based on what we understand the EU standards require. Basically, the standard requires breath by breath testing at the surface with the test head alone, at 10, 40, and 62.5 RMV and then repeated at a depth of 50 MSW (165). These test rates come from table 6, in EN 15333-1 there are other test rates as well, however it is not clear in the standard when the other rates need to be tested. 5.7.3 states the CO2 shall not exceed 20 MBR at when tested at 10 RMV and shall not exceed 10 MBR when tested at an RMV of 40, and 62.5 according to table 6. EN-250 is used for testing SCUBA full face masks and it requires testing at 10RV and 62.5 RMV only using the same 20, and 10 BBR limit.

4.0 European CE Breath by Breath Washout Testing - continued

Step One

We start with the test head alone and use a small fan to lightly blow at the back or side of the head in an effort to minimize CO2 collection around the face. We start our test head base line at the highest RMV first (62.5), injecting CO2 based on the US Navy 4% of RMV and slowly increase it until we have a steady 5% ET as required by CE. At this point we then determine the time delay between the sample leaving the mouth sample point and being read in the sample cell of the analyzer. Once the delay is determined we use it for each of the test RMV's which gives the delay for use with all the test RMV'S starting at the highest RMV first and working to the lowest. 62.5, 40, and 10. Each RMV will have the same sample delay but a different injection rate. On average for 62.5 RMV we are injecting CO2 at 2.78 alpm, for 40 RMV, 1.76 alpm, and 10 RMV 0.35 alpm. The numbers may change slightly based on temperature barometric pressure and background CO2 however overall, they remain very close.

Step Two

After completing the surface base line tests in step one we document the CO2 injection flows from the Brooks® mass flow controller for each test RMV then we check and document the actual flow using Dive Labs bubble system to verify the actual true flow corrected for temperature and pressure. Once this is done these will be the actual flow rates used for testing the equipment to be tested.

Step Three – Surface Testing

Next, we install the helmet, mask or equipment in the face forward position, and ensure the system is sealed, and secure. Next, we start breathing and CO2 injection. When testing at 10 RMV it can take as long as 5 to 8 minutes for the CO2 peak to settle. As the test RMV's increase the time to stabilize decreases. At RMVS of 40 and 62.5 the loop will usually stabilize in less than two minutes. Once the CO2 loop has stabilized, we then record the data, and print out the loop using at least a 5- loop average. With many helmets and full-face masks, the CO2 will usually settle out with a peak between 6-8%. The peak is not as important as the body of the loop. The peak can be high, as long as it washes out. After recording and printing the data if the maximum allowable CO2 of 10 MBR (1.0%SEV) for 40 and 62.5 RMV, or 20 MBR (2.0% SEV) for 10 RMV testing. Testing up to this point this is very similar to the way the US Navy tests, and for many years this is the way Dive Lab tested.

Unwritten Practice

What is not in writing in the CE standards as far as re-inspired CO2 testing goes, or perhaps technically it is, but certainly not explained, after the above testing in step three, with everything still running, the CO2 injection is slowly reduced until the peak end tidal reading is once again peaking at 5% E.T. This is done to represent the human bodies response to the increase in CO2 caused by the combination of increase breathing resistance, in dead space, pathway flow or the combination. The normal human response when the CO2 rises is to increase the breathing rate or decrease the level of exertion so the body can balance out the blood level CO2. So, to simulate this, those performing CE tests have been simply backing off on the amount of CO2 being injected until as previous with the head only, the 5% ET line is reached, then the data is recorded, and this ET number is used as the final answer.

Problem

However, there is a problem with this because there is nothing written in the standards that allows this, nor is there guidance as to how much the CO2 injection can be reduced. Dive Lab has conducted tests on some equipment where the CO2 injection had to be reduced by over 50% or greater in order to get back to 5% end tidal. In essence, this would be the same as increasing the breathing rate 50%. So, this means if at 40 RMV we had to cut back up to 50% on the amount of CO2 being injected to get to the 5% line, this would be the same as the diver having to increase respiration by 50%, which would now be 60 RMV. The question then becomes, is this reasonable, and at what point does it not become reasonable.

We feel there is a much simpler, and more understandable way. Instead of reducing the CO2 injection, we recommend increasing the breaths per minute to get the ET CO2 either back to the 5% end tidal line like that of a human, or simply below the limit of 10 or 20 mbr depending on RMV. So basically at 10 RMV you would increase the breaths per minute until you get back to the 5% ET line. However, this needs to be done in a reasonable manner and there needs to be a limit as to how much you can increase the RMV. As an example, if we were testing a dust mask at 10 RMV and in initial testing it showed 22.80 MBR (2.28 % SEV), then we would slowly increase the breathing in hopes of coming in under the 20 MBR limit. At the 10 RMV original test RMV, even if we had to increase the RMV to 17 RMV (7 RMV Increase), to get back down to the 5% ET line that would be a 70% increase in ventilation, the question now becomes is that a reasonable increase in RMV?, and is this something a user could do easily. In actually it took a 7 RMV increase to get back to the 20 MBR limit, however it only required a 4 RMV (4 BPM) increase to actually get just under the 20 MBR limit.

This means at a test rate of 10 RMV we may need to increase the BPM by 17 BPM which is a 70% increase. For 40 RMV, a maximum RMV increase of 15%, (6 bpm) and 62.5 RMV a maximum of 10% increase (6.25) = 69 RMV.
The above is just a suggestion, understanding that as the test RMV breathing rate increases the percentage of RMV increase to simulate the human response will decrease.

Problem - continued

Regardless, both methods, reducing the injection rate, or increasing RMV thru an increase of BPM will work. By increasing the breaths per minute rather than cutting the CO2 injection it becomes very apparent what the user of the equipment would have to do to get back to an ET of 5% and then a determination as to whether or not the increase is reasonable can be made.

Respirator Mask Example

Dive Lab tested a very popular high-performance respirator mask used for protecting industrial workers. The mask had a peak CO2 value of 7.8 MBR, and a re-inspired CO2 of 22.80 MBR, which is 2.8 MBR above the limit. We then increased the number of breaths per minute until the 5% ET line was reached which required a five breath per minute (5 BPM) increase, which lowered the CO2 from 22.8 to 14.78 MBR, well below the 20 MBR CE limit. The 5 BPM increase was a 50% increase in RMV.

We then did the same kind of test at 62.5 RMV resulting in a peak CO2 of 6% ET, and re-inspired CO2 value of 9.60 MBR, just under the 10 MBR limit. Then to take it one step further, we increased the RMV to get back to 5% ET, it required an increase of 5 BPM, (70 RMV) to get to back to 5% ET, resulting in a re-inspired value of 8.65 MBR. The increase of 5 BPM represents an increase of 14 % in RMV. Very reasonable.

Unreasonable Example

Another example, we tested a Full-Face Snorkel Mask at 10 RMV, and the re-inspired peak ET CO2 was 14 % and a re-inspired CO2 of 75.77 MBR, (7.57 % SEV), Dangerously High, but not uncommon for these types of masks. We then increased the breathing rate until we got back to 5% ET, which required going from 10 RMV to 25 RMV, a 150% RMV increase. And even though we got to 5%, the actual re-inspired CO2 still showed 27.27 MBR, which was still 7.27 MBR above the limit. Completely unreasonable. Next, we went back to 10 RMV, allowed the system to stabilize, then reduced the CO2 injection until the 5% ET line was reached. This required cutting the CO2 injection from .350 ALPM, to .110 ALPM which is a 75% reduction in CO2 in order to get back to the 5% line resulting in an ET CO2 value of 28.47 MBR. This clearly shows that decreasing the CO2 flow, or increasing the RMV will accomplish the same thing, However, in this case the CO2 is so high, neither procedure would be reasonable.

Testing at Depth

After the above testing is done just under the surface of the water at one ATA, we then install the sample catheter combination for testing at depth and perform the testing again at 50 MSW (165 fsw). Prior to pressing to depth, we re-scale the computer CO2 analyzer for the test depth. At 165 fsw (50 MSW) we are at 6 ATA, therefore we are now looking for the surface SEV of .0833 %. So we usually set the CO2 scale at around 1% During the first test at depth, careful attention is paid to the start of inhalation, and the delay is carefully adjusted to be the same as during the surface testing at 1 ATA. The delay at depth is not adjusted using the computer, but by slowly trimming back the surface catheter so the start of inhale on the time line matches that of the previous tests done on the surface. If the work of breathing has not changed significantly the re-inspired CO2 numbers should be very close to those of the surface testing.

Summary

It is very important to Dive Lab that proper standardized procedures for measuring the re-inspired CO2 in man worn equipment be easily understood. We believe increasing the breathing rate is the simplest and easily understandable way to emulate the human response to increased CO2. This can allow respiratory experts to define limits on the RMV increase as opposed to simply decreasing the injection rate. For the three CE test rates, 10, 40, and 62.5 we believe a reasonable RMV increase should be no more than, 50% for 10 RMV, 20% for 40 RMV, and 12 % for 62.5 RMV. The CE standards have done much to improve equipment and test procedures but there is always more that can be done especially with the advent of new technology and procedures. It is extremely important that manufactures know what to expect from their equipment as well as the consumer knowing what is required and what to expect.

Dive Lab welcomes all comments, criticism and looks forward to moving forward.

Mike F. Ward