Calorimetry

If there are any measures that typify, or define, who an exercise physiologist is and what he/she does, then it is the science of exercise testing and indirect calorimetry. All exercise physiologists should "own" this content and related skill sets. Our knowledge and abilities to conduct and interpret exercise test results stand us apart from all other basic and applied scientists. Central to these skills and knowledge sets is the understanding of expired gas analysis and how it enables us to measure whole body and muscle metabolism during exercise. To do this correctly, and to be masterful in your capacity to interpret exercise test results, you need to master the science of calorimetry, and in particular, expired gas analysis indirect calorimetry.

Calorimetry is the science concerning the measurement of heat production by the body (Calorie=heat; metry=science). As such, calorimetry is a means to quantify **metabolic rate**, as increased metabolism infers increased rates of chemical reactions, which all release heat. The greater the number of reactions per unit time, the greater the heat release. Remember this, for knowing the basis of calorimetry to be heat release is profoundly important for understanding how the heat production origin of calorimetry is then used to calculate variables such as **oxygen consumption (VO_2), carbon dioxide production (VCO_2)** and **energy expenditure**. These latter three computed (not measured) variables are fundamental to the majority of laboratory techniques and research of exercise physiology.

Methods of Calorimetry

Obviously, the heat released from the body can be measured directly, and is done so in large chambers, or rooms (**calorimeters**), specially equipped to provide accurate measurements of heat release. For applications of direct calorimetry to exercise, several difficulties arise. For accurate data, metabolic conditions need to be stable for extended periods of time. This is in opposition to the study of exercise physiology, where exercise presents an immediate and dramatic increase in metabolic rate. Added heat production is also released from the exercise apparatus, as well as the friction of body and machine interaction, such as the friction of foot impact on a motorized treadmill belt. Clearly, direct calorimetry cannot be used to study the energetics of exercise physiology and other methods must be developed for this purpose.

Indirect calorimetry consists of several different methods, all with different degrees of validity for application to exercise. Heat production can be indirectly computed from measuring nitrogen excretion and intake into the body. However, once again, this method requires a large time interval over which to apply the measures of nitrogen balance. The same large time window applies to the application of doubly labeled body water.

The indirect method of calorimetry best suited to exercise physiology involves the measurement of expired gases influenced by metabolism. Such gases are oxygen and carbon dioxide, respectively. In simplified form, knowing how much added oxygen was inspired compared to exhaled per unit time equates to VO_2. Knowing how much added carbon dioxide was exhaled compared to inhaled, equates to VCO_2. From a conceptual perspective, this approach at indirect calorimetry, called **expired gas analysis indirect calorimetry (EGAIC)**, is as simple as this (Figure 1).

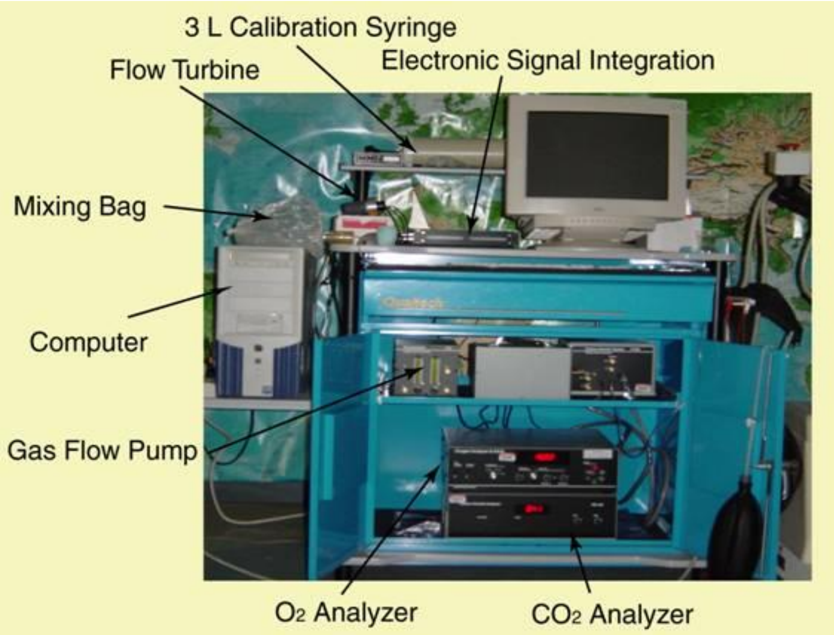

Figure 1. Equipment used in expired gas analysis indirect calorimetry (EGAIC), consisting of a flow turbine, expired gas mixing chamber/bag, gas flow pump, electronic gas analyzers for oxygen and carbon dioxide, a means to remove moisture in the expired gas, and of course computer hardware and software to run the system.

Expired Gas Analysis Indirect Calorimetry

Think about how you breath when at rest, or during exercise. You breathe air in, you breath air out. During such breathing for a person at rest, the gas content, or fraction, changes during inspiration and expiration for each of oxygen (O_2) and carbon dioxide (CO_2) (Figure 2). Note two very important observations for the data coinciding with the plateau in each gas measurement; 1) that expired air contains a lower fraction of O_2 (**FEO_2**) than room air, and 2) that expired air contains a larger fraction of CO_2 (**$FECO_2$**) than room air. Also note what the room inspired air FO_2 and FCO_2 (**FIO_2** and **$FICO_2$**, respectively) are. I was always taught, and have been teaching in the past, that PIO_2 is 0.2093 (20.93 %), FIN_2 is 0.7903 (79.03%) and $FICO_2$ is 0.0003 (0.03%). However,

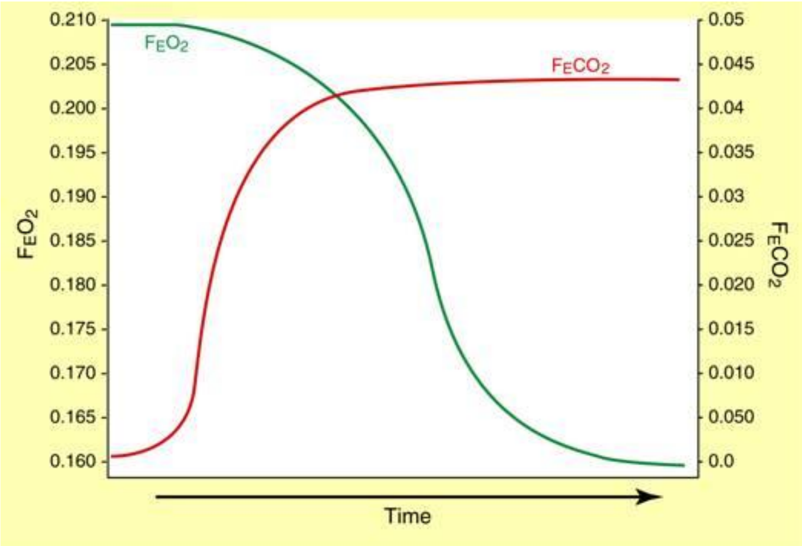

Figure 2. The changes in expired gas fractions for oxygen and carbon dioxide during each inspired and expired breathe while at rest.

after researching more on the topic of accurate gas fractions in atmospheric air, I now know that these values are not correct, as shown in Figures 3 and Table 1 based on reference values for air at sea level from the CRC Handbook of Chemistry and Physics (1997). However, there is minimal impact on computations in EGAIC as the corrections to FIO_2 and $FICO_2$ are minor. Added comment will be given to these computation issues in the next Topic.

While many exercise physiologists accept inspired gas fractions as constants, many other like to measure FIO_2 and $FICO_2$, as they can change in a room full of people, or in the presence of pollution, etc.

Table 1. Table of the gases and their relative fractions (% by volume) in atmospheric air.

Gas	Symbol	% by Volume*
Nitrogen	**N_2**	78.084
Oxygen	**O_2**	20.9476
Argon	**Ar**	0.934
Carbon dioxide	**CO_2**	0.0314
Neon	**Ne**	0.001818
Helium	**He**	0.000524
Methane	**CH_4**	0.0002
Krypton	**Kr**	0.000114
Hydrogen	**H_2**	0.00005
Xenon	**Xe**	0.000008
Ozone	**O_3**	0.000007
Nitrogen dioxide	**NO_2**	0.000002
Iodine	**I_2**	0.000001
Carbon monoxide	**CO**	trace
Ammonia	**NH_3**	trace
Radon	**Rn**	trace

*At sea level and 15 °C.

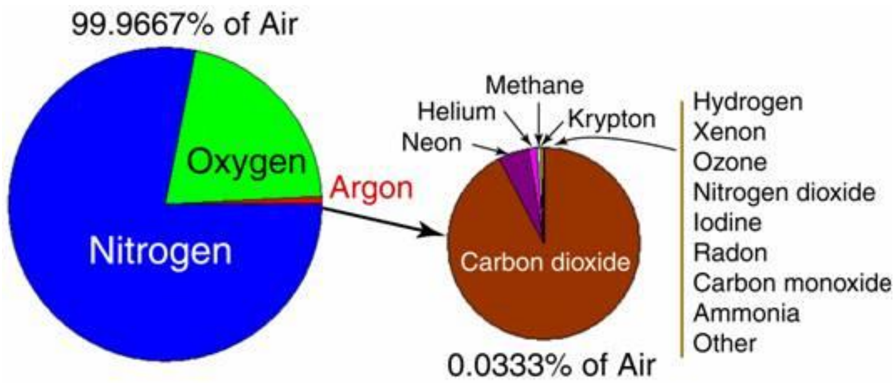

Figure 3. Pie charts for the content of different gases in atmospheric air. Clearly, nitrogen, oxygen and argon predominate as the primary gases in air. The remaining gases are so low that they require a separate pie chart to provide visual clarity.

Calorimetry

When you exercise and increase metabolic rate, the body extracts more O_2 and there is a decrease in FEO_2. Conversely, when exercising the body is producing more CO_2 and there is an increased $FECO_2$. As previously mentioned, these facts form the computational constructs for computing each of whole body VO_2 and VCO_2. The only additional measurements needed are the volumes of air inhaled **(VI)** and exhaled **(VE)**, as expressed in each of Equations 1 and 2.

$$\begin{aligned} VO_2 &= inspired\ O_2 - expired\ O_2 \\ &= (VI \times FIO_2) - (VE \times FEO_2) \end{aligned}$$ Equation 1

$$\begin{aligned} VCO_2 &= \exp ired\ CO_2 - inspired\ O_2 \\ &= (VE \times FECO_2) - (VI \times FICO_2) \end{aligned}$$ Equation 2

When accounting for the constants for FIO_2 and $FICO_2$, equations 1 and 2 can be expressed as equations 3 and 4.

$$VO_2 = (VI \times 0.2095) - (VE \times FEO_2)$$ Equation 3

$$VCO_2 = (VE \times FECO_2) - (VI \times 0.00031)$$ Equation 4

One tip I can give for memorizing $FICO_2$ is that it is a fraction <1 consisting of "*3 zeroes and a 3*". Also note that when adding FIO_2, FIN_2 and $FICO_2$, the sum is 0.9906. This leaves a fraction of 0.0094 for the rare gases of atmosphere air such argon, neon, helium, krypton and hydrogen.

I will present and explain the remaining computations of EGAIC in the next Topic.

Douglas Bags

A common procedure for EGAIC prior to more recent advances in electronics and computer data acquisition was the collection of expired air into gas collection bags (Figure 4). Originally, meteorological balloons were used, and then these were replaced with bags made of material resilient to carbon dioxide diffusion (Figures 4 and 5). Such bags have come to be called **Douglas bags** in honor of C.G. Douglas who first pioneered this method.

Figure 4. The author using a Douglas bag to collect expired air from a student riding a Monark cycler ergometer.

Douglas bag expired air collection is still done today when a time averaged sample of expired gas is sufficient for the testing purpose. Once the gas has been collected, it is analyzed for oxygen and carbon dioxide content, and then the volume is measured using a gas flow meter. These three measurements are then used in the calculation of EGAIC, as explained in the next Topics.

Nevertheless, the increasing ease and automation of calibration for today's commercial systems of EGAIC are making the Douglas bag approach more and more redundant. Nevertheless, the Douglas bag approach is a useful method for aiding the teaching of EGAIC, and for this reason, we still teach this procedure here at UNM.

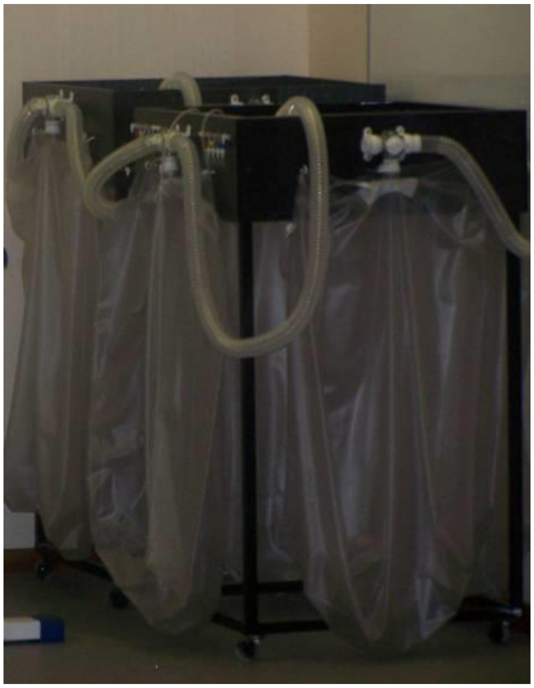

Figure 5. A rack of Douglas bags used for repeated expired gas sampling. Courtesy of Lars McNaughton, the Department of Exercise, Health and Sports Sciences, Hull University, England.

Glossary Words

calorimetry is the science concerning the measurement of heat production by the body.

metabolic rate is the rate of metabolism, typically expressed by the measurement of oxygen consumption, resulting from the sum of all reactions in the body at rest.

oxygen consumption (VO_2) is the rate of oxygen consumption.

carbon dioxide production (VCO_2) is the rate of carbon dioxide production.

energy expenditure refers to the total energy expended by the body for a given task/condition.

calorimeter is a specialized instrument for directly measuring the heat release from the body.

indirect calorimetry involves methods of quantifying energy expenditure by the body by indirect means.

expired gas analysis indirect calorimetry (EGAIC) refers to the predominant method of indirect calorimetry, requiring computations from three measurements; ventilation, and the expired gas fractions for oxygen and carbon dioxide.

FEO_2 is the expired gas fraction of oxygen.

$FECO_2$ is the expired gas fraction of carbon dioxide.

FIO_2 is the inspired gas fraction of oxygen.

$FICO_2$ is the inspired gas fraction of oxygen.

VI refers to inspired ventilation, typically expressed as L/min.

VE refers to expired ventilation, typically expressed as L/min.

Douglas bags are specialized bags, impermeable to CO_2, that are used to collect expired air from subjects.