Indirect Calorimetry and Energy Expenditure

You may be asking yourself why measuring the body's VO_2 and VCO_2 allows understanding of, and more importantly precise calculation of, **energy expenditure**. Of course, increasing metabolism means increasing VO_2, which in turn means a greater rate of chemical reactions and increased heat production. However, how is a VO_2 value used to compute values for heat production? The process required to answer these questions first involves providing background on how the science of calorimetry was developed, with particular emphasis on the field of nutrition.

Gas	Symbol	% by Volume
Nitrogen	N_2	78.084
Oxygen	O_2	20.9476
Argon	Ar	0.934
Carbon dioxide	CO_2	0.0314

Early Developments in Calorimetry

Calorimetry is an old science, with roots dating back to the late 19^{th} century. Such work began with trying to quantify the heat release from completely combusting specific types of molecules. The device used for this is called a **bomb calorimeter**, as is illustrated in Figure 1. The bomb calorimeter is an insulated chamber that has an inner compartment where a food source is placed. Oxygen is added to this compartment so that when the food source is ignited by a small electric current, there is a rapid combustion of the food in the oxygen rich environment. The combustion of the food releases heat, consumes oxygen and produces carbon dioxide. Thus, immediately after the combustion, several measurements are made.

1. the O_2 content of the air in the inner chamber
2. the CO_2 content of the air in the inner chamber
3. the increase in temperature of the water within the compartment surrounding the inner chamber

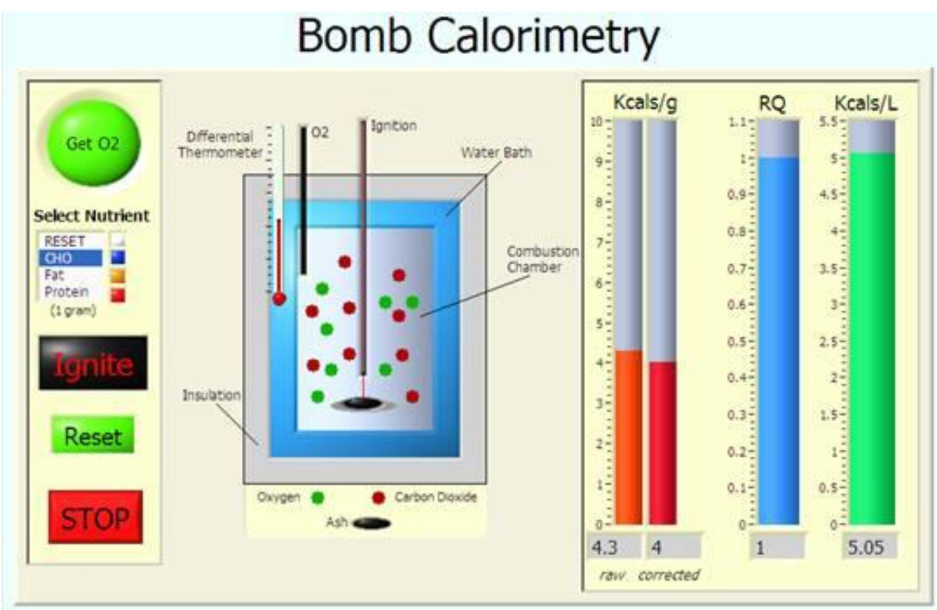

Figure 1. Illustration of the bomb calorimeter, with added features to highlight measurements and results for energy of combustion for carbohydrate.

Thus, bomb calorimetry provides accurate data of the VO_2, VCO_2 and heat production from the complete **combustion** of reference food items. Thus, if the food item was 1 gram of glucose, then bomb calorimetry could measure the VO_2, VCO_2 and heat production from the complete combustion of 1 gram of glucose. The same would occur for 1 gram of fat, or 1 gram of protein. When performing these analyses, the results of Table 1 are obtained.

Table 1. Results from bomb calorimetry, along with adjusted values for human metabolism, for select nutrients.

Nutrient Compound	Bomb Cal Kcals/gram	Body* Kcals/gram	RQ	Kcals/L VO_2
Carbohydrate				
Mixed	**4.1**	**4.0**	**1.0**	**5.05**
Glycogen	**4.2**		**1.0**	5.05
Glucose	**3.7**		**1.0**	4.98
Fructose	**3.7**		**1.0**	5.00
Glycerol	**4.3**		**0.86**	5.06
Fat				
Mixed	**9.3**	**9.0**	**0.7**	**4.73**
Palmitate (C16:0)	**9.3**		**0.7**	4.65
Stearate	**9.5**		**0.69**	4.65
Triacylglycerol (C18:0)	**9.6**		**0.7**	4.67
Triacylglycerol (C10-15:0)	**8.4**		**0.74**	4.69
Protein				
Mixed	**5.7**	**4.0**	**0.81**	**4.46**
Alanine	**4.4**		**0.83**	4.62
Aspartate	**2.69**		**1.17**	4.60
Glutamate	**3.58**		**1.0**	4.58
Isoleucine	**6.89**		**0.73**	4.64
Alcohol	**7.1**	**7.0**	**0.82**	**4.86**
Mixed Diet			0.84	4.83

* after Atwater correction factors (see text)

When focused on carbohydrate, Equation 1 provides the summary reaction for complete combustion of glucose.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + energy\ (heat) \qquad \text{Equation 1}$$

Thus, the complete combustion of 1 mole of glucose will consume 6 moles of O_2, produce 6 moles of CO_2, and release energy (Table 1). As the **molar gas volume** equals 22.414 L/mol STPD, this is a lot of VO_2 and VCO_2. However, I hope you remember back to metabolism when it was very clear that metabolites in the body are in the μmolar to mmolar concentration range!

We can convert the above data based on 1 gram of glucose as follows. As glucose weighs 180.1 grams/M, 1 gram of glucose is 0.0055525 M. Thus, multiplying the VO_2 and VCO_2 by this factor (6 x 0.0055525) yields a VO_2 and VCO_2 of 0.033315 M. Of course, the ratio of VCO_2 to VO_2, known as the respiratory quotient (RQ), remains equal to 1.0. Thus, 1 gram of glucose oxidation yields 0.033315 mol of VO_2 and VCO_2, which when multiplied by the molar gas volume equates to 746.7 mL.

Now, all we have to do is understand the heat release data from bomb calorimetry. The data of Figure 2 reveal that the corresponding energy release for glucose oxidation in the body equals 3.7 Kcals/gram. To compute the Kcals/L, we simply adjust the Kcals/gram by the gas volume applied from bomb calorimetry as shown in Equation 2.

$$3.7 \times \left(\frac{1{,}000}{746.7} \right) = 4.9551\, Kcals / L \qquad \text{Equation 2}$$

Be aware that the calculation for Equation 2 was for glucose. The computation based on a mixed carbohydrate diet results in a slightly different value of 5.05 Kcals/L VO_2. Based on this, keep in mind that the so called constants used for mixed carbohydrate and fat are averages of a variety of compounds for that food class, and that meaningful differences do exist for energy content (per gram or L VO_2) for different carbohydrate, fat and amino acid compounds.

Also note that for the bomb calorimeter all the energy of this combustion is released as heat. Inside the body, this is not the case as some of the energy is released as free energy and used to perform cell work. As a general rule, only between 70 to 75% of the energy released in the complete combustion of a food source during metabolism is released as heat. Nevertheless, the total energy release from the combustion of a food source is what is important, and bomb calorimetry gives us this information.

The body vs. Machine

OK, I know you are wondering what a machine like the bomb calorimeter has to do with body metabolism. Well, the answer is everything!

Sure the body is not an explosive device that immediately combusts nutrients into their final end products. Rather, the body is a regulated entity, where metabolism is designed and controlled to provide small packets of energy release in a series of reactions that eventually account for the complete combustion of energy nutrients such as glucose, palmitate, and numerous amino acids.   Nevertheless, the physical principles that govern combustion are the same for the body as any machine. The complete combustion of nutrients in the body yield similar VO_2, VCO_2 and energy release as they do in a bomb calorimeter, which must occur to uphold the 1^{st} law of thermodynamics, as you studied earlier. However, slight differences do exist due to the energy of digestion and waste removal within the body, as was researched between 1890 and 1920 by Wilbur Olin Atwater. Such corrections have become know as **Atwater factors**.   The largest correction applies to amino acids and proteins, as amine groups are released from amino acids and circulated to the liver for conversion to urea, and then excreted in urine. Clearly, the chemical energy in amine groups are not released during catabolism within the body. Such Atwater adjusted values were also provided in Table 1as data for the body.

The other important difference between the energetics of food combustion in a bomb calorimeter vs. the body, is that within the body food combustion is drawn out over numerous reactions. This allows for as many ATP molecules to be formed as possible from the free energy release.

Comparing Macronutrients

When comparing the Atwater corrected data (for the body) for carbohydrate, fat and protein (Table 1), clear differences exist for the RQ and energy expenditure data between the macronutrients. There is more than double the energy release from mixed fat vs. mixed carbohydrate or mixed protein oxidation, and all three macronutrient sources have very different RQ values. When applying such data to the body, as the body mainly catabolizes fat and carbohydrate for energy catabolism, only data for fat and carbohydrate are utilized. This fact was known very early into the science of calorimetry, and the German scientist Rubner developed a table of reference data for converting RQ data to %contributions from fat vs. carbohydrate catabolism (Table 2). This chart has become known as the non-protein RQ table.

Table 2. The non-protein RQ table.

RER	Kcals/L	%CHO	CHO (Kcals)	%Fat	Fat (Kcals)
1.00	5.047	100	5.047	0	0
0.99	5.035	96.8	4.874	3.18	0.000
0.98	5.022	93.6	4.701	6.37	0.160
0.97	5.010	90.4	4.529	9.58	0.230
0.96	4.998	87.2	4.358	12.8	0.480
0.95	4.985	84.0	4.187	16.0	0.640
0.94	4.973	80.7	4.013	19.3	0.798
0.93	4.961	77.4	3.840	22.6	0.960
0.92	4.948	74.1	3.666	25.9	1.121
0.91	4.936	70.8	3.495	29.2	1.281
0.90	4.924	67.5	3.324	32.5	1.441
0.89	4.911	64.2	3.153	35.8	1.600
0.88	4.899	60.8	2.979	39.2	1.758
0.87	4.887	57.5	2.810	42.5	1.920
0.86	4.875	54.1	2.637	45.9	2.077
0.85	4.862	50.7	2.465	49.3	2.238
0.84	4.850	47.2	2.289	52.8	2.397
0.83	4.838	43.8	2.119	56.2	2.561
0.82	4.825	40.3	1.994	59.7	2.719
0.81	4.813	36.9	1.776	63.1	2.880
0.80	4.801	33.4	1.603	66.6	3.037
0.79	4.788	29.9	1.432	70.1	3.197
0.78	4.776	26.3	1.256	73.7	3.356
0.77	4.764	22.3	1.062	77.2	3.520
0.76	4.751	19.2	0.912	80.8	3.678
0.75	4.739	15.6	0.739	84.4	3.839
0.74	4.727	12.0	0.567	88.8	4.000
0.73	4.714	8.4	0.396	91.6	4.160
0.72	4.702	4.8	0.224	95.2	4.318
0.71	4.690	1.1	0.052	98.9	4.638
0.70	4.686	0	0.000	100	4.686

As you learned in the study of metabolism, fat catabolism produces relatively fewer CO_2 molecules compared to O_2 consumption, causing the lower RQ of 0.707 for pure fat catabolism. As already shown, the RQ for pure carbohydrate catabolism is 1.0.

An interesting data variable is the energy yield expressed relative to VO_2 for a given macronutrient. This is termed the **caloric equivalent for oxygen**, and approximates 5.05 for mixed carbohydrate and 4.73 for mixed fat. While fat catabolism yields more energy per gram, it is less efficient relative to VO_2. As you learned in the study of metabolism, this difference can be explained by differences in the biochemistry of carbohydrate vs. fat catabolism, where fat catabolism prior to acetyl CoA formation produces a greater proportion of FADH to NADH electron carrier molecules, resulting in a lower ATP equivalent, less ATP per VO_2, and hence, the lower caloric equivalent for oxygen for fat than carbohydrate. In other words, to get the energy release from fats, cells are required to rely more on the consumption of oxygen by their mitochondria. However, for carbohydrates, more additional energy release can also occur in the glycolytic pathway than for the β-oxidation of fats.

Wrapping it Up To Compute Energy Expenditure

You are now equipped with all the information you need to connect cellular and whole body VO_2 and VCO_2 to understand heat production and the source of macronutrients used in energy catabolism, and to compute actual energy expenditure during exercise.

When a person is at rest, or exercising at a low to moderate intensity, the metabolic or ATP demands of the cells of the body can be met through ATP regeneration from cellular respiration; the consumption of oxygen and production of carbon dioxide. These conditions are referred to as steady state. During steady state, the RER measured from expired gas analysis mimics the RQ of cellular respiration, as there is minimal to no CO_2 produced from proton buffering in the blood. Thus, if the VO_2 and VCO_2 are known from expired gas analysis indirect calorimetry, and therefore the RER is known, then actual energy expenditure can be calculated as shown in Equation 3.

$$Energy\ \exp enditure\ (Kcals/\min) = VO_2\ (L/\min) \times Caloric\ equivalent\ \ for\ the\ RER\ (Kcals/L)$$

Equation 3

Thus, for a condition of steady state exercise requiring a VO_2 of 2.75 L/min and an RER of 0.92, the caloric equivalent is 4.948 Kcals/L VO_2 (Figure 3). Thus, Equation 4 computes an energy expenditure of 13.607 Kcals/min.

$$\begin{aligned} Energy\ \exp enditure\ (Kcals/\min) &= 2.75 \times 4.948 = 13.607\ Kcals/\min \\ &= 13.607 \times 4.168\ kJ/Kcal = 56.97\ kJ \end{aligned}$$

Equation 4

If a person sustained this exercise condition for 45 min, then total energy expenditure would equal 612.3 Kcals, or 2,564 Kjoules (Equation 5).

$$\begin{aligned} Energy\ \exp enditure\ (Kcals/\min) &= 13.607 \times 45 = 612.3\ Kcals/\min \\ &= 612.3 \times 4.168\ kJ/Kcal = 2.564\ kJ \end{aligned}$$

Equation 5

Glossary Words

energy expenditure refers to the energy used to fuel metabolism.

bomb calorimeter is an instrument used to completely combust fuels and measure the oxygen consumed, carbon dioxide produced and total heat released.

combustion refers to the breakdown of fuels.

molar gas volume is the volume of gas per mol, which is a constant for all gases, equaling 22.414 L/mol STPD.

Atwater factors are correction factors applied to the energy release for fuels measured from bomb calorimetry for application to the body. The corrections adjust for the energy expenditure involved in digestion for carbohydrate and fat, and for differences in combustion between the bomb calorimeter and body, such as for amine group processing in the body for amino acids.

caloric equivalent for oxygen is the energy release from the catabolism of macronutrients expressed relative to the consumption of oxygen required in the catabolism of the specific macronutrient.