A mathematical model for constituent ratios of energy expenditure in human

YU Wen-San1,*, ZHAO Yan-Yan2
1Department of Nutrition and Food Hygiene, West China School of Public Health; 2Department of Pharmacology, West China School of Preclinical and Forensic Medicine, Sichuan University, Chengdu 610041, China

Abstract: In order to assess the constituent ratios of energy expenditure in human, the deductive process of establishing a mathematical model for assessing the constituent ratios of the three major nutrients in energy expenditure in human was described in this paper. Total oxygen consumption, total carbon dioxide output and total nitrogen (urine nitrogen + skin nitrogen) excretion are related to the oxidation of the three major nutrients and the physiological combustion values of the three nutrients are already known. Based on these measurable and known parameters, the mathematical model established by the authors will help understand the characteristics of the tested individual’s energy expenditure.

Key words: energy expenditure; indirect calorimetry; physiological combustion value; energetic nutrients; constituent ratio; mathematical model

Experimental Technique

Introduction

Direct calorimetry and indirect calorimetry are traditionally used to determine energy expenditure in human[1]. However, direct method can only estimate total energy expenditure. It cannot calculate the ratios of the heat generated by oxidation of the three major energy substrates in human. The traditional indirect calorimetry and the energy expenditure mathematical model are based on the assumption that total oxygen consumption, total carbon dioxide output and nitrogen excretion in human are related to the oxidation of three major nutrients. Nitrogen excretion is dependent on the amount of protein oxidation in human[2]. These values are measurable. In addition, the oxygen consumption and carbon dioxide output per gram of three nutrients oxidized in human are known. So, the nonprotein respiratory quotient (NPRQ) and respiratory quotient (RQ) can be calculated. With these values, the total energy expenditure could be determined with corresponding established figures[3] or tables[3,4]. Indirect calorimetry can not only estimate the total energy expenditure, but also calculate constituent ratios of energy expenditure produced by oxidation of the three major energy substrates in human. However, the latter application has largely been ignored.

In this paper, we will describe the process of establish-
a mathematical model for estimating constituent ratios of total energy expenditure. Our model cited original equations from the traditional indirect calorimetry, but its deduction was different from the traditional ones. We used the physiological combustion values of the three major nutrients in stead of using the concept of NPRQ and RQ. So, neither figure nor table was necessary. This method directly calculates energy generated by three nutrients and the constituent ratios of each one. It will help understand characteristics of the tested individual’s energy expenditure in different situations, such as under different working conditions, with different labor intensities, at various competition levels or in specific physiological or pathological status. This method is valuable in different fields, such as clinical medicine, preventive medicine, sports medicine, aerospace medicine, etc. And it is simple, convenient, economic and could be easily adopted.

Establishment of the mathematical model

The detailed theoretic explanation and deduction are described as follows: Before the test, the subject should take a bath, dress in clean clothes and urinate immediately before the test starts.

1. Assuming the total nitrogen excretion (in gram) produced by protein oxidation in an individual is TNE. Urine and the water used for bathing during the testing period are collected. The nitrogen contained in urine and bathing water are measured. The clothes of those who heavily perspired during the test are immersed in water, in which the nitrogen contained is also measured. Total nitrogen excretion (TNE) (in gram) is the sum of urine nitrogen excretion (UNE) and skin nitrogen excretion (SNE) in the subject during the testing period.

2. Assuming the oxidized protein (in gram) in an individual is PG.

3. Assuming oxidized fat (e.g. tripalmitin) (in gram) is FG, oxidized carbohydrate (starch or glycogen) (in gram) is CG, and total O2 consumption (in liter) and total CO2 production (in liter) of three oxidized energetic nutrients in an individual are TVO2 and TVCO2, respectively. Indirect calorimetry with a respiration chamber can be used to determine TVO2 and TVCO2. It is known that O2 consumptions (in liter) of each gram of carbohydrate, fat and protein oxidation in human are 0.829, 2.019, 0.966; and CO2 outputs (in liter) of each gram of three nutrients oxidation in human are 0.829, 1.427, 0.774, respectively. Then the following equations can be derived:

\[
\begin{align*}
\text{TVO}_2 &= 0.829 \text{ CG} + 2.019 \text{ FG} + 0.966 \text{ PG} \\
\text{TVCO}_2 &= 0.829 \text{ CG} + 1.427 \text{ FG} + 0.774 \text{ PG}
\end{align*}
\]

i.e.,

\[
\begin{align*}
0.829 \text{ CG} + 2.019 \text{ FG} &= \text{TVO}_2 - 0.966 \text{ PG} \quad (1) \\
0.829 \text{ CG} + 1.427 \text{ FG} &= \text{TVCO}_2 - 0.774 \text{ PG} \quad (2)
\end{align*}
\]

Equation (1) is modified as

\[
0.829 \text{ CG} = \text{TVO}_2 - 0.966 \text{ PG} - 2.019 \text{ FG} \quad (3)
\]

By substituting (TVO2 – 0.966 PG – 2.019 FG) for 0.829 CG (3) in equation (2), one is modified as:

\[
\begin{align*}
\text{TVO}_2 - 0.966 \text{ PG} - 2.019 \text{ FG} + 1.427 \text{ FG} &= \text{TVCO}_2 - 0.774 \text{ PG} \\
0.592 \text{ FG} &= \text{TVO}_2 - \text{TVCO}_2 - 0.192 \text{ PG}
\end{align*}
\]

By substituting (1.689 TVO2 – 1.689 TVCO2 – 0.324 PG) for FG (4) in equation (1), one is modified as:

\[
\begin{align*}
0.829 \text{ CG} = \text{TVO}_2 - 0.966 \text{ PG} - 3.410 \text{ TVO}_2 + 3.410 \text{ TVCO}_2 + 0.654 \text{ PG} \\
0.829 \text{ CG} = 3.410 \text{ TVCO}_2 - 2.410 \text{ TVO}_2 - 0.312 \text{ PG} \\
\text{CG} &= 4.113 \text{ TVCO}_2 - 2.907 \text{ TVO}_2 - 0.376 \text{ PG} \\
\text{CG} &= 4.113 \text{ TVCO}_2 - 2.907 \text{ TVO}_2 - 2.350 \text{ TNE}
\end{align*}
\]

4. Assuming the energy produced by protein, fat and carbohydrate (starch or glycogen) oxidation in an individual are PE, FE and CE, respectively.

\[
\begin{align*}
\text{PE} &= 4.1 \text{ kcal/g} \times \text{PG} (g) \\
&= 4.1 \text{ kcal/g} \times 6.25 \text{ TNE} (g) \\
&= 25.625 \text{ TNE} (\text{kcal})
\end{align*}
\]

Where 4.1 kcal/g is the physiological combustion value of protein.

\[
\begin{align*}
\text{FE} &= 9.3 \text{ kcal/g} \times \text{FG} (g) \\
&= 9.3 \text{ kcal/g} \times (1.689 \text{ TVO}_2 - 1.689 \text{ TVCO}_2 - 2.025 \text{ TNE}) (g) \\
&= 15.708 \text{ TVO}_2 - 15.708 \text{ TVCO}_2 - 18.833 \text{ TNE} (\text{kcal})
\end{align*}
\]

Where 9.3 kcal/g is the physiological combustion value of fat.

\[
\begin{align*}
\text{CE} &= 4.1 \text{ kcal/g} \times \text{CG} (g) \\
&= 4.1 \text{ kcal/g} \times (4.113 \text{ TVCO}_2 - 2.907 \text{ TVO}_2 - 2.350 \text{ TNE}) (g) \\
&= 16.863 \text{ TVCO}_2 - 11.919 \text{ TVO}_2 - 9.635 \text{ TNE} (\text{kcal})
\end{align*}
\]

Where 4.1 kcal/g is the physiological combustion value of carbohydrate (starch or glycogen).

5. Assuming total energy produced by oxidation of three energetic nutrients in an individual is TE.

\[
\begin{align*}
\text{TE} &= \text{PE} + \text{FE} + \text{CE} \\
&= 25.625 \text{ TNE} + (15.708 \text{ TVO}_2 - 15.708 \text{ TVCO}_2 - 18.833 \text{ TNE}) + (16.863 \text{ TVCO}_2 - 11.919 \text{ TVO}_2 - 9.635 \text{ TNE})
\end{align*}
\]
= 3.789 TVO₂ + 1.156 TVCO₂ – 2.843 TNE (kcal)

6. Assuming proportions of energy expenditure contributed by protein, fat and carbohydrate in an individual are PEP, FEP and CEP, respectively.

PEP = PE/TE × 100%
FEP = FE/TE × 100%
CEP = CE/TE × 100%

**Discussion**

We have already known the amounts of oxygen consumptions, carbon dioxide productions and physiological combustion values per gram of three nutrients (protein, fat and carbohydrate) oxidized and the amount of nitrogen excreted per gram of protein metabolized in human. If we can measure the total CO₂ output, total nitrogen excretion and total O₂ consumption in an individual at any given time, it is possible to calculate the total energy expenditure and the energy released by oxidation of the respective major nutrient. The amounts of protein, fat and carbohydrate oxidized respectively during the process can also be determined.

Similarly, another mathematical model for estimating constituent ratios of an individual’s energy expenditure can be established based on energy equivalent values of protein (4.49 kcal/L O₂ or 5.58 kcal/L CO₂), carbohydrate (5.05 kcal/L O₂ or 5.05 kcal/L CO₂) and fat (4.62 kcal/L O₂ or 6.63 kcal/L CO₂)

There are several methods to assess energy expenditure in human[1,6,7]. Each method has its advantages and disadvantages. In past decades, method of direct calorimetry has been replaced by that of indirect calorimetry or noncalorimetry (such as doubly labeled water method). Direct calorimetry is not practical, mainly because of its need of a large isothermal calorimeter[1].

Noncalorimetry using doubly labeled water (DLW. ²H₂¹⁸O) method to measure total energy expenditure in human[7]. It is costly and time-consuming, so it is difficult to be adopted.

Indirect calorimetry is based on the assumption that total oxygen inhale, total carbon dioxide exhale and UNE can be measured, and oxygen consumptions and carbon dioxide productions per gram of protein, fat and carbohydrate (starch or glycogen) oxidized in human, and their energy equivalent values are known[1,4]. The amount of protein oxidized is calculated by the value of TNE multiplied by the transfer coefficient of nitrogen to protein—6.25. The nonprotein O₂ consumption (NPVO₂) and nonprotein CO₂ production (NPVCO₂) are derived by TVO₂ and TVCO₂ minus the oxygen consumed and carbon dioxide produced in protein metabolism, respectively. Based on these values, the NPRQ is derived. By referring to some figures or tables, such as relationships between NPRQ and (a) the proportion of the NPVO₂ used for fat and carbohydrate oxidation and (b) the energy equivalent of a liter of oxygen[11] or the relationships between RQ and the proportion of carbohydrate and fat utilized for energy[11], the total energy released or grams of oxidized carbohydrate and fat can be calculated.

This traditional indirect calorimetry using several equations, figures or tables had estimated the total energy expenditure in human, but it ignored constituent ratios of energy expenditure. In the tables[3,4], the RQ does not equal to NPRQ. Therefore, estimation of the contribution of energy generated by oxidation of each energetic nutrient to total energy expenditure based on the tables is not accurate.

In this paper, we described the process of determining constituent ratios of energy expenditure with our mathematical model. In our model, instead of using NPRQ and RQ, physiological combustion values and TNE (UNE+SNE) are used. It needs no figures or tables. Accurate measurements of the required parameters, e.g. total O₂ inhale, total CO₂ exhale and TNE are keys in using this method.

We believe that our model is more convenient and more accurate in assessing the constituent ratios of energy generated by three nutrients. This method has significant values both practically and theoretically. It helps understand the characteristics of energy expenditure in different physiologic and pathologic conditions and labor intensities.

**REFERENCES**