

Bioenergetics

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- 1- Introduction (History of Nutritional Energetics)**
- 2- Energy Exchange in Biological Systems**

Bioenergetics

Theory:

- 1- Introduction (History of Nutritional Energetics)
- 2- Energy Exchange in Biological Systems
- 3- Energy Forms
- 4- Energy Balance in Fish
- 5- Bioenergetics models
- 6- What drives growth
- 7- The nature of growth
- 8- Pattern of deposition of nutrients
- 9- Energy Utilization
- 10- Urinary and Branchial Energy and Metabolizable Energy
- 11- Factors Affecting Metabolic Waste Output
- 12- Heat production

Practical: Applied experiments & report

Refs.

- 1- Pattern and cost of growth and nutrient deposition in fish. Bureau *et al.*
- 2- Some aspects of the biology of feeding and growth in fish. Talbot
- 3- Bioenergetics. Bureau *et al.*
- 4- Optimising nutrient and energy intake by fish. Glencross and Allan



*Giovanni di Paolo (15th cent.),
for Dante's Divine Comedy*

What is bioenergetics?

The study of the processing of energy by living systems, *at any level of biological organization.*

In fisheries science, we typically

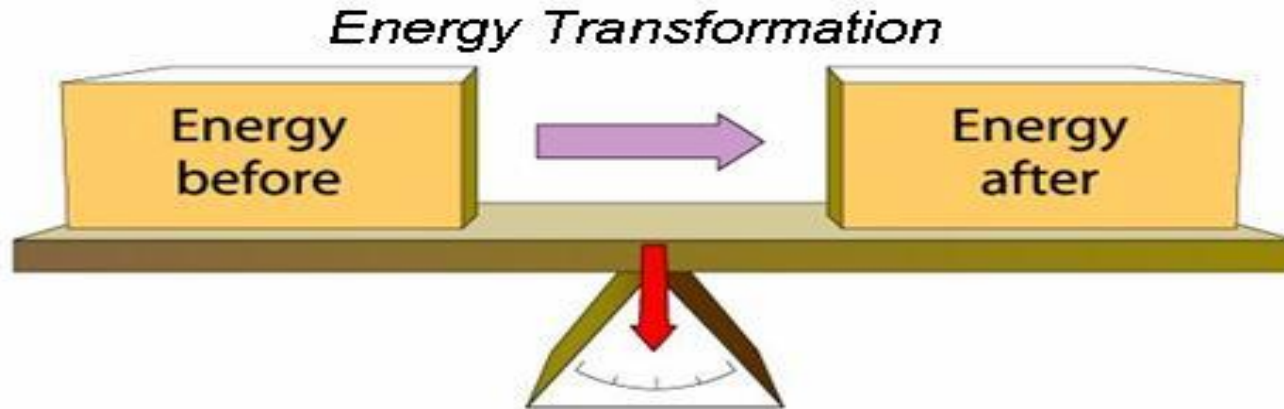
- consider the bioenergetics of individuals
- use this to develop budgets for populations
- make projections about fish production in particular areas (e.g., Lake Ontario salmon production)

Fish bioenergetics is a subset of a much broader field called **ecological energetics**

What is Bioenergetics?

“.....the study of the flow and transformation of energy in and between living organisms and between living organisms and their environment”

The First Law of Thermodynamics



Bioenergetics

The **catabolism** of food is organized within the animal to harness chemical (free) energy and substrates for use in anabolic and other life-sustaining processes. The physiological mechanisms which achieve this are very complex, allowing the catabolism of a large variety of food molecules using the finite number of enzyme systems which are found in animal tissues . To look quantitatively at the utilization of all dietary components is extremely complex. However, since feeding, growth, and production can be described in terms of partition of dietary energy yielding components between **catabolism** as fuels and **anabolism** as storage in tissues, **the study of the balance among dietary energy intake, expenditure, and gain offers a relatively simple way of looking at dietary component utilization by animals.** This approach is called bioenergetics or nutritional energetics.

History of Nutritional Energetics

Nutritional energetics has been studied for more than 200 years. In 1779, Adair Crawford observed that the amount of air a man “phlogisticated” in a minute was the same as that altered by a burning candle. Despite the fact that Crawford formulated ideas about the origin of animal heat in terms of the *phlogiston* (*HEAT*) theory that was popular at the time, his observations were some of the first showing a relationship among gas exchanges, heat production, and chemical reactions in animals. In 1783, Antoine Lavoisier and Pierre Laplace performed a series of exceptional experiments, considered as the foundation of bioenergetics and modern nutrition. They observed that heat produced by a guinea pig could be measured by the amount of ice melted and that the heat produced could be related to the respiratory exchange in a quantitative way.

Based on this series of studies Lavoisier formulated his classical conclusion **that life is a process of combustion**

History of Nutritional Energetics

Lavoisier was, thus, the first to recognize the true **role of oxygen in the generation of heat by animals**. Lavoisier's contribution to the study of animal energetics was not limited to his elucidation of the relationship between respiration and the production of heat but also included several aspects of energy metabolism of animals. His studies with S'eguin on the metabolism of man, which involved the measurement of oxygen consumption and carbon dioxide production, showed that **oxygen consumption is increased by the ingestion of food, by the performance of muscular work, and by exposure to cold**. Lavoisier also measured the **minimal metabolism in the resting**, post-absorptive state and showed proportionality between pulse frequency and metabolism. He also showed that within a species, **oxygen consumption is proportional to body size**.

History of Nutritional Energetics

Nutritionists working at the **Weende Agricultural Experimental Station in Germany, in the nineteenth century**, recognized that the components of foods which make a significant contribution to the **energy** supply of the animal could be characterized as three classes of compounds: **proteins, fats, and carbohydrates**. The stoichiometry of the oxidation of these classes of compounds allowed the **calculation of the energy released as heat from measurements of respiratory exchange, oxygen consumption, and carbon dioxide production, along with measurements of urinary nitrogen excretion**. This method of measuring heat production is referred to as **indirect calorimetry (or respirometry)**. In 1894, Rubner validated this approach to calorimetry by showing that the **heat produced by a dog is equal to the heat of combustion of the fat and protein catabolized minus the heat of combustion of the urine**. Rubner, thus, was the first to demonstrate the fundamental laws of thermodynamics applied to intact living animal systems

Kleiber, and Brody and Proctor, in 1932, showed that **metabolism was related directly to body weight** and metabolism was **proportional to a power of weight higher than 2/3**, that is, about **0.75**. Kleiber came to the conclusion that the **$\frac{3}{4}$ power of body weight** was the most reliable basis for **predicting the basal metabolic rate** of animals and for **comparing nutrient requirements among animals of different sizes**. He also provided the basis for the conclusion that the total efficiency of energy utilization is independent of body size. In 1945, **Brody** published *Bioenergetics and Growth*, and in 1961, **Kleiber** published *The Fire of Life*, two books, discussing several aspects of energy metabolism of animals, that remain very influential to this day. **Ege and Krogh (1914) were the first to apply the principles of bioenergetics to fish. Ivlev (1939) worked with carp.** Since then, there have been several hundred reports on studies of energy utilization and expenditure for several species of fish. Many reviews have also been made on fish bioenergetics, including those by Phillips (1972), Brett and Groves (1979), Cho *et al* (1982), Elliott (1982), Cho and Kaushik (1985), Tytler and Calow (1985), Smith (1989), Cho and Kaushik (1990), Kaushik and M´edale (1994), Cho and Bureau (1995), and M´edale and Guillaume (1999), which are most relevant to aquaculture.

Energy Exchange in Biological Systems

The first law of thermodynamics, also known as the law of conservation of energy, states that the total energy (E) of a system, including its surroundings, remains constant unless there is input of energy (heat or work). It implies that within the total system, energy is neither lost nor gained during any changes. However, within that total system, energy may be transferred from one part to another or may be transformed into another form of energy (heat, electrical energy, radiant energy, or mechanical energy). All biological **organisms** must obtain supplies of free energy from their environment to sustain living processes. Non-biological systems may utilize heat energy to perform work, but biological systems are essentially isothermic and use chemical energy to sustain life processes. **Autotrophic organisms** couple their metabolism to some simple processes in their surroundings, such as sunlight and inorganic chemical reactions, such as the transformation of **Fe²⁺ to Fe³⁺**. **Heterotrophic organisms** obtain free energy from the breakdown of organic molecules in their environment. Bioenergetics, or biochemical thermodynamics, is the study of the energy changes accompanying such biochemical reactions

Life processes (e.g., **anabolic reactions, muscular contraction, active transport**) obtain energy by chemical linkage. This chemical coupling results in some energy being transferred to synthetic reaction and some energy lost as heat. As some of the energy liberated in the degradative reaction is transferred to the synthetic reaction in a form other than heat, the normal chemical terms “**exothermic**” and “**endothermic**” cannot be applied. The terms **exergonic** and **endergonic** are used to indicate that a process is accompanied by the loss or gain, respectively, of free energy. In practice, an endergonic process cannot exist independently but must be a component of a coupled exergonic–endergonic system where the overall net change is exergonic. The **exergonic reactions are termed catabolism**, whereas the **synthetic reactions are termed anabolism**. The combined catabolic and anabolic processes constitute metabolism. A method of coupling an exergonic to endergonic process is to synthesize a compound of high-energy potential in the exergonic reaction and to incorporate this new compound into the endergonic reaction, thus transferring free energy from the exergonic to the endergonic pathway. **Adenosine triphosphate (ATP)** is one of the compounds serving as a transducer of energy from a wide range of exergonic reactions to an equally wide range of endergonic reactions or processes.

ATP is a phosphorylated nucleotide containing **adenine, ribose, and three phosphate groups**. ATP has an intermediate standard free energy of hydrolysis among high-energy phosphate molecules, whose characteristics allow it to play an important role in energy transfer. As a result of its position midway down the list of standard free energies of hydrolysis, **ATP is able to act as a donor of high-energy phosphate to form compounds with lower free energies of hydrolysis**. Likewise, provided the necessary enzymatic machinery is available, **ADP can accept high-energy phosphate to form ATP** from compounds with high energies of hydrolysis. In effect, an ATP/ADP cycle connects those processes that liberate free energy to those processes that utilize it. Thus, **ATP is continuously consumed and regenerated. However, it is worth recalling that the total ATP/ADP pool is sufficient to maintain an active tissue for only a few seconds.** The system that couples respiration to the generation of the high-energy intermediate, ATP, is termed **oxidative phosphorylation**. Oxidative phosphorylation enables **aerobic organisms** to capture a far greater proportion of the available free energy of respiratory substrates compared with **anaerobic organisms**.

The **mitochondrion** is the organelle in which most of the capture of energy derived from respiratory oxidation takes place. The mitochondria contain the series of catalysts known as the **respiratory chain** that collect and transport reducing equivalents and direct them to their final reaction with oxygen to form water. Also present is the machinery for trapping the liberated free energy as high-energy phosphate. Mitochondria also contain the **enzyme systems** responsible for generating the **reducing equivalents** (such as **NADPH**) in the first place, i.e., the enzymes of β -oxidation and of the citric acid cycle. The latter is the **final common pathway for the oxidation of all the major foodstuffs**. the coupling of **exergonic** and **endergonic** reactions does not harness all the energy, and a significant portion of the **energy is dissipated as heat**. **One mole of glucose, for example, contains about 2803 kJ of free energy. When it is combusted in a calorimeter to CO₂ and water, 2803 kJ is liberated as heat.**(1 Cal = 4.184 J, or 1 kcal = 4.184 kJ.)

When oxidation occurs in the **tissues**, some of the energy is not lost immediately as heat but is captured in high-energy phosphate bonds. Under aerobic conditions, glucose is completely oxidized to CO₂ and water, and the equivalent of **36 high-energy phosphate** bonds is generated per molecule. The total energy captured in ATP per mole of glucose oxidized is **1398 kJ**, or the equivalent of roughly **50%** of the enthalpy of combustion. The rest is **dissipated as heat**. In turn, when ATP generated by the **catabolism of glucose** is hydrolyzed during coupling with an **endergonic** reaction, only a fraction of the free energy may be retained in the synthesized compounds and the rest is liberated as heat. Therefore, ultimately the free energy liberated by **exergonic** reactions that is not captured in the products of anabolism (**protein, lipids, carbohydrates, nucleic acids, etc.**) is liberated as heat by biological organisms. A very important aspect from a bioenergetics point of view is **that heat produced by a chemical reaction is always the same, regardless of whether the process went directly or proceeded through a number of intermediate steps**. This means that the amount of heat produced by an animal depends on the chemical nature (energy content) of the compounds catabolized or the overall reaction and not the chemical reaction pathways over which this catabolism occurred.