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***Topic:* Biological Work in Thermodynamics**

Topic Question: How does an understanding of thermodynamics help us appreciate the remarkable efficiency of biological systems in performing work?

Subject: Biology

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There are countless living things that live of all kinds which include the tiniest of bacteria due to largest of redwood trees and doesn't seem to be quiet. The processes, which can be summed up as biological work, are also very important for the existence of life and continuity of species. Whether it is the inner molecular work of protein molecules, which spins in a cell or a succession of wing beats by a hummingbird, biological work includes processes which induce energy transfer and utilization, partial energy transformation and variable motor-organization. This is where an equally intriguing point where biology crosses with thermodynamics awe in explaining how organisms control such energy.

Thermodynamics is the branch of physics which explains and deals with transformations of various types of energy, so it is a useful tool to analyze the biological systems. The four thermodynamic laws, which arise from the conservation of energy in any cells, accentuate the extreme naturalization of biological work performance by living creatures. We need to understand those laws to be able to appreciate what is it that organisms manage to achieve on daily bases.

The first law of thermodynamics is also called the principle of the conservation of energy because this principle states that energy cannot be created out of nothing or destroyed; it can be only transferred or changed from one form to another. In the *biological systems, energy is mainly provided in the form of ATP (adenosine triphosphate) which is formed mainly due to processes like cellular respiration and photosynthesis. ATP is the unit of energy for a cell which provides the necessary energy for various activities within the cell like contraction of muscles, synthesis of proteins and active transport of certain substances.*

The concept of the second law of thermodynamics is disorder / randomness / the degree of disarray within a system which introduces the measure of entropy. The law states that for an isolated system, the total amount of entropy can only increase. A spontaneous natural process will therefore always result to an increase in the disorder level of the system. In living biological systems, however, order is conserved and even increased. The paradox is resolved because unlike physical systems, biological systems are not isolated. They are self-contained units that consume energy and matter from their environment and in doing so, they are able to create order but at the cost of outsourcing more disorder into their surroundings.

The concept of free energy plays an important role in assessing the efficiency of biological processes. Free energy is a value which signifies the amount of energy that can perform work whenever the temperature and pressure are maintained constant. A decrease in free energy change (ΔG), indicates that the process is taking place spontaneously, in contrast to increases or positive (ΔG) of that type of ΔG that indicates non-spontaneous processes. Many of the biological processes occur with negative ΔG thus these processes can occur spontaneously and do work. Enzymes, which are biological catalysts, are also important for increasing the probabilities of occurrence of such processes by decreasing their activation energy.

One useful indicator of the performance of biological systems is the amount of work they do compared to their energy costs. This energy cost may be understood with respect to biological processes, which though not perfectly efficient, are indeed quite efficient. Various factors may explain this efficiency:

Gibbs Free Energy as It Pertains to Biological Reactions:

In thermodynamics, the concept of the Gibbs free energy (G) is especially central since it measures the energy available in a system at constant temperature and pressure to do work. The equilibrium constant determines the alteration of Gibbs free energy during the reaction, thus indicating whether the reaction will be spontaneous (if $\Delta G < 0$) or non-spontaneous (if $\Delta G > 0$). In many biological processes, the value of ΔG is negative, which means that energy is liberated, and the reactions take place without needing any trades of energy into the system. During evolution, biological systems learned to integrate exothermic and endothermic reactions in an appropriate manner to optimize energy. Such coupling is achieved through ATP hydrolysis in scenarios when many cellular events cannot spontaneously happen. Another important and relevant ingredient is provided by enzymes, which can be defined as biological catalysts, which reduce the energy barrier or activation energy threshold for the occurrence of the reactions to take place thereby increasing reaction kinetics and efficiency.

Enzyme activity: Enzymes are extraordinary substances in biological systems that intensify the rate of chemical reactions related to metabolism. Enzymes assist in increasing speed of biological reactions due to the lowering of allowed energy that is essential for the reaction to take place. Each enzyme has a particular substrate on which it acts, and its activity is limited within an optima, temperature and pH, to avoid unnecessary reactions that would consume more energy than required.

Enzyme Catalysis and Reaction Efficiency

Enzymes serve as awe-inspiring biocatalysts that assist in increasing metabolic activity in cells. They do so by lowering the activation energy that is needed before a biological process can be accomplished, enabling biological processes to happen in a rate that is reasonable for life forms. Enzymes are effective to specific substrates and only work when the temperature and pH are favorable thus preventing expenditure of energy on non-productive processes.

For example, the metabolite glucose is used in several alien enzymatic processes referred to as glycolysis and is eventually converted to one molecule of pyruvate, with energy stocked as ATP and as reducing power in NADH. The biochemical reactions of the enzymes in glycolysis guarantee that the optimum conditions for *glucose utilization towards the production of ATP are achieved at every phase of the reactions.*

Energy Linking in Cells/ Organisms

One of the ways to make a biological system highly efficient is by maximizing the energy derived from the exergonic and endergonic reaction pairs. This occurs via energy currencies such as ATP. Hydrolysis of ATP (ATP → ADP + P) is a type of free energy – releasing the formation of ADP and inorganic phosphate usually releasing a large free energy (ΔG ≈ -30.5 kJ/mol). The chemical bonds cleaved from the hydrolysis of ATP and ADP Pi are used to perform endergonic process for example energy derived from hydrolysis of ATP:

Active Transport: Ion gradients such as sodium or Ca2+ across the membrane of cells are created by active transport such as Na+/K+ ATPases and ionic homeostasis. These electrochemical pumps use ATP to move ions in the opposite direction to the concentration gradient, which is particularly necessary for electric signal transmission, contraction of muscles and maintaining the size of cells.

Energy Transformations/Bioenergetics: The process of disentangling proteins, nucleic acids, and polysaccharides from their associated monomer units is an energy consuming affair which involves the interruption of normal balanced models. Energy-rich ATP bonds are broken during protein synthesis when peptide bonds are being made and during DNA replication or RNA transcription when phosphodiester bonds are formed.

Muscle Contraction: Myofibrils muscle contraction is believed to take place by the arrange and slide model, force exerted by the contraction of myosin ATP yr sluggish motor the energy that leads to the contraction of muscle fibers where movement is produced.

The cells achieve this metabolic coupling in such a way that they have enough energy to carry out the various biological processes. This metabolic coupling not *only supports the functioning of the cellular activities but also economizes on the use of energy which is the beauty of biological thermodynamics.*

Rationalization of Metabolic Pathways

The evolution of all biological systems includes optimization of work done to the most acceptable level of efficiency. Processes that cut across the metabolic pathways, including glycolysis, citric acid cycle (CAC), and oxidative phosphorylation (OXPHOS), are highly regulated to achieve the best energy production and consumption. For example:

Feedback Inhibition: One of the main metabolic control mechanisms is the feedback inhibition of enzymes acting on critical steps of a given metabolic pathway by the final product of that pathway that inhibits one of the enzymes upstream from the product. This helps in averting the excessive generation of precursors as intermediates and thus saves energy in processes.

Compartmentalization: Membranes of eukaryotic cells enclose compartments within which some of the distinct metabolic pathways are conducted. Mitochondria contain citric acid cycle and oxidative phosphorylation enzymes while the cystol is the site of glycolysis. This isolation protects dysfunctional reactions from each other and increases the efficiency of metabolism.

Substrate Channeling: Enzymatic reactions within some pathways proceed through the direct transfer of intermediates between enzymes through substrate channeling. This has the advantage of reducing the losses in diffusion processes and assisting in increasing the rate of reactions.

These strategies prevent energy imbalances and allow cells to ameliorate constant changes in environment, thus emphasizing the importance of thermodynamics and biological activities.

Energy-Efficient Transport Mechanisms

Intervention in biological systems also includes embedding in the solutions efficient provisions on transport, so that energy losses are reduced. Ion Channels and Transporters, which are membrane transport proteins, selectively permit only specific ions/molecules to go through cellular membranes. There is a range of mechanisms of these transporters:

Passive transport: No energy is expanded in the movement of molecules to equalize the concentration gradient; a form of mass transfer known as facilitated diffusion.

Active transport: This form of transport requires the use of some energy usually in the form of ATP, but it is strictly regulated to maintain balance in the cells. For instance, in coupled transport, secondary active transport moves one molecule against its concentration potential to move another in the same direction, efficiently utilizing energy.

Bulk Transport: A protein complex allows for membrane deformities to cause engulfment of large molecules by a cell (endocytosis), and will facilitate the reverse process of secretion of large protein complexes (exocytosis), thereby using little ATP as opposed to individual molecular transport.

Thermodynamic efficiency of these transport mechanisms provides insight on the extent to which energy management by cells is realized in complex biological systems.

Thermodynamics in Biology and its Application

Biological systems show unique ability to change to fit within changing environmental factors. This adaptability is linked to thermodynamic principles in which cells and organism are always in a joust between energy expenditure, intake and storage for maximization of survival. In other words, during starvation states cells usually change the rationing of cytoplasmic ATP molecules for essential processes by switching on fat supply breakdown or gluconeogenesis.

Thermodynamics also forms the backbone in assessing the differences in the rates of metabolism between organisms. For instance, aquatic reptiles (which are ectothermic) depend on the warmth from the surroundings as opposed to endothermic animals like birds and mammals who produce heat for temperature regulation. This variation in metabolism reflects the evolution of different forms of animals according to their environment and energy sources / constraints.

In this paper we find the correlation between biology and thermodynamics which explains the efficiency of biological systems as far as mechanical work is concerned. When one views energy transformations, entropy, enzymes and metabolism regulation from the angle of thermodynamics, it is hard not to admire the complexity and efficiency with which life is carried out. Study of biological thermodynamics is not only enriching our views of some aspects of biology, but also serves as a motivation for new and effective biotechnological, medical and energy-yielding advancements. In an ongoing effort to understand the thermodynamic machineries of life, we further enhance our understanding of the adaptability and efficiency of living things.