

## Energy in Biothermodynamics: A Comprehensive Review

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Received: 30-09-2025; Revised: 10-10-2025; Accepted: 31-10-2025; Published: 25-11-2025

### Abstract

This review investigates the application of thermodynamic principles to biological systems, emphasizing the human body as a model of an open, self-regulating system. It explores similarities and differences between living organisms and classical thermal machines. The human body continuously transforms chemical energy into mechanical and thermal work, following the same physical laws that govern inanimate systems. By analyzing energy conversion, entropy, and efficiency, this paper demonstrates how thermodynamic principles can deepen our understanding of physiological processes and inspire advancements in medical technology.

Keywords: Biothermodynamics; Human body; Thermodynamic laws; Energy conversion; Metabolism; Entropy.

### 1 . Introduction

Thermodynamics provides the conceptual foundation for studying how energy is generated, transformed, and dissipated in living organisms. The human body operates as an open system that exchanges both matter and energy with its surroundings through processes such as metabolism, respiration, and heat transfer [1,2]. Understanding these exchanges is essential for advancing physiology, biomedical engineering, and human adaptation to environmental changes [3,4]

### 2 . Fundamental Thermodynamic Principles in Biological Systems

The first and second laws of thermodynamics govern energy transformations in all biological systems. The first law states that energy is conserved, while the second introduces the concept of entropy as a measure of disorder or energy dispersion [5]. During metabolism, chemical energy derived from nutrients is converted into mechanical and thermal energy, inevitably increasing entropy as part of life's irreversible processes [6].

### 3. Comparative Analysis: The Human Body and Thermal Machines

Both thermal machines and the human body obey the same thermodynamic principles but differ in purpose and operational mechanisms. Machines aim for maximum efficiency, while the human body prioritizes adaptability, regulation, and survival [7–9].

**Table 1. Comparison between the human body and a thermal machine**

Human body	Thermal machine	Property
Metabolic processes [13]	Carnot cycle [10]	Working principle [10]
limited by the second law of thermodynamics [11]	Limited by Carnot's second law [10]	Efficiency[10]
Chemist (food)	Thermal [12]	Power source[12]
Chemical to mechanical and thermal [14]	Thermal to mechanical [12]	Energy conversion[13]
Biological[13]	Mechanical [13]	Organization [14]

#### 4. Mechanisms of Energy Exchange with the Environment

The human body regulates temperature and maintains energy balance through conduction, convection, radiation, and evaporation. These mechanisms allow thermoregulation and adaptation to varying environmental conditions such as temperature and humidity [6,7]. The integration of physical and biochemical feedback mechanisms ensures homeostasis despite continuous energy exchange with the environment.

#### 5. Applications of Thermodynamics in Physiology and Medicine

Biothermodynamic models have multiple applications in medicine and bioengineering. They help in optimizing metabolic efficiency, improving the design of thermal medical devices, and understanding entropy-related disorders [2,5]. Recent studies have extended these models to evaluate tissue-level energy efficiency, enhance infrared and thermal imaging, and develop adaptive wearable systems for monitoring physiological states [6,7].

#### 6. Discussion

Recent research (2020–2025) highlights the importance of non-equilibrium thermodynamics in describing biological systems [8,9]. The human body's energy efficiency arises from complex biochemical feedback that maintains dynamic equilibrium. Entropy production models have become essential tools for explaining physiological regulation and disease mechanisms [7,9,13]. These approaches link energy dissipation with system complexity, providing new insights into adaptive metabolism and health diagnostics.

#### 7. Conclusions and Practical Implications

Although both thermal machines and the human body follow the same physical laws, their functional objectives differ. The human body, as an open and adaptive system, is optimized for survival and self-regulation rather than maximal mechanical efficiency. Applying thermodynamic principles in biomedicine can foster innovation in diagnostic technologies, bioengineering systems, and energy-based therapeutic interventions [1,2,14].

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