2025 Volume: 01 Issue: 05 www.ijrpa.com Review Article

International Journal Research Publication Analysis

Page: 206-223

THERMODYNAMIC EXPLANATION OF DEATH AND THE PROCESS OF DYING

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Article Received: 08 August 2025
Article Revised: 28 August 2025
Published on: 18 September 2025

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ABSTRACT

One of the challenges of biology has been the definition of life. Most of our attempts on defining 'life' have finished in a catalogue of properties which, more or less, describe only the living beings' functions, not life. Our problem begins when we lose the notion of reality provided by nature, and go off the point with personal ideas. In this article, the operational definition of life and a meaning of death, based on empirical and observational data, will be expanded on, utilizing concepts from thermodynamics. We also look at the process of heat movement and transfer in the human body, the stages of death, and death in stricto sensu.

KEYWORDS: Death, Stages of Death, Entropy, Death Dynamics.

1. INTRODUCTION

We cannot assure that owning a complex molecular structure is an exclusive attribute of living beings. There are inert structures which are more intricate than those of a living being, a galaxy, for example. If we observe a corpse of a tree or a dog, we would observe that its molecular structure is identical to the molecular structure of that being when it was alive. Nevertheless, we distinguish with relative competence when a tree is dead and when it is alive. What we observe, however, in the example above, is that the energy of dead beings is dispersed or relocated into more microstates than when they were alive, i.e. their local entropy production [1-3].

$$\sigma = \frac{dS}{dt}$$

Increases, in such form that all their thermodynamic processes become irreversible ($\sigma > 0$). Biologically, reversibility refers to the possibility of inverting a provisional inhibition of a metabolic process. Some researchers have said that living beings are characterized by the order of their structures and that their order is maintained through non-spontaneous processes [4-8]. Nevertheless, we find abiotic systems which acquire autonomously more order than living beings. The universe's evolution is a good example. Another characteristic which has been attributed to living beings is their capability to evolve. However, there are not systems in the knowable universe which do not evolve. Other theoretical scientists have tried to unify the five attributes of the living beings by saying that the five attributes must be present in a single system for being considered alive [9-11]. However, what could we say about mammals' erythrocytes, which don't replicate? Nucleic acids are not 'living molecules' which some authors have mentioned repeatedly. Isolated nucleic acids do not maintain a quasi-stable state of its enthalpy [12-14]. Conversely, ATP synthase performs all its functions even if it is isolated from a biomembrane. On the other hand, any cell deprived of its ATP synthases, does not survive. So life is maintained by the electrodynamics generated by these tiny molecular complexes [15].

Let us consider the virus. Viruses reproduce and have order and complex structures; besides, they evolve; however, viruses don't replicate spontaneously, as every other organisms do. Viruses must make contact with living cells, invade them and take control of the synthesis of proteins and nucleic acids of the host cells. If there are not living cells available, the viruses will not reproduce. The replication of viruses is akin to biomass disintegration, in the four-fold processes of the production of biogas [16-21]. Viruses illustrate the counterpart of the essential characteristics of living beings: viruses do not interchange energy autonomously with the environment and they cannot manipulate their internal energy to avoid the spontaneous deterioration of their structures. They are like dust, or rather, like crystals. Viruses are not living beings. To expound on this statement, via thermodynamics, it is argued here that the Gibbs' fundamental algorithm does not apply with viruses [22]. Gibbs' formula permits the calculation of the differential of the internal energy (dU) of a biosystem or any living being, which is determined by several differentials that are translated into work, as shown below:

$$\mathrm{d}U = T\mathrm{d}S - P\mathrm{d}V + F\mathrm{d}l + \sum_{i=1}^{m} \mu_i \, \mathrm{d}n_i + \psi \mathrm{d}q$$

where T is the temperature of the system, dS is the local entropy of the system, P is the compression pressure, dV is the differential of volume caused by the compression, F is a given force exerted on the system, dl is the differential of elongation or size change, m is a determined number of molecules, i is a unit vector in a given direction, μi is the chemical potential of the unit vector, dn_i is a certain number of atoms or molecules, ψ is an electrodynamic potential, and dq is any amount of electrical charge [23].

Now, let us consider mammals' erythrocytes (blood cells). Mammals' erythrocytes don't possess nucleic acids; nevertheless, we say that the erythrocytes are alive. Mammals' erythrocytes lack mitochondria but they experience apoptosis, or programmed cell death. Mammals' erythrocytes have not a single opportunity of replication; though, we say that mammals' erythrocytes are alive; there is no doubt about it because they are obliged to die when getting old and obsolete (other cells induce apoptosis to erythrocytes) [24]. Evidently, mammals' erythrocytes fill all the parameters of the Gibbs' fundamental equation at any given time, except when the erythrocytes die. We can also look at the criterion of life in terms of what is called a thermodynamic process. *A thermodynamic process may be defined as the progression of energy changes taking place between an initial state and a final state* [25-29]. On this definition, it can be argued that viruses are not living beings because their thermodynamic processes belong to inert beings (abiotic systems), even if they may reproduce under favorable conditions. However, the mammals' red blood cells' thermodynamic processes match with those of living systems. Hence, we consider the mammals' red blood cells alive, although they cannot reproduce.

2. DEATH

2.1 Definition of death

Prior to the 1980s, the legal standard defined death as the absence of cardiopulmonary function including the loss of all vital signs [30]. However, as medical technology advanced, there were situations where one might lose brain function and maintain cardiopulmonary function. This led the American Medical Association, the American Bar Association in collaboration with the National Conference of Commissioners on Uniform State Laws to come together in the 1980s to expand the definition of death through the Uniform Determination of Death Act (UDDA).Under this law, death can be defined as the loss of cardiopulmonary function or the loss of brain function including the brainstem and cortex[31].

2.2 Clinical signs and stages of death

Signs of death or strong indications that a warm-blooded animal is no longer alive are: respiratory arrest (no breathing), cardiac arrest (no pulse), and brain death (no neuronal activity).

The heart and lungs are vital organs for human life due to their ability to properly oxygenate human blood (lungs) and distribute this blood to all vital organs (heart). Hence failure of the heart to pump blood or the lungs to obtain oxygen can lead to a cardiopulmonary death where the heart stops pumping and there is no pulse. In the brain, this can be manifested by a hypoxic state which leads to cerebral edema and thus an increase in intracranial pressure. The rise in intracranial pressure can lead to further disruption in cerebral blood flow, leading to necrosis or tissue death. The aforementioned mechanism is the most common cause of brain death, however this increase in intracranial pressure does not always occur due to an arrest in cardiopulmonary function [32]. Traumatic brain injuries and subarachnoid hemorrhages can also increase the intracranial pressure in the brain leading to a cessation of brain function and hence death. While cardiopulmonary death can be easily assessed by looking for the presence of a pulse, or identifying electrical activity through EKG tracings, assessment of brain death is slightly more nuanced. Per the United Kingdom Medical Royal Colleges, a diagnosis of brain death is a two-fold process including, firstly: identifying the cause of irreversible brain damage and excluding reversible causes of brain damage, and secondly: conducting a series of and clinical laboratory tests to assess brain stem function [33].

The definition of legal death and its formal documentation in a death certificate, vary according to the jurisdiction. The certification applies to somatic death, corresponding to death of the person, which has varying definitions but most commonly describes a lack of vital signs and brain function [34]. Death at the level of cells, called molecular death or cell death, follows a matter of hours later. These distinctions, and the independence of physicians certifying legal death, are significant in organ procurement.

Post-Mortem Changes: Post-Mortem changes refer to the series of changes that occur to a body after death. These changes can generally be divided between early post-mortem changes and late post-mortem changes (also known as decomposition). These changes occur along a continuum and can be helpful in determining the post-mortem interval, which is the time between death and examination. The stages that follow shortly after death are:

- Pallor mortis, paleness which happens in the first 15–120 minutes after death.

- Algor mortis, the reduction in body temperature following death. This is generally a steady decline until matching ambient temperature.
- Rigor mortis, the limbs of the corpse become stiff (Latin rigor) and difficult to move or manipulate.
- Livor mortis, or dependent lividity, a settling of the blood in the lower (dependent) portion of the body.
- Putrefaction, the beginning signs of decomposition

Of these, with obvious mortal damage to the body, the textbook conclusive signs of death clear to a lay person are: rigor mortis, livor mortis, and putrefaction [35]. The cardinal signs of death may refer to the ending of breathing, heartbeat and circulation, or to algor mortis, livor mortis and rigor mortis. The adoption of brain death as a definition has lessened the centrality of these signs. In a clearer contemporary terminology, algor mortis, livor mortis and rigor mortis are called "early postmortem" changes, in distinction from the "immediate postmortem" changes associated with the cessation of bodily functions, as indicated by vital signs. With an ophthalmoscope, changes to the blood in the retina are quickly visible [36].

Those stages are followed, in taphonomy, by

- Decomposition, the reduction into simpler forms of matter, accompanied by a strong, unpleasant odor.
- Skeletonization, the end of decomposition, where all soft tissues have decomposed, leaving only the skeleton.
- Fossilization, the natural preservation of the skeletal remains formed over a very long period. This stage may not occur, depending on the circumstances and the conditions of the surrounding environment.

Decomposition Stages

Descriptions of decomposition have had varying numbers of discrete stages. A 5-stage process developed by Galloway and colleagues that is commonly used in forensic pathology is detailed below [37]:

Stage 1: Fresh – about half of bodies show signs of lividity and no signs of insects.

Stage 2: Early Decomposition – Bacteria grow throughout the body, releasing gases, including cadaverine, which in turn bloat the body and cause an unpleasant odor.

Stage 3: Advanced Decomposition – This stage brings further discoloration to the body. The gases from bacterial decay begin to escape, causing a strong odor.

Stage 4: Skeletonization – The internal organs liquefy and the body begins to dry out.

Stage 5: Extreme Decomposition – Advancing of the skeletonization with bleaching, exfoliation, and loss of wide portions of long bone.

2.3 The Coma Stage

Coma is a state of prolonged unconsciousness that can be caused by a variety of problems — traumatic head injury, stroke, brain tumor, drug or alcohol intoxication, or even an underlying illness, such as diabetes or an infection. Coma is a medical emergency. Swift action is needed to preserve life and brain function. Doctors normally order a series of blood tests and a brain scan to try to determine what's causing the coma so that proper treatment can begin [38]. A coma seldom lasts longer than several weeks. People who are unconscious for a longer time might transition to a persistent vegetative state or brain death. The signs and symptoms of a coma commonly include

- Closed eyes
- Depressed brainstem reflexes, such as pupils not responding to light
- No responses of limbs, except for reflex movements
- No response to painful stimuli, except for reflex movements
- Irregular breathing

Many types of problems can cause a coma. Some examples are [39]

- Traumatic brain injuries: These are often caused by traffic collisions or acts of violence.
- Stroke: Reduced or interrupted blood supply to the brain (stroke), can result from blocked arteries or a burst blood vessel.
- Tumors: Tumors in the brain or brainstem can cause a coma.
- Diabetes: Blood sugar levels that become too high (hyperglycemia) or too low (hypoglycemia) can cause a coma.
- Lack of oxygen: People who have been rescued from drowning or those who have been resuscitated after a heart attack might not awaken due to lack of oxygen to the brain.
- Infections: Infections such as encephalitis and meningitis cause swelling of the brain, spinal cord or the tissues that surround the brain. Severe cases of these infections can result in brain damage or a coma.
- Seizures: Ongoing seizures can lead to a coma.
- Toxins: Exposure to toxins, such as carbon monoxide or lead, can cause brain damage and a coma.

- Drugs and alcohol: Overdosing on drugs or alcohol can result in a coma.

2.4 Types/Causes of Death

Senescence or biological aging is the gradual deterioration of functional characteristics in living organisms. The word senescence can refer to either cellular senescence or to senescence of the whole organism. Environmental factors may affect aging – for example, overexposure to ultraviolet radiation accelerates skin aging. Different parts of the body may age at different rates. Two organisms of the same species can also age at different rates, making biological aging and chronological aging distinct concepts.

Terminal illness or end-stage disease is a disease that cannot be cured or adequately treated and is reasonably expected to result in the death of the patient. This term is more commonly used for progressive diseases such as cancer or advanced heart disease than for trauma. In popular use, it indicates a disease that will progress until death with near absolute certainty, regardless of treatment. A patient who has such an illness may be referred to as a terminal patient, terminally ill or simply as being terminal.

Accident - This is an unintended, normally unwanted event that was not directly caused by humans. The term accident implies that nobody should be blamed, but the event may have been caused by unrecognized or unaddressed risks. Examples are vehicle collisions, fire, or liquid spillage.

Injury, also known as physical trauma, is damage to the body caused by an external force. This may be caused by accidents, falls, hits, weapons, and other causes. Major trauma is injury that has the potential to cause prolonged disability or death [40].

Complications: Although many people gradually recover from a coma, others enter a vegetative state or die. Some people who recover from a coma end up with major or minor disabilities. Complications can develop during a coma, including pressure sores, urinary tract infections, blood clots in the legs and other problems.

2.5 Death Trajectory

Death trajectory refers to the pattern of dying when a patient is given a projected death date with limited or no medical recourse for the remaining existence of the individual's life. The death trajectory is dependent on the cause of death, whether it is sudden death, chronic illness, or the steady decline in health due to senescence (aging) [41]. Death trajectory is

analyzed in two separate aspects: duration and shape. Duration refers to the period of time a patient has to live, which can be anywhere from imminent death to several months. Shape refers to how that duration is then graphed. In other words, the shape is "the course of dying, its predictability, and whether death is expected or unexpected".

Sudden Death Trajectory: Sudden or premature death occurs when the death of an individual is not perceived to be imminent. In a sudden death trajectory, an otherwise healthy and high-functioning individual will suddenly and unexpectedly die without any observable indications of oncoming demise. People are at a high or normal level of functioning until the moment of death occurs. These types of deaths include fatal accidents and inconspicuous health issues like myocardial infarction or severe stroke. Deaths that align with a sudden death trajectory may happen over the course of a few days or in a matter of seconds [42]. There is a sharp decline in human function in a short period of time.

Fig. 1: Illustration of the Premature Death Trajectory

Natural Death Trajectory: A natural death trajectory is typically a long, steady decline due to old age. In these cases, the death trajectory is based on how the mind and body degenerate, including the speed of organ failure. In these cases, it is much easier to anticipate a person's death.

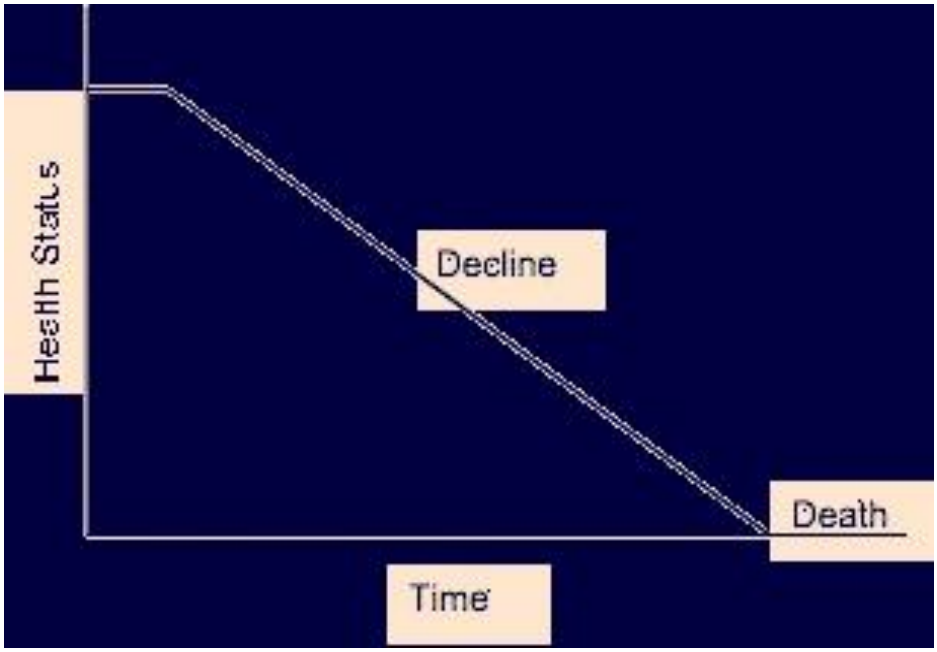

Fig. 2: A typical natural death trajectory chronicling a long, steady decline in health over time.

The Chronic Malady Trajectory: The chronic malady trajectory occurs with types of death caused by auto-immune diseases such as HIV or other incurable illnesses. This process of death is characterized by an overall decline in health accompanied by acute crises and intermittent recoveries. The chronic malady trajectory projects emotional stress or turmoil. The patient may eventually become mentally and emotionally exhausted.

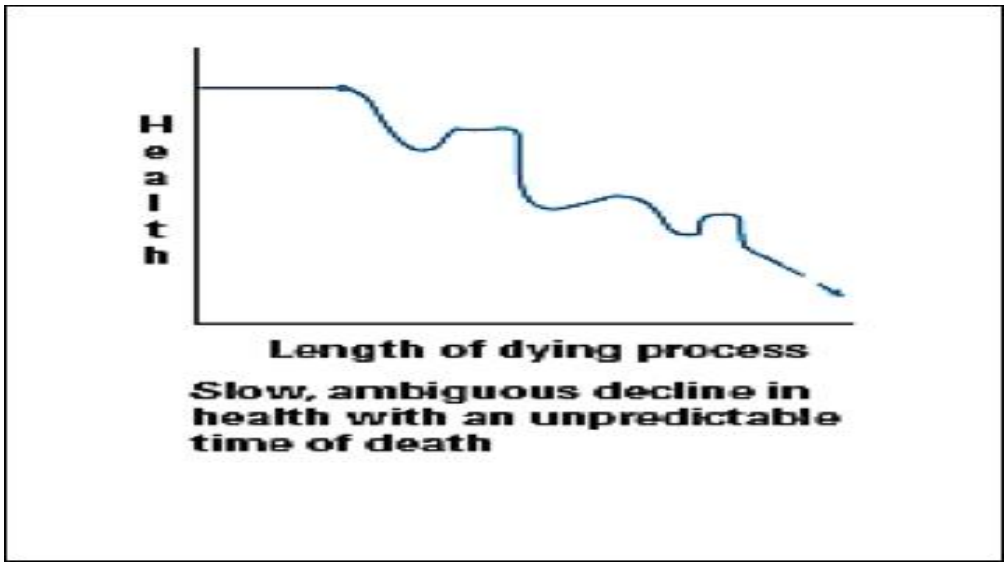

Fig. 3: A chronic malady trajectory showing an overall decline in health with intermittent rises and falls in human function.

3.0 Thermodynamics and Decomposition of Human Body

3.1 Heat Movement in the Body

Heat is continuously generated in the human body by metabolic processes and exchanged with the environment and among internal organs by conduction, convection, evaporation and radiation. Transport of heat by the circulatory system makes heat transfer in the body — or bio-heat transfer — a specific branch of this general science. As in all entities, the principle of conservation of energy yields [43-44]:

$$\dot{Q}_{generated} = \dot{Q}_{stored} + \dot{Q}_{lost} + \dot{W}$$

Where the terms denote, from left to right, the rate of heat generation due to metabolic processes; rate of heat stored in body tissues and fluids; heat lost to the environment and adjacent tissues; and the rate of work performed by the tissue. This latter quantity is usually negligible at the tissue level. In the tissue element shown in Figure 4, heat due to metabolic processes (5–10,000 W/m^3) is generated at a variable rate, which, when integrated over the entire control volume, obtains:

$$\dot{Q}_{generated} = \int_v \dot{q}_m(\bar{x}, t)\, dv$$

Where $\bar{X}$ denotes the spatial coordinate and t is time.

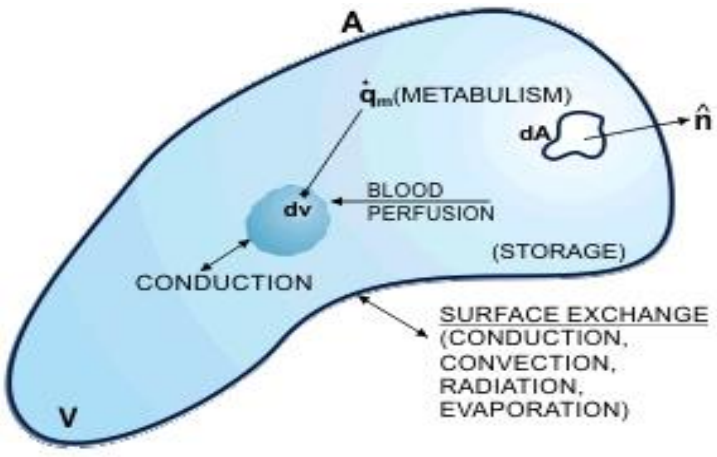

Fig. 4: Control Volume of Tissue Element.

Under unsteady conditions, part of the heat flow will be stored in the control volume:

$$\dot{Q}_{stored} = \int_v \rho c(\bar{x}) \frac{\partial T(\bar{x}, t)}{\partial t} dv$$

Where ρ is tissue density (900–1600) kg/m^3); c is tissue specific heat (2.1–3.8 kJ/kgK); and T is tissue temperature.

The term representing heat lost to adjacent tissues and to the environment contains a number of

components, one of which is heat exchanged by diffusion (Fourier's Law of conduction) [45]:

$$\dot{Q}_{conducted} = -\int_A k\bar{\nabla}T(\bar{x}, t) \cdot \hat{n}\, dA$$

Where k is the thermal conductivity of the tissue (0.29–1.06 W/mK); T is tissue temperature gradient; $\bar{\nabla}$ is outward-pointing unit vector; and A is control volume surface area.

$$\dot{q}_{blood} = \rho_b c_b \dot{w}_b (T_a - T_v)$$

A second component of the heat lost to adjacent tissues is due to blood perfusion. Blood circulates in a variety of vessels ranging in lumen diameter from the 2.5 cm aorta to the 6–10 mm capillaries. Due to this four-fold size distribution, heat transport effects of blood are coupled to the specific group of vessels under consideration. A common approach to modeling this effect is to assume that the rate of heat taken up by the circulating blood at the capillary level equals the difference between the venous and arterial temperatures times the flow rate (Fick's Law) [46]: Where rbcb is blood heat capacity (≈4000 kJ/m3K) and wb is volumetric blood perfusion rate (0.17–50 kg/m3s). At the capillary level, blood flow velocity is very slow and thermal equilibration with surrounding tissue occurs. Thus, Eq. (5) may be modified by setting Tv = T (Pennes, 1948) [47]. When all the terms are substituted into Eq. (1) and integrated over the entire volume and surface area, the well-known bio-heat equation is obtained:

$$\rho c \frac{\partial T}{\partial t} = \bar{\nabla} \cdot k\bar{\nabla}T + \rho_b c_b \dot{w}_b (T_a - T) + \dot{q}_m .$$

Equation (6) has been very useful in the analysis of heat transfer in various body organs and tissues characterized by a dense capillary bed. Other thermal effects due to blood flow are not adequately accounted for by Eq. (6), including: 1) countercurrent heat transfer between adjacent vessels; 2) directionality effects due to the presence of larger blood vessels; and 3) heat exchange with larger vessels in which complete thermal equilibrium may not be assumed. These issues have been analyzed by Chen and Holmes (1980) and by Weinbaum et al. (1984) [48].

Heat is exchanged with the environment through a complex combination of conduction, convection, radiation and evaporation [49]. Clothing worn by humans and natural integuments also play a role. As a good approximation, these effects may be calculated by an equation of the form:

$$\dot{Q}_i = h_i A_D (\bar{T}_s - T_o)$$

Where Q1 is the amount of heat exchanged and hi is the heat exchange coefficient (2.3–2.7 W/m^{2}K for free convection, 7.4V0.67 for forced convection, where V is wind velocity, m/s [50-54], and 3.8–5.1 for radiation); $\bar{T}_s$ is average body surface temperature; T_o is environmental temperature; and A_D is Dubois' body surface given by:

$$A_D = 0.202 m^{0.425} h^{0.725}$$

Where m is body mass in kg, and h is height in m.

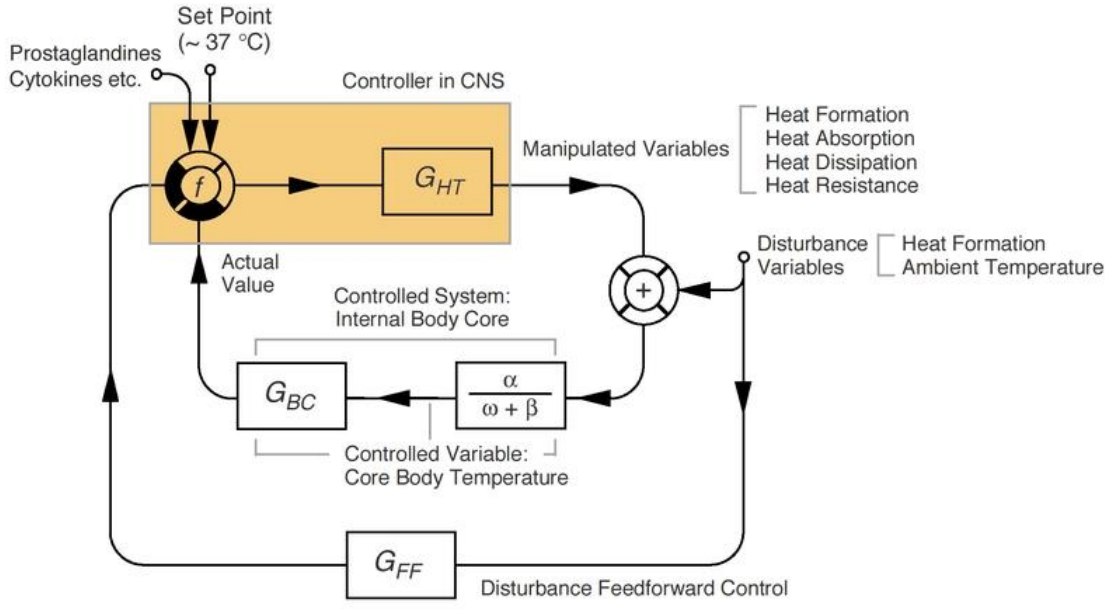

Fig. 5: Simplified Control Circuit of Human Thermo-Regulation.

3.2 Biological Definition of Death

Biological death is the reintegration of the spontaneous diffusion or dispersion of the quantum energy of the bio-systems towards more available microstates. As such, death is the state of a thermodynamic bio-system in which that thermodynamic system cannot obtain non-spontaneously energy from the environment and organize non-spontaneously the energy obtained from the environment [55]. Consequently, a dead bio-system discontinues the forcing of the energy into the bio-system's compartments; which, in the living case, would transform into internal energy that could be used for the progression of the processes that permits the bio-system to maintain a quasi-stable entropic state. When a living thermodynamic system dies, it reintegrates the differential of the entropy between it and its environment, i.e. the local entropy of the bio-system will be higher than zero and it won't be transferred to the environment, but the bio-system will take entropy from the environment.

Apparently, the maintenance of a quasi-stable entropic state of a bio-system contradicts the second law of thermodynamics; however, we argue that it does not because the entropy of the bio-system increases at levels higher than the entropy of the environment, consequently, the entropy of the bio-system will be transferred to the environment, that is, from the system in a higher entropic state (the bio-system) to the system at a lower entropic state (the environment). A violation to the second law of thermodynamics would imply that the entropy flowed from a system with a lower entropic state to a system with a higher entropic state. It doesn't occur in bio-systems because the universe is always in a lower entropic state than as compared to bio-systems.

4. CONCLUSION

Life is not defined by its molecular structure, or its order, its complexity, its evolution or its reproduction. Life and biological death are entropic states of some thermodynamic systems. The energy state of life permits bio-systems to maintain a quasi-stable entropic state, while the energy state of death allows a bio-system to reintegrate the entropic differential between that bio-system and the universe. We could say that the Gibbs' fundamental equation is the 'equation of life', of such form that we could determine whether a system is biotic or not by simply trying to apply the formula on the work (W) done by that bio-system and on the amount of heat used by that system for doing work. Any of the Gibbs' fundamental equation parameters can be adjusted by expanding or reducing them according to the studied bioprocess or according to the bio-system's physiology. The entropic state of a bio-system is

always increasing; however, the bio-system is capable of transferring the gained entropy towards any other system with a lower entropy state. If we consider some alternate phases of the entropy, like order and complexity, we would find that the universe is always more ordered and complex than any bio-system. Hence, the universe entropic state is always lower than the entropic state of the bio-systems.

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