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Entropic analysis of human body's longevity as a function of physical activity level

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Abstract: The literature reveals the application of the laws of thermodynamics for predicting life span and the effects of the physical activity level on longevity. But the vastly simplified literature models seem to suggest a reduction in duration of life with increased activity level, which is the opposite of medical recommendations, that means that exercises increase the longevity. The main objectives of this paper are to re-present the previous model, check and confirm the previous results and improve the model by formulating a simplified phenomenological relation between life span, specific entropy generation of the body (SEG-life, in MJ/kg.K) and physical activity level. The model was validated considering different individuals. In this study, it is suggested that the principle of cumulative entropy generation limit should be relaxed in function of lifestyle and type of exercise performed during life, differently from what it is defined by the literature. So, it is proposed a relax to the limit on SEG-life as a result of various physical activity levels.

Key words: Bio thermodynamics, entropy generation, human lifespan, longevity, physical activity, physiology.

INTRODUCTION

The use of thermodynamics properties to describe real process is frequent in the literature. The most common uses of thermodynamic properties, as enthalpy and entropy, are in industrial route and in biotechnological systems. These master uses can be represented by Ramos et al. (2019), Kaveh et al. (2021) and Silva et al. (2021). Nevertheless, most of the thermodynamic concepts can be appointed in living bodies, as presented by Mady et al. (2013), as long as it is proved that the human body also respect the Laws of Thermodynamics (Mady 2014). The principle of energy conservation was stated for the human body for Julius Mayer, after observing the relationship between heat and work regarding physiology (Aquilini et al. 2021).

According to Rosen (2002), there are benefits of using the principles of thermodynamics to evaluate technologies and environmental impact. Kaveh et al. (2021) defend that systems efficiency and optimization must be designed by thermodynamic analysis. Exergy should prove to be useful in such activities to engineers and scientists, as well as decision and policy makers (Rosen 2002).

The living body is an open system that is not in thermal, chemical or mechanical equilibrium with the environment. In order for this unbalanced state to be maintained, there are constant biological reactions inside the body that require the exchange of energy and matter with the environment generating entropy (Silva & Annamalai 2008). As stated by Hershey (2010), the human being goes from a state of high order until reaching a state of maximum disorder, when the natural death of the body occurs. The biological aging process is characterized by the progressive decline in the efficiency of physiological functions (Hulbert et al. 2007). Understanding of the aging mechanisms is of major interest to scientists, physicians and general population as well, but attempts at understanding the causes of aging are limited by the complexity of the problem (Padalko 2014).

According to literature, certain external conditions, habits and pathologies are capable of impacting the entropic generation rate of the body which may extend or shorten its useful life. According to Henriques et al. (2020), the smoking habit can reduce in about 15 years the person lifespan.

In human body, thermodynamics is normally used to study thermal comfort. Turhan & Akkurt (2019) affirm that thermal comfort is strongly related to the thermal balance of the human body with its environment, and so the First Law must be applied. Internal reactions, as different hormonal scenarios, are now studied to evaluate and improve human comfort with the environment (Molliet & Mady 2021).

The published mathematical models that describe the functioning of the human body under the thermodynamic concepts are traditionally specific. Only one variant factor is usually analyzed and not the different interactions that occur in the human body, especially when the practice of physical activity has been considered. According to Silva & Annamalai (2008), Aoki (1989, 1990) and Rahman (2007), physical activity generates an increase in the entropy generated by the body. In other words, exercising would result in an early death. However, it contradicts medical recommendations, which indicate that the practice of physical activity contributes to a more lasting aging and with a better quality of life. At this point, a contradiction is noted.

According to Hulbert et al. (2007), the most accepted theory that estimates life span is the oxidative stress theory of aging; this theory comes from the natural fact that oxygen consumption (though respiration) inevitably results in a production of free radicals, which damage cell in a long term, because of its extreme reactivity that can generate new molecules, bringing a propagating oxidative damage. The free radical theory of aging hypothesizes that oxygen-derived free radicals are responsible for the age-related damage at the cellular and tissue levels (Padalko 2014). Although, this theory is not completely adequate to explaining the maximum life span. And so, the authors suggest that the variation in membrane fatty acid is the missing concept that may link the mechanism between metabolism and longevity, as long as this membrane affects the process of lipid peroxidation and its products.

The present paper aims to establish a mathematical relationship capable of connecting thermodynamic properties to human physiology and the biological impacts of physical exercise, providing a more detailed analysis of the effects of activity on longevity. Although the complexity of the human body and its reactions, this paper looks for a simplification of the system to make possible a modeling. It is believed that a complete and more realistic model contributes to assessing the impact of different lifestyles on longevity, and so it is proposed an enhancement from previous papers.

MATERIALS AND METHODS

Thermodynamical models

Few thermodynamic models that describe the human body's functioning can be obtained in literature. These models are even rarer when physical activity and athletic performance of the body are considered in the analysis. However, the descriptions proposed by Silva & Annamalai (2008), Aoki (1989, 1990) and Rahman (2007) are prominent. According to Pearl (1928), the duration of life varies inversely as the rate of energy expenditure during its continuance.

According to Mady (2014), Aoki (1989, 1990) was one of the authors that stood out in the search to apply thermodynamic laws to the human body. Aoki (1989) suggests a method for calculating the entropy generated by the human body, with a greater focus on the behavior of the body according to environmental conditions. In other words, Aoki (1989) considers thermal exchanges (by radiation, evaporation, convection and heat loss) and masses exchanges (water and gases) between the individual and the environment. To this end, the author considers data reported by Hardy & Du Bois (1938) in an experimental analysis of a specific individual to the heat and the mass changes by the body.

Rahman (2007) considered the model proposed by Aoki (1989, 1990) and proposed modifications in order to make it more encompassing. Rahman (2007) suggests that mathematical relationships should be used to calculate bodily exchanges with the environment, as well as to determine body temperature, and thus make the model independent of experimental data.

Rahman (2007) bases in Givoni & Goldman's model (1972) to define the rectal temperature of the body. Equation (1) summarizes the model. According to these authors, the temperature is defined by the metabolic real rate (M [W]), the clothing thermal changes coefficients (Clo and $\frac{i_m}{Clo}$ dimensionless) and the capacity required (E_{req} [W]) and maximum capacity ($E_{\max}$ [W]) of body evaporation. Equations (2-4) are empirical, proposed by Givoni & Goldman (1972) and the temperature needs to be calculated.

$$T_r = 36.75 + 0.004M + \frac{0.025}{Clo}\left(T_a - 36\right) + 0.8e^{0.0047\left(E_{req} - E_{\max}\right)} \tag{1}$$

$$E_{req} = M + E_{R+C} \tag{2}$$

$$E_{R+C} = \frac{11.6}{Clo}\left(T_a - 36\right) \tag{3}$$

$$E_{\max} = 25.5\frac{i_m}{Clo}\left(44 - \phi_a P_a\right) \tag{4}$$

where T_a is the ambient temperature [°C], E_{R+C} is the heat ambient charge[W] and $\phi_a P_a$ is the vapor pressure [mmHg]. The clothing thermal change coefficients are defined according to the air effective speed (v_{eff}) [m/s], calculated with the Equation (5), and with the type of clothes considered, as presented in Table I.

$$v_{eff} = v_{air} + 0.004(M - 105) \tag{5}$$

where v_{air} is the air speed considered, in m/s.

For the metabolic rate, Rahman (2007) uses the equations defined by Harris & Benedict (1918), presented in Equations (6,7). The impact of physical exercise is estimated with a factor of activity (FA). This factor is defined in function of the intensity and quantity of exercise practiced in a week.

Table I. The clothing thermal changes coefficients (Givoni & Goldman 1972).

Clothing Type	Clo	$\frac{i_m}{Clo}$
Shorts	$0.57{v_{eff}}^{-0.30}$	$1.20{v_{eff}}^{+0.30}$
Shorts and shirt	$0.74{v_{eff}}^{-0.28}$	$0.94{v_{eff}}^{+0.28}$
STD	$0.99{v_{eff}}^{-0.25}$	$0.75{v_{eff}}^{+0.25}$
STD + OG	$1.50{v_{eff}}^{-0.20}$	$0.51{v_{eff}}^{+0.20}$

Rahman (2007) assumes that exercising impacts on an increase in the metabolic rate, and so the effect of the habit can be estimated by multiplying these factors to the calculated metabolism level.

$$M_{men} = 66.5 + 13.8m + 5.0y - 6.8a \tag{6}$$

$$M_{women} = 655.1 + 9.6m + 1.8y - 4.7a \tag{7}$$

where m is the mass in kg, y is the height in cm, a is the age in years and M is defined in kcal/day.

Rahman (2007) also uses the paper developed by Kandjov (1999) to calculate the energies associated with the changes in evaporative and convective changes. According to the type of air circulation and speed, the heat change coefficients are defined. For the evaluations, the author considers a forced convection and a 2 m/s air speed.

Silva & Annamalai (2008) propose a model that aims to relate entropic generation from the thermodynamic analysis of the biochemical reactions of human metabolism. The method proposed by the authors considers that all activities performed by the body depend on the energy provided by the metabolism; this energy is stored on the body in ATP (adenosine triphosphate) molecules, which are known as the life-sustaining work currency of the body (Annamalai 2021). Thus, the assessment of entropy generated by the metabolic reactions of oxidation of the consumed nutrients would give a good approximation of the total entropy generated by the body. Silva & Annamalai (2008) assume that the entropy generated by the inflow and outflow of water and air is very small and so it is possible to disregard it.

For the development, it is considered the equivalence of free Energy of Gibbs, given by $G_k = h_k - T_k s_k$, where h_k is the enthalpy and s_k is the entropy of the product. Starting from the First and Second Laws of thermodynamics, performing operations and simplifying, the entropic generation is given by Equation (8).

$$\dot{\sigma}(t) = \frac{\sum_j \left(1 - \eta_j\right) \cdot \dot{m}_j(t) \cdot \ \left(-\Delta G^0_{c,j}\right)}{T_b} \tag{8}$$

where j are the nutrients ingested, assumed by the authors as carbohydrates (CH), proteins (P) and fats (F), $\Delta G_{c,j} < 0$ and temperature T_b is the body temperature in Kelvin, considered constant at 310.15K (37°C), inasmuch as there is a consideration that the system is isothermal, as sudden variations in this value may not be tolerated by the organism. The amounts in mass of each macronutrient consumed vary throughout life as does the person's level of physical activity, since they depend on the metabolic demands of each one. Metabolism, in turn, depends on the individual's physiological conditions, which is calculated with some empirical relations defined by IOM (2002). In the same way that Rahman

(2007) did, Silva & Annamalai (2008) assume that the physical activity impact can be estimated with the product between the calculated metabolism and a physical activity level (PAL). The PAL is a factor defined in function of the amount of activity practiced.

The Gibbs energy of each macronutrient and the respective metabolic efficiencies are shown in Table II.

Table II. Properties of nutrients (Silva & Annamalai 2008).

Nutrient, *j* (Formulae)	M_j [g/mol]	HHV_j [kJ/kg]	$HHV_{O_{2_j}}$ [kJ/kg O_2]	$h_{f,j}$ [MJ/kmol]	$\Delta G_{c,j}$ [kJ/kg]	$s_{298,j}$ [kJ/kmol]	η_j (metabolic efficiency %)
Glucose ($C_6H_{12}O_6$)	180	15630	14665	-1260	-16070	212.0	34.6
Amino acid ($C_{4,57}H_{9,03}N_{1,27}O_{2,25}S_{0,046}$)	119	22790	14705	-385	-22430	--	10.4
Palmitic acid ($C_{16}H_{32}O_2$)	256	39125	13635	-835	-38465	452.4	32.2

At this point, it is important to mention that the values presented of energy released for each one of the nutrients are in an optimal oxygen providing. As explained by Annamalai (2021), the quantity of energy released per mole of macronutrients (the efficiency of the decomposition process) varies according to the oxygen available. The author also calls the attention to the fact that the severe oxygen deficiency can cause trouble for energy providing and make easier the stockage of other subproducts on the body, as lactic acid after glycolysis pathway, which may lead to the destruction of healthy cells. Cancer and virus cells, including those of COVID-19 patients, rely on the glycolysis pathway to provide the building blocks for uncontrollable cell growth (Annamalai 2021).

According to Hershey's (2010) assessment, the limit of accumulated entropic generation would be 10,025 kJ/kg.K (2,395 kcal/kg.K) for men and 10,678 kJ/kg.K (2,551 kcal/kg.K) for women. Silva & Annamalai (2008) defined new values, which are 11,508 kJ/kg.K for men and 11,299 kJ/kg.K for women. These last two authors even emphasized that the difference between the data occurs due to the consideration of basal metabolic rate. These values are defined with the integration of the curves generated by Silva & Annamalai's model (2008), considering the life expectancy defined by the CIA (2004), which are 74.63 years for men and 80.36 years for women.

As concluded by Silva & Annamalai (2008) and Rahman (2007), the level of physical activity has a significant effect on life expectancy, as increasing this value causes the entropic limit to be achieved more quickly. Thus, physical activity would result in a decrease in life expectancy. Table III shows the life expectancy values defined by Silva & Annamalai (2008) according to PAL.

Some other authors also applied the thermodynamic laws to the human body to evaluate longevity in function of entropy generation by the metabolism for different dieting types, following methodologies similar to Silva & Annamalai (2008). For example, Kuddusi (2015) used Turkey habits data, while Patel & Rajput (2021) used India ones. The main aim from these studies was to define a relation between regional food habits and longevity in different parts of each country. Both of them defined a range of life span according to each region: Kuddusi (2015) found a variation between 69.54 to 88.20 years for Turkey and Patel & Rajput (2021) defined that the life span ranges in 66 to 79 years

Table III. Effect of physical activity level on lifespan (Silva & Annamalai 2008).

Case	Male	Female
Sedentary	85.05	95.75
Low Active (base)	73.78	81.61
Active	63.78	69.53
Very Active	53.20	57.68

in India. So, it is possible to conclude that different patterns of alimentation vary and impact in the way body's work.

Relationship between physical activity, triggered pathologies and life expectancy

According to World Health Organization (2020), a minimum of 150 minutes of moderate intensity physical activity or at least 75 minutes of intense physical activity per week is recommended. For additional health benefits to be realized, adults between 18 and 64 years of age should perform 300 minutes of moderate physical activity per week.

Studies done by Nieman & Wentz (2019), Weyh et al. (2020) and Leskinen et al. (2018) state that the daily practice of physical exercise strengthens especially the immune and cardiorespiratory systems, improving health and prolonging life. Lee et al. (2017) concluded that runners have a 30-45% lower risk of death than non-runners.

Willet et al. (1999) showed that there is a strong and linear association between Body Mass Index (BMI) and the development of type II diabetes, hypertension, cardiovascular disease and cholelithiasis in men and women. In addition, it has been proven by Calle & Kaaks (2004) that excess of adiposity contributes to the incidence of and/or death from cancer, kidney and liver complications. According to Winett & Carpinelli (2000), regularity of physical activity is associated with the maintenance of lean mass and negatively associated with hypertension, high cholesterol, type II diabetes and mortality.

Furthermore, in addition to being already associated with pathologies that are risk factors for COVID-19, such as heart disease and diabetes, obesity was identified as the main factor associated with deaths of under 60 years old people for the new coronavirus, according to the UFMG School of Medicine (2020). Laddu et al. (2021) suggest that the practice of physical exercises is capable of reducing the severity of viral pathologies, such as COVID-19. According to Silveira et al. (2020), despite the lack of data about the new coronavirus, there is evidences that regular exercise reduces the intensity of symptoms and the risk of death from respiratory diseases.

Mady (2014) states that the human being under baseline conditions after physical activity is more efficient than prior to the activity (even of short duration), due to the adaptations that the body undergoes. In addition, according to an experimental procedure conducted by Mady et al. (2013) with runners at different levels of training (and consequently different metabolic levels), it was concluded that for the same speed, individuals with better conditioning present less loss to the environment and that for the same amount of energy spent, a better trained person develops a higher level of work.

In a study conducted by Dhana et al. (2016) the effects of different activities on longevity were analyzed. The study was based on data available in the literature for a statistical model construction for a calculation of life expectancy; it was constructed multistate life tables to calculate the effects of total PA and PA types on life expectancy. It was concluded that higher levels of physical activity are associated with increased life expectancy and more years lived without the incidence of cardiovascular disease. Table IV presents the results obtained by Dhana et al. (2016) of the increasing expectations for different activities. The separation between activity levels is given according to the weekly practice time.

Table IV. Increase in lifespan in years per gender, effect by physical activity (Dhana et al. 2016).

		Men	Women
Walking	*Moderate*	1.3	0.8
	High	1.3	0.7
Cycling	*Moderate*	2.1	2.4
	High	3.7	2.1
Domestic Work	*Moderate*	1.3	1.4
	High	1.1	2.6
Sports	*Moderate*	3.1	1
	High	1.2	0.9
Gardening	*Moderate*	2.7	1.1
	High	2.7	0.3

Methodology

Throughout the development of the study, a literature review was carried out aimed at the knowledge of the methodologies used in the description of the process of interest. It was noted that there are few models available in literature that use thermodynamical concepts to describe the entropy generation by the human body. Thus, the models of Silva & Annamalai (2008) and Rahman (2007) were identified and studied. Since Rahman's model (2007) was strongly based on Aoki's model (1989), it was also studied and evaluated. For the purpose of comparison between the models, it was sought to reproduce the data obtained following the recommended methodologies and the data presented by the authors. In addition, it was possible to evaluate the detailing used by each author to describe the system and the likelihood of the data obtained from entropic generation with real life expectancy values.

Once the models were obtained, a comparison is made to define which of them would be chosen to be improved. Analyses and suggestions for improving the model were made, in order to obtain a broader modeling of the assessed situation. The main aim was to focus on the effect of physical activity on human longevity. As a result of this modeling, the validation of generated data was necessary, in addition to the comparison of situations, habits and body variations proposed in favor of defining life expectations in different scenarios.

Another part of the literature review was focused on the impact of the practice (or non-practice) of any kind of physical activity on life expectancy, as well as exercising recommendations according to competent bodies. The evaluation of pathologies triggered by the lack of physical exercises was therefore necessary. It has allowed the comparison of living conditions in different situations and panoramas, specially focused on the increase in life expectancy brought on exercising.

Finally, the results were obtained using the new proposed model and life expectancy described by Dhana et al. (2016). The critical analyses were then made. All the phases mentioned are shown in Fig. (1), summarizing the steps taken to complete the study.

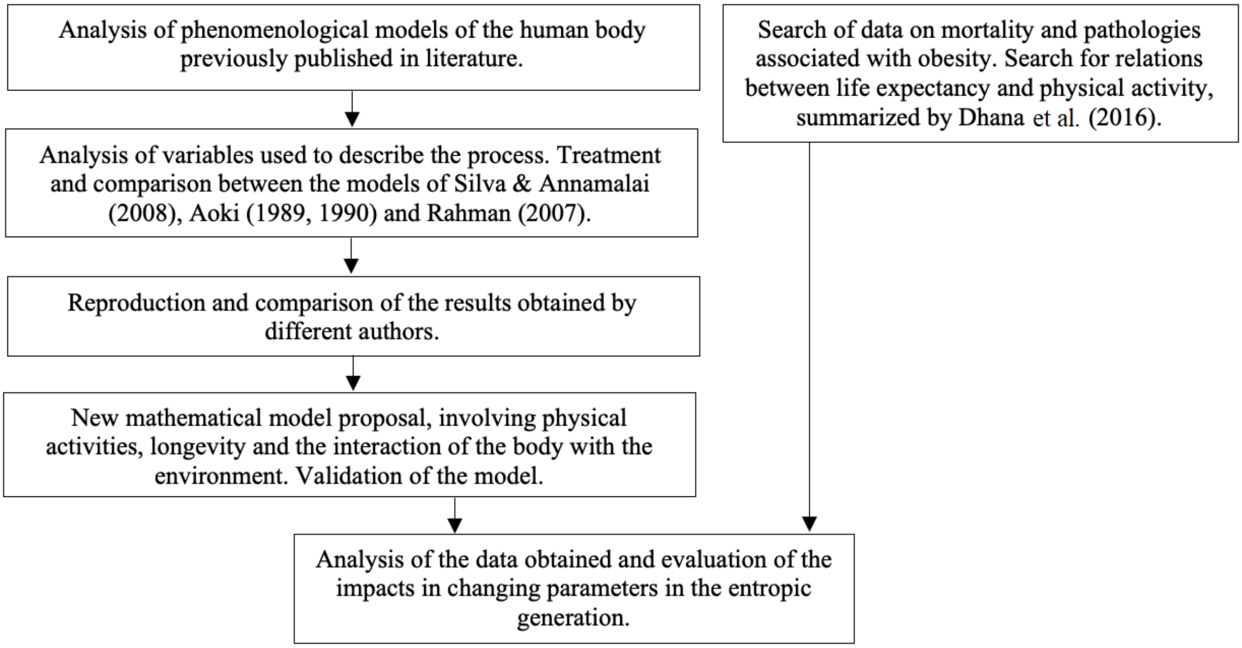

Figure 1. Flowchart of the proposed methodology.

RESULTS AND DISCUSSION

In order to compare the models, the methodologies of each one were followed and the data given was used. The models presented by Aoki (1989) and Silva & Annamalai (2008) resulted in a satisfactory coincidence between what was presented in the papers, what was obtained in the reproduction and between each other. Despite the methodology and concepts applied being in agreement with reality, some divergences were found between the values described by Rahman (2007) and the obtained values, and so it can be concluded that the reproduction of Rahman's model (2007) was not possible. Table V bellow summarizes the pros and against of each model.

After the analysis, the model proposed by Silva & Annamalai (2008) was defined as the most suitable to fit the aims proposed by the present study. Thanks to that, this model was the one chosen to be enhanced. So, some changes are proposed in order to create a more comprehensive model based on the model proposed by Silva & Annamalai (2008). Some concepts firmed by Rahman (2007) are still in use for that objective.

Table V. **Comparative between models.**

	Aoki's model (1989, 1990)	Rahman's model (2007)	Silva & Annamalai's model (2008)
Evaluates internal reactions of the organism	no	no	yes
Evaluates the body's reactions to the environment	yes	yes	no
Applies better known equations to calculate metabolism	no	yes	no
Considers loss of heat and mass	yes	yes	no
Applicable to several individuals	no	yes	yes
Allows activity level assessment	no	yes	yes
Allows assessment of different climates	no	yes	no
Allows assessment of different diets	no	no	yes
Considers continuous metabolic elevation	no	yes	yes
Results compatible with the expected	yes	no	yes
Possible reproduction of results	yes	no	yes

First, it is suggested that the metabolic calculation should be done with equations from Harris & Benedict (1918), as proposed by Rahman (2007) and explained by Equations (6,7), and with the equations described by WHO/FAO/UNU (1985), explained by Equations (9-11). There are other equations in literature to calculate the whole-body metabolic rate, as Kleiber's law (Annamalai 2021) that uses an allometric relation and body mass to define the metabolism, but the ones from Harris & Benedict (1918) are more academically and professionally accepted, as long as they use more individual characteristics. Also, according to Hulbert et al. (2007), metabolism is not directly proportional to body mass.

Furthermore, such equations provide values closer to those defined by more precise and specific methods, such as indirect calorimetry (Schneider & Meyer 2005). Each of the equations is designed for a specific gender and/or age group.

$$M_{0-12\ months} = m \cdot (123 - 8.9 \cdot months + 0.59 \cdot months^2) \tag{9}$$

$$M_{boys,1-18\ years\ old} = 17.5m + 651 \tag{10}$$

$$M_{girls,1-18\ years\ old} = 12.2m + 746 \tag{11}$$

where m is the mass in kg, *months* is the age in months and M is defined in kcal/day.

As proposed by Silva & Annamalai (2008), weight and height were established according to CDC (2000) database from 0 to 20 years old, considering the average population of the United States belonging to the 50th percentile. After this, weight and height consistency are considered.

The factors of activity (FA) used are the same as in Rahman (2007), since the same method of metabolic calculation is used. Five levels of physical activity are considered for comparisons:

(i) sedentary (FA = 1.2), without weekly exercise;

(ii) little active (FA = 1.375), performing 150 minutes of activity per week, as recommended by WHO (2020);

(iii) active (FA = 1.55), performing 300 minutes of activity per week, as suggested by WHO (2020) for additional gains;

(iv) very active (FA = 1.725), with 500 minutes of activity per week;

(v) extremely active (FA = 1.9), with 900 minutes of activity per week simulating a situation of athletes.

These FAs are only considered for individuals over 10 years old. According to WHO/FAO/UNU (1985), up to 10 years old, a single correction factor of 5% should be considered for the calculation of the total energy requirement. As stated, this percentage is sufficient to describe the level of physical activity and other metabolic demands. So, the FA is 1.05 until 10 years old.

These factors are used to define the real metabolic rate, calculated by the product between the FA and the metabolism rate, given by Equations (6,7) and Equations (9-11). The definition of the real metabolic rate is quite import for the model. This value is used to: 1) find the quantity of macronutrients that must be consumed by the person, and then the entropic generation caused by the internal process of digestion; 2) define the body temperature, which defines the heat change values with the environment. This factor is extremely important to be considered since basal metabolic rate is not a good measure of total energy expenditure (Hulbert et al. 2007). According to Alexander (2002), humans seem to have a strong tendency to walk in ways that minimize metabolic energy costs, even if the energy cost of locomotion is a major item in human energy budgets.

In addition, it is suggested to follow a new recommendation for daily macronutrient intake. These values are used in Equation (8), defined by Silva & Annamalai (2008). According to Menon & dos Santos (2012), the recommendation for fat intake is 1 g/kg of weight/day and for protein, 1.6-1.7 g/kg of weight/day. Depending on the pathological limitations or the exercise load performed by the individual, these recommendations may be higher, reaching up to 3.4 g of protein/kg of weight/day. The amount of carbohydrate becomes variable depending on the individual's basal demand and so being defined by the calculation of dietary supplement.

Since the model by Silva & Annamalai (2008) follows an entropic generation methodology only within the organism, the interaction of the body with the environment is suggested to be accounted. This interaction causes great heat losses that the body suffers. Hulbert et al. (2007) proved that there must be more factors than only basal metabolic rate to the determination of maximum life span.

According to studies by Wang et al. (2016) it is noted that heat loss through evaporation is the modality that is most influenced by the temperature of the surroundings. Likewise, according to Wang & Hu (2018), evaporation is the main factor responsible for the release of heat when the body is subjected to an increase in the level of physical activity. Thus, it is proposed that the energy of evaporation and the entropy associated with this exchange should be considered, respectively Equations (12) and (13). The energy of evaporation is described by the equation of Kandjov (1999), as Rahman (2007) suggested. This inclusion allows to evaluate the impact that the environment can have on the individual's entropic generation and on their life expectancy.

$$E_{evp} = h_e \cdot A \cdot (e_w - e_a) \tag{12}$$

$$s_{evp} = E_{evp}/T_r \tag{13}$$

where h_e is the evaporative heat transfer coefficient [W m^{-2} hPa^{-1}], e_w is the water vapor pressure at the skin surface temperature [hPa], e_a is the water vapor pressure in ambient air [hPa], A is the total skin area [m^2] and T_r is the rectal temperature [K].

The evaporative heat transfer coefficient depends on the ambient air boundary, and so on the air speed. It was considered a medium occurrence of a forced air movement over the human body and a 2 m/s air speed. Then, the coefficient is calculated by Equation (14), defined by Kandjov (1999).

$$h_e = 11.35 \cdot {v_{air}}^{0.618} \cdot (p_0/p)0.382 \tag{14}$$

where p is the atmospheric pressure [hPa] and p_0 is the atmospheric pressure at sea level [hPa].

The total skin area is calculated by Equation (15), which was proposed by Du Bois & Du Bois (1916) and Rahman (2007) and where m is the body mass [kg] and y is the individual's height [m].

$$A = 0.202 \cdot m^{0.425} \cdot y^{0.725} \tag{15}$$

The rectal temperature is calculated with the model proposed by Givoni & Goldman (1972), described in Equation (1) and Equations (2-4) associated. The skin temperature is calculated with the Equation (16), proposed by Burton & Bazett (1936), and it is used to define the water vapor pressure on the skin. In this development, the body temperature T_b is fixed in 37°C.

$$T_b = 0.65T_r + 0.35T_s \tag{16}$$

The water vapor pressure is calculated with the empirical formula of Tetens (AMS 2012), which is based on Dalton's Laws of partial pressure of mixtures and presented on Equation (17).

$$\phi P = e = \alpha \cdot \exp^{\frac{17.3T}{(237.3+T)}} \tag{17}$$

where α is equal to 610.8 for results in Pascal (Pa) or 4.58 for results in mmHg and T is the temperature in °C of the surface.

Therefore, it is suggested that the value found for the E_{evp} thermal exchange be multiplied by correction factors: 1) Thermal exchange coefficient of clothing *Clo*, described by Givoni & Goldman (1972) on Table I, since it is not the entire surface of the skin that is exposed to evaporative loss; 2) fraction of wet surface w, equivalent to 0.06, when there is no sweat, and equivalent to 1, when the skin is completely wet (Mady 2014).

The wet surface fraction factor should be determined with the duration of physical activity being taken into account. It is assumed that during activity, the skin is completely covered with sweat, increasing the rate of thermal loss while at rest the skin is dry. Thus, knowing the activity time during the week, the average time in a day is calculated. Considering the proportion of the number of minutes of activity and the total number of minutes in a day, the wet surface fraction factor is defined.

Thus, the total entropic generation over time ($\sigma(t)$) is given by the sum of the entropy associated with the metabolism of macronutrients, given by Equation (8), and the entropy associated with the thermal exchange by evaporation to the surrounding (s_{evp}), given by Equation (13). The process steps are summarized in Fig. (2). The entropic generation rate ($\dot{\sigma}_m(t)$) is calculated by the ratio between entropic generation and the individual's mass at the corresponding age.

For all following situations, an ambient temperature of 27° C and an air speed of 2 m/s shall be considered. The consideration of forced convection is done, just like Rahman (2007) did. It gives a 17.42 W m^{-2} hPa^{-1} evaporative heat coefficient.

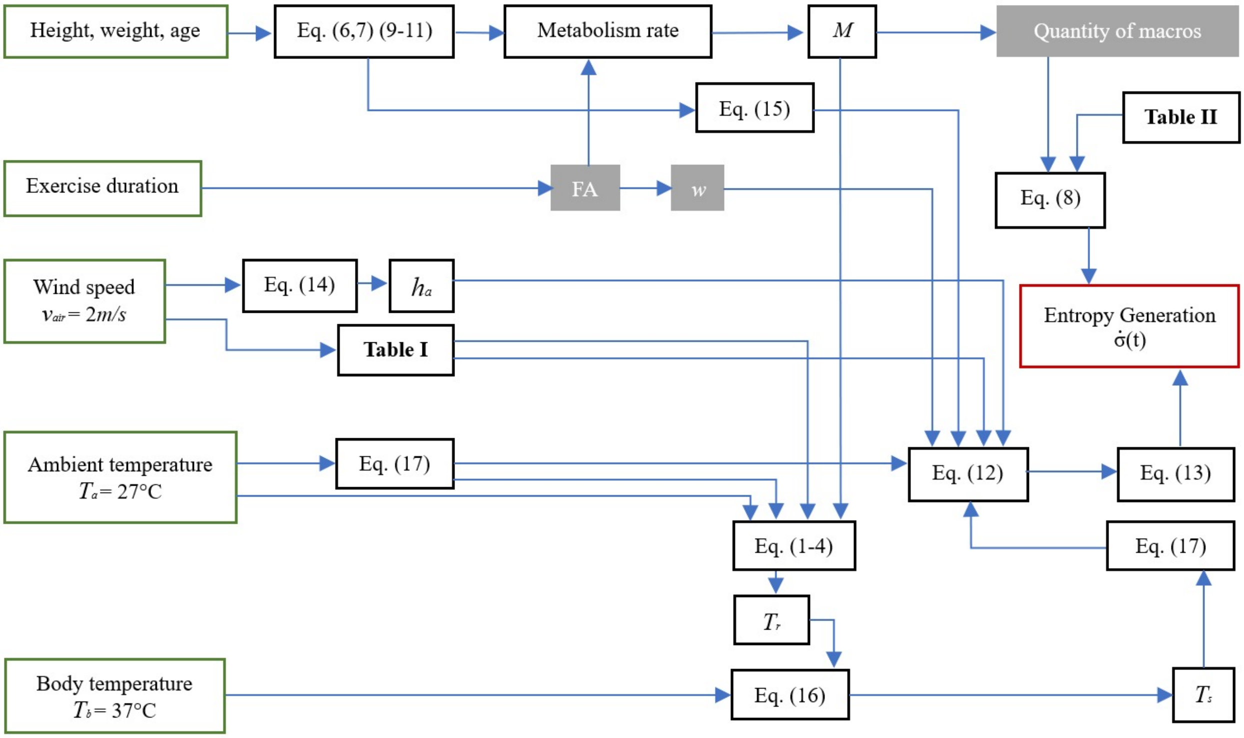

Figure 2. New model process flow.

The inputs of the model are represented in green, while the output is in red. The main equations used are placed on the flow. Also, some of the calculated quantities are presented, as results from some of the equations. The grey boxes represent that the relation between input and output of the box is not mathematical and depends of procedures previously described.

As such, the proposed model presents an agreement in the results with the expected values, which were defined by Silva & Annamalai (2008). Fig. (3) below shows the graphical comparison of the results from Silva & Annamalai's (2008) base case and the base case used in the present study, where it is possible to see the similarity of the curves. That difference occurs due especially to the metabolism calculation correction and with the addition of entropy generated because of environmental interaction.

In a numerical comparison, it may be considered a young male adult of 20 years old, 71kg and 1.77m. The reproduction of Silva & Annamalai's model (2008) gave an entropy generation of 0.3658 kJ/kg.K per day. The new model proposed resulted in a 0.4017 kJ/kg.K per day entropy generation, considering the pattern ingestion of 1g of fat and 1.6g of protein for kg body mass. The values are close, but there is a difference caused by the difference in the methodology.

Therefore, the base case considered in the present paper is an individual with medium height and weight (as described by CDC (2000)), a FA=1.2 (meaning sedentary level of activity), who takes the adequate amount of each macronutrient (1g of fat and 1.6g of protein for kg body mass).

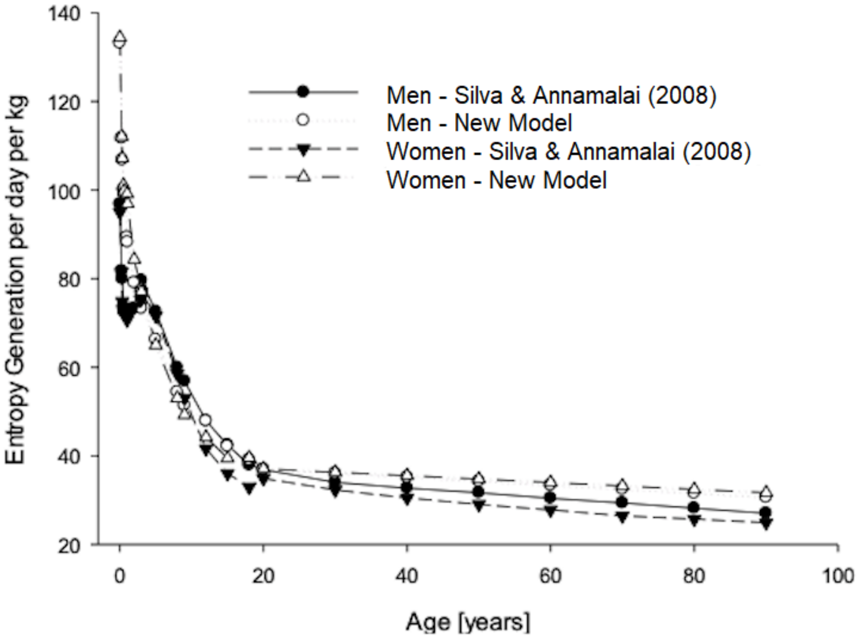

Figure 3. Entropic Generation for men and women.

The generated entropy limit values that were defined by Hershey (2010) (11,508 kJ/kg.K for men and 11,299 kJ/kg.K for women.) are adequate for the proposed models and/or for the considerations made by the author. In this way, Silva & Annamalai (2008) also defined new values, according to their model. Keeping it in mind, new values of maximum entropic generation must be defined, which would contemplate the new model and the new considerations that have been made.

To this end, a similar methodology to Silva & Annamalai (2008) is adopted. Considering a linear variation between the calculated points and applying the trapezoidal method for integration at the curves of Fig. (3) within life expectancy, it was possible to obtain the entropic generation limit.

Using data from the World Bank (Public Data 2020) of average life expectancy in the world, the limit of entropic generation was defined using the base case of the proposed model. As they are 70.21 years for men and 74.7 years for women, the respective entropic limits of 11,327 kJ/kg.K and 11,972 kJ/kg.K are obtained. These values were compiled on Table VI, with values defined by Hershey (2010) and Silva & Annamalai (2008) previously presented.

Table VI. Cumulative Entropy Generation Limit, in kJ/kg.K.

	Men	*Women*
Hershey (2010)	10,025	10,678
Silva & Annamalai (2008)	11,508	11,299
New model	11,327	11,972

As demonstrated, the values defined in the present study are higher than the ones lately defined on the two models. There are some main reasons for that: the difference on the way of calculating the metabolic rate and different obtained values; the interactions with the environment considered on each model, which is not evaluated by Silva & Annamalai (2008) and neither is described by Hershey (1974) [*apud Silva & Annamalai (2008)*], and raises the entropy generation rate; and the life expectancy for the base case, that was around 5 years smaller on the new model.

Thus, it is suggested that a quantitative assessment should be made with the new model proposed. So, one ought to evaluate the impact of physical activity and feeding habits on human life according to the new modeling. The three proposed and compared subjects are described in Table VII.

Table VII. Description of the evaluated subjects in the current work.

Age	0-15	15-40	40-70	70+
Subject (1)	FA=1.2			
	2g F and 1.6g P			
Subject (2)	FA=1.2	FA=1.55		FA=1.2
	1g F and 1.6g P			
Subject (3)	FA=1.2	FA=1.9	FA=1.55	FA=1.2
	1g F and 1.6g P	1g F and 2.4g P	1g F and 1.6g P	

Subject (1) would represent a lifelong sedentary person, subject (2) would be a person who exercises during the young/adult/elderly phase and always eats properly, aiming to improve the quality of life, and subject (3) would approach the reality of an athlete, who performs a greater activity load and eats a higher amount of protein during the active age (15-40 years) and later starts to eat and practice exercises to maintain quality of life. For this comparison, all the subjects are male.

The data obtained for the three compared subjects are presented in Fig. (4), in which the entropic generation is presented in kJ/K per male individual per kg of weight per year throughout life. It is noted that a step increase occurs when the level of activity performed by the person is added.

If the values defined for the base individual are considered as fixed generation limits, as stated by Rahman (2007), Silva & Annamalai (2008) and Hershey (2010), the life expectancy of the subjects (2) and (3), described in Table VII, would be 56.29 and 47.04 years, respectively. Even if the resulting reduction were expected, as presented by the authors previously cited, the variation was not expected to be so relevant. At the same time, it is noted that subject (1)'s life expectancy would be 70.36 years, a value slightly higher than the base expectation. Thus, it is emphasized that these results, considering the model and the limit of entropy generated during life, contradict several studies and statements that determine that the practice of physical activity and adequate food ingestion increase human longevity.

A comparison with Hulbert et al. (2007) is then possible, since the authors affirm that the membrane fatty acid composition influences the metabolic rate and degree of oxidative stress and that dietary calorie restriction is an effective method of life span extension (almost linear related). In other words, an active person in a better composed shape may have an extension of life.

In this way, the present study defends a modification of the concept of entropic generation limit throughout life. It is suggested that the defined value is specific to an evaluated group, considered a

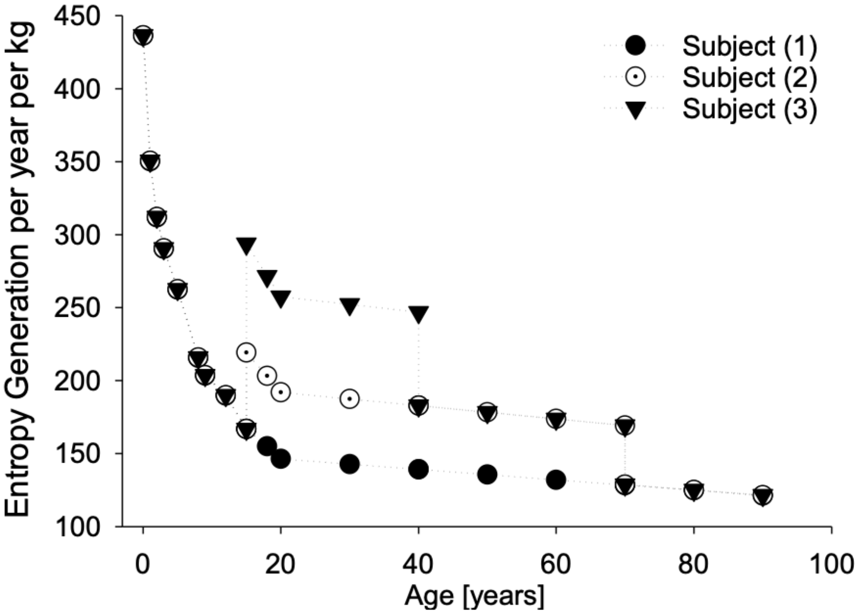

Figure 4. **Entropy generation rate for different lifestyles.**

base case, which can be changed and increased according to the conditions to which the subject is exposed, such as the ambient temperature of the place where the person lives and the activity level practiced. So, the value of entropy generation during life should be relaxed according to PAL.

At this point, it is important to emphasize that the oxidative stress theory of aging was able to explain how exercise does not bring a reduction of life span. It is known that free radicals' levels are higher in metabolically activated tissues and exercises increase metabolism. As presented by Hulbert et al. (2007), the human body has some uncoupling proteins, which are activated during voluntary exercise and have the role of controlling the reactive oxygen species production in muscle mitochondria.

Since the focus of the study is the assessment of the entropic generation affected by the practice of physical exercises, new limits are evaluated according to the life expectancy that can be reached with the habit of exercising. Following the values calculated by Dhana et al. (2016) for the increase in life expectancy by the activity, presented in Table IV previously, new values of entropy limit generation have been defined, presented in Table VIII below, following the statement of a flexing value according to PAL. For this, it was considered that the "moderate" level is equivalent to subject (2) assessed and the "intense" level is equivalent to subject (3).

This consideration of more flexible values of entropic limits meets the concepts that physical activity and heathy habits improve live expectancy. As affirmed by Mori (2020), experiments using animal models have demonstrated that life and health span can be extended through changes in lifestyle and potentially by drug or nutritional interventions.

On the other hand, studies have shown that environmental factors, as ambient mean temperature, also have great impact on life expectancy. According to Speakman (2005) and Sohal (1986), people who live in warmer places tend to live less, or so: lower ambient temperatures favor longevity. Although

Table VIII. Cumulative Entropy Generation Limit, effect of physical activity, in kJ/kg.K.

Type of exercise	Intensity	SEG-life [kJ/kg.K]
Walking	*Moderate*	13,883
	High	15,526
Cycling	*Moderate*	13,985
	High	15,833
Domestic Work	*Moderate*	13,883
	High	15,501
Sports	*Moderate*	14,113
	High	15,514
Gardening	*Moderate*	14,062
	High	15,705

the evaluation was not carried out in the present work, it would be possible to develop it in future papers.

As presented by Hulbert et al. (2007), the body understands the voluntary exercise and makes better process to improve the usage of energy, reducing the free radicals' productions, and that's why it is possible to say that the body creates a tolerance to reactive oxygen species keeping the maximum life span potential. As entropic generation is fixed and inevitable for every process or reaction that happens, the suggestion is that the theorical maximum value should be changed.

CONCLUSION

Entropy analysis was applied to the human body aiming at defining a new thermodynamical model to relate cumulative entropy generation, physical activity, environment relation and longevity. Some papers found in the literature were studied and used as base to be improved in this new modeling. It was possible the use the base from previous papers since all the concepts and associations made are correct and coherent with thermodynamics laws.

It follows that the proposed adaptations make possible the search to develop a more representative model as it is kept the simplicity of the model. The aims of the present study have been achieved. In the present study, a model was proposed to evaluate the behavior of entropic generation by the human body in order to correlate this to the level of physical activity and the environment in which it acts. The intention was to integrate the micro scale of thermodynamic processes in the organism, from the analysis of the metabolism of nutrients, with the macro process, in which exchanges between the individual and the environment take place. These two ways of defining the accumulative entropic generation of the human body make the proposed model innovative. The usage of two fronts of variables provides a better comparison from the process and bio analysis, making the individual integrated to the environment.

Considering the data of medium life expectancy in the world and an individual for base case, it was found an entropic limit of 11,327 kJ/kg.K for man and 11,972 kJ/kg.K for women. Some situations were then created to build a comparison between lifestyles. Since comparative assessments allow the conclusion that sedentary life should be chosen for the longest life, a relaxation in the entropy limit generated by the body until its expirations is suggested. In a carried-out analysis, it was noted that the cumulative entropy generation can be increased by approximately 40% with the regular practice of activity, according to the raise of expectancy done by this habit.

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Inara Magno Nogueira proposed the study of the functioning human body based on thermodynamics laws and the impact of external aspects on longevity; she was also responsible for literature review, data collection and organization, methodology proposal, development of models, discussion of results and writing of manuscript. Esly Ferreira da Costa Junior suggested numerical procedures for the modeling. Andréa Oliveira Souza da Costa worked on discussion of results and reviewing of manuscript; she was responsible for the supervision of the project.

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