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ASSESSMENT OF HEALTH PARAMETERS FOR AN INDIVIDUAL PRESENTING METABOLIC SYNDROME: AN EXERGETIC ANALYSIS

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Abstract. *Thermodynamics can be applied to estimate the efficiency of metabolic processes in the human body and its relationship with life expectancy. Metabolic syndrome, a metabolic disorder that includes insulin resistance and is associated with various comorbidities, primarily obesity, has a direct impact on life expectancy due to its metabolic alterations. Therefore, the present article aims to study the effects of these modifications in individuals with metabolic syndrome and their relationship with life expectancy. For this purpose, a mathematical model was sought in the literature to evaluate processes in the human body using exergy parameters. The model divided the body into two control volumes, representing the various systems of the body and cellular metabolism. The destroyed exergy was evaluated to determine the exergetic age, and a simplified thermal model with four different types of tissues was analyzed. Simulations were performed with three distinct groups of individuals (control, moderately obese, and obese) to evaluate the impact of metabolic syndrome on life expectancy. The results show a significant increase in the rate of destroyed exergy as the individual's mass increases, with a higher rate in the obese group. However, when considering the rate of destroyed exergy per unit mass, the obese group has a lower rate than the moderately obese and control groups, suggesting that the increase in the individual's mass outweighs the exergy expenditure, which is consistent with previous studies. When applying the model to cases of weight loss or weight gain, it was observed that these individuals tend towards a similar value, with only a 1.8% difference when considering the accumulated exergy per unit mass, indicating that the earlier these changes occur, the greater the impact on the individual's life expectancy. It is concluded that, by analyzing the curves of accumulated exergy, obese individuals would take longer to reach the limit value of accumulated destroyed exergy, suggesting a longer life expectancy. However, the discrepancy with reality may be related to metabolic alterations resulting from metabolic syndrome and its effects on physiological functions of the human body. Furthermore, remaining in the condition of obesity can reduce life expectancy by up to 15 years. This highlights the importance of prevention and treatment of obesity and other factors of metabolic syndrome.*

Keywords: exergetic analysis, entropy, metabolism, metabolic syndrome, rate of living theory.

1. INTRODUCTION

Thermodynamics is the branch of physics responsible for studying the behavior present in energy exchanges. To arrive at a real understanding of these systems, the concept of exergy was created, which combines the first and second laws of thermodynamics, where the quantitative nature is given by the energy balance and the qualitative aspect is represented by the concept of entropy (Henriques, 2018; Mady and Oliveira, 2013). One of the most promising fields of study in this area is focused on living organisms, where it is possible to obtain health parameters by estimating the efficiency of processes that occur within the body (Szargut, 2005). The human body is a complex thermodynamic system that continuously exchanges heat with the environment and requires energy to function properly, which is derived from the oxidation of nutrients present in food (Souza, 2009).

One of the first works that related exergetic analysis to living organisms was conducted by Prigogine and Wiame (1946), where they established that over the course of life, organisms tend towards a state of minimal entropy generation, which later became known as the principle of minimum entropy generation. Along with the idea proposed by Rubner (1908) that the total energy per unit mass consumed by mammals remained constant throughout life, several authors have analyzed the relationship between entropy generation and life expectancy (Henriques et al., 2020; Rubner, 1908). It is

worth noting that metabolism is primarily responsible for the irreversible processes in the body, so the higher the metabolism, the shorter the individual's life expectancy (Henriques, 2018; Hershey, 2009; Mady et al., 2013).

In this regard, Hershey (2009) argues that life parameters based on the concept of entropy are more efficient in measuring an individual's longevity, as its value is cumulative and reaches its peak just before death. Henriques (2018) evaluated several authors to analyze how different pathologies influence the thermodynamic performance of the human body, where it was observed that diseases such as obesity and smoking cause metabolic alterations, increasing accumulated entropy and, consequently, decreasing lifespan. Another study in this line determined, through an exergetic analysis, the life expectancy for a Brazilian under baseline conditions using exergy terms (exergy, destroyed exergy, and exergetic efficiency) as parameters to indicate the life expectancy of this individual, as there is a maximum value for this magnitude (Mady et al., 2013).

Based on what is demonstrated in these works, it is possible to conclude that metabolic diseases directly affect an individual's life expectancy, and metabolic syndrome is an example of such dysfunction. Metabolic syndrome is characterized by insulin resistance, a hormone responsible for glucose transport, which is one of the main sources of energy for the body (Medicine, 2008; Sinaiko, 2007). This is due to complex metabolic disorders and is strongly associated with other diseases such as type 2 diabetes and cardiovascular diseases (Lira Neto et al., 2018). In addition, metabolic syndrome also includes other conditions such as hypertension, abdominal fat, dyslipidemia, glucose metabolism imbalance, and especially obesity (Oliveira et al., 2020). With that said, the present article aims to study the outcome of these modifications in individuals with metabolic syndrome and their relationship with life expectancy.

2. METHODOLOGY

To assess the impact on the life expectancy of a patient with metabolic syndrome, a literature review will be conducted to find a mathematical model to evaluate the processes that occur in the individual's body. After that, a simulation will be performed to obtain parameters based on exergy and compare them with values found in the literature.

3. MODEL DESCRIPTION

Through the literature review, the human body model by Mady and Oliveira (2013) was selected. The model was chosen for its analysis of cellular metabolism and interactions between the environment and the body. For this purpose, the human body was divided into two control volumes, CV1 and CV2. The first corresponds to the thermal, circulatory, and respiratory systems, while the second represents cellular metabolism. The schematic representation of the body is shown in Figure 1. It illustrates the rates of heat transfer through convection (Q_c) and radiation (Q_r), mass flow through vaporization (H_e), and respiration ($H_{ex} - H_a$) to the environment. It also represents the interactions between CV1 and CV2, where Q_M is the heat transfer from cellular metabolism to the body. Henriques et al. (2020) further argue that for daily periods, the mass inflow and outflow are equal, and the daily variations in body mass due to substance flow and storage can be neglected.
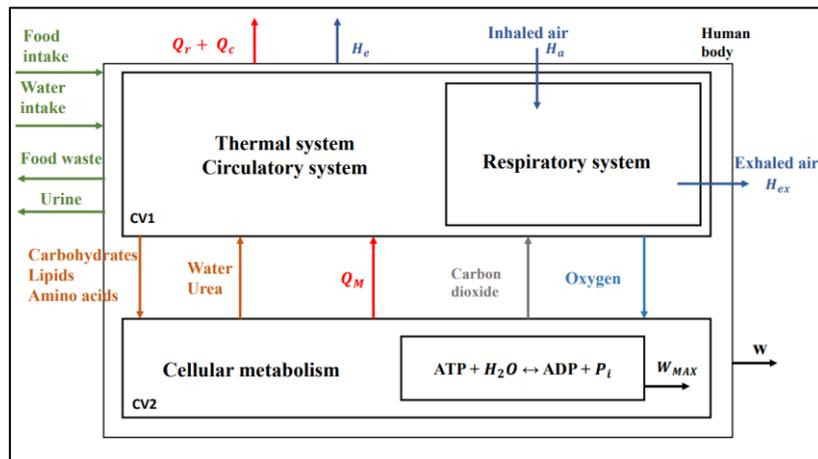

Figure 1. Human body model - Adapted from Mady and Oliveira (2013).

Continuing, using now the analysis by Mady (2013), where the exergy balance is applied to the whole body, thus obtaining a relation for the total destroyed exergy rate of the body ($\dot{B}_{d,corpo}$) by summing up the exergy lost rate for each of the control volumes, as shown in Equation 1.

$$\dot{B}_{d,corpo} = \dot{B}_{d,CV1} + \dot{B}_{d,CV2} \tag{01}$$

$\dot{B}_{QM,corpo}$ represents the rate of exergy released due to the metabolic reactions occurring in the second control volume, while the terms $\dot{B}_c$, $\dot{B}_r$, $\Delta\dot{B}_{res}$, $\dot{B}_{ev}$ symbolize, respectively, the rate of exergy transferred by conduction, the rate of exergy transferred by radiation, the exergy flow due to respiration, and the exergy flow due to evaporation. The expression $\frac{dB_{corpo}}{dt}\Big|_{\Delta T}$ describes how the rate of exergy of the body varies due to variations in the ambient temperature, where this term depends on the ambient temperature (T_0) and the rate of change of entropy $(\frac{dS_{corpo}}{dt}\Big|_{\Delta T})$ and internal energy $(\frac{dU_{corpo}}{dt}\Big|_{\Delta T})$ of the body due to variations in the ambient temperature, as shown in Equation 3.

$$\dot{B}_{d,CV1} = \dot{B}_{QM,corpo} - \frac{dB_{corpo}}{dt}\Big|_{\Delta T} - \left(\dot{B}_c + \dot{B}_r + \Delta\dot{B}_{res} + \dot{B}_{ev}\right) \tag{02}$$

$\dot{B}_{QM,corpo}$ represents the exergy rate released due to the metabolic reactions occurring in the second control volume, while the terms $\dot{B}_c$, $\dot{B}_r$, $\Delta\dot{B}_{res}$, $\dot{B}_{ev}$ symbolize, respectively, the exergy rate transferred by conduction, the exergy rate transferred by radiation, the exergy flow due to respiration, and the exergy flow due to evaporation. The expression $\frac{dB_{corpo}}{dt}\Big|_{\Delta T}$ describes how the exergy rate of the body varies due to changes in the ambient temperature, where this term depends on the ambient temperature (T_0) and the rate of change of entropy $(\frac{dS_{corpo}}{dt}\Big|_{\Delta T})$ and internal $(\frac{dU_{corpo}}{dt}\Big|_{\Delta T})$ of the body due to variations in the ambient temperature, as shown in Equation 3.

$$\frac{dB_{corpo}}{dt}\Big|_{\Delta T} = \frac{dU_{corpo}}{dt}\Big|_{\Delta T} - T_0\frac{dS_{corpo}}{dt}\Big|_{\Delta T} \tag{03}$$

As applied by Henriques (2018), it is assumed that changes in the exergy rate due to variations in ambient temperature only occur in the first control volume. It is worth noting that to solve each term in the equations, it is necessary to refer to the expressions presented in Henriques' work (2018), specifically equations 16 to 20 and 27 to 47, while essential parameters for their solution are taken from Mady (2013).

Returning to the analysis of the destroyed exergy rate for the entire body, now applying the exergy balance to the second control volume representing cellular metabolism, it is found that this portion of the destroyed exergy rate $(\dot{B}_{d,CV2})$ depends on the exergy metabolism (B_M), the exergy rate released to the first control volume $(\dot{B}_{QM,corpo})$, and a component of work performed by the body $(\dot{W})$. The term B_M corresponds to the complete oxidation of nutrients ingested through food and the formation of ATP (adenosine triphosphate) molecules, which are responsible for storing and transporting energy throughout the body. Equation 4 determines the destroyed exergy rate for the second control volume. It is worth noting that changes in the exergy rate due to variations in ambient temperature in the second control volume are zero, as mentioned earlier, as such changes are not considered in this volume.

$$\dot{B}_{d,CV2} = \dot{B}_M - \dot{B}_{QM,corpo} - \dot{W} \tag{04}$$

Finally, to establish the exergy balance for the entire body, it is sufficient to substitute Equations 2 and 4 into Equation 1 and rearrange the expressions, as shown in Equation 5. It is also possible to quantify the energy efficiency of the body, assuming that the ambient temperature remains constant, as demonstrated in Equation 6.

$$B_{d,corps} = B_M - (B_c + B_r + B_e + \Delta B_a) - W - \frac{dB_{corps}}{dt}\Big|_{\Delta T} \tag{05}$$

$$\eta_{corp} = 1 - \frac{B_{d,corps}}{B_M} \tag{06}$$

Through a similar analysis, Mady and Oliveira (2013) compared the values of metabolism in terms of energy and exergy and demonstrated that the difference between the two was not greater than 5%, allowing for their approximation. Therefore, by integrating the destroyed exergy rate in the body over the course of life, its cumulative value was determined, thus obtaining its exergetic age, which would be a better indicator for evaluating life expectancy than chronological time.

4. HUMAN THERMAL MODEL

For the human thermal model, as proposed by Mady et al. (2013), a simplification of the human body was used, where it is represented by a cylinder with circular cross-sections composed of four different types of tissues: skin, fat, muscle, and core, as shown in Fig. 2, each with its corresponding metabolism. In this model, in order to solve the

equations, the temperature in the tissues was considered to be uniform and initially equal to the condition of thermal neutrality. It was also taken into account that heat conduction occurred radially, as well as metabolism in relation to nutrient intake and heat transfer between blood and tissues.
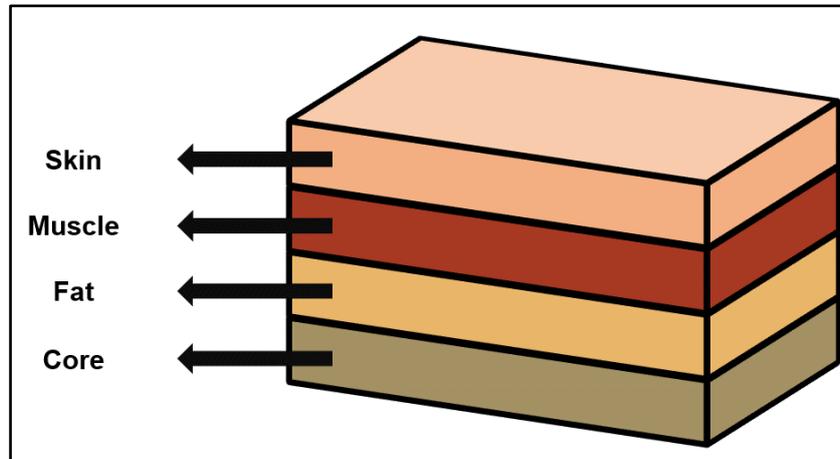

Figure 2. Phenomenological representation of the human body with four layers representing tissues - Adapted from Garcia et al. (2018).

The model was evaluated by Garcia et al. (2018), where the authors estimated the relationship between body composition, destroyed exergy, and exergy transfer to the environment, also determining thermodynamic properties for each type of tissue. In this study, the impact of body metabolism on the generation of destroyed exergy and exergy transfer to the environment was analyzed, and the results were obtained by comparing the addition of muscle mass and fat mass in the exergy index.

5. SIMULATION

The simulation of the problem was performed using the Python programming language, where the equations describing the processes occurring in the body were implemented based on the methodology developed by Henriques (2018). The sample was divided into three groups: control, moderately obese, and obese, taking into account the mass of each individual, the body fat percentage (BF), and the metabolism per unit surface area for each group, as shown in Table 1. Based on this information, the dimensions of each layer of the simplified thermal model were determined to resemble the properties of each group.

Table 1. Anthropometric data for various Brazilian classifications 2010 - Henriques (2018).

Age (years)	Control				Moderately Obese			Obese		
	Height [m]	Mass [kg]	BF [%]	M [W]	Mass [kg]	BF [%]	M [W]	Mass [kg]	BF [%]	M [W]
0	0.67	8	20,3	29,1	8	20.3	29,1	8	20,3	29,1
2	0,92	14	20,3	44.4	14	20,3	44,4	14	20.3	44,4
4	1,06	18	20,3	50.1	18	20,3	50.1	18	20.3	50,1
6	1,18	22	20,3	55.3	22	20,3	55,3	22	20.3	55,3
8	1,3	28	20,3	60,9	33	21.5	65.3	47	22.3	76.3
10	1,39	33	20,3	66,6	39	22,8	71.4	57	24,4	83,4
12	1,51	42	20,3	76,5	50	24,2	82	71	26.8	95,8
14	1.64	52	20,3	87.4	62	25.6	93.8	89	29.4	109,5
16	1,7	60	20,3	94,7	71	27,2	101,6	102	32,2	118,7
17	1,72	62	20,3	96.4	74	28,8	104,3	107	35,4	121,9

18	1,73	62	20,3	96.9	78	29.8	106,4	112	36.1	124,4
20	1,73	63	20,3	96.9	78	29,8	106,4	113	36.1	124,4
25	1,73	63	20,3	96.1	78	29,8	105,6	113	36.1	123,4
30	1,72	62	20,3	93,3	77	29,8	102,4	111	36.1	119,8
40	1,71	61	20,3	89,6	76	29,8	98.4	110	36.1	115.1
50	1.70	60	20.3	85.3	75	29.8	93.6	109	36.1	109.5
60	1.68	59	20.3	79.7	74	29.8	87.5	107	36.1	102,3
70	1.67	58	20.3	74.3	73	29.8	81.6	105	36.1	95,4
80	1.66	57	20.3	69.6	72	29,8	76.4	104	36.1	89.3

Next, the data of the thermophysical properties for each of the four types of tissues used to represent the human body were also incorporated, as presented in Table 2. In this table, the terms ρ, k, c, M''' and wb_t correspond, in order, to mass density, thermal conductivity, specific heat, metabolism per unit volume, and blood perfusion, which represents the blood flow that will be reoxygenated in the lungs.

Table 2. Thermo-physical properties of human body tissues - Mandy (2013).

Layer	$\rho \left[\dfrac{kg}{m^3}\right]$	$k \left[\dfrac{W}{m \cdot K}\right]$	$C \left[\dfrac{J}{kg \cdot K}\right]$	$M''' \left[\dfrac{W}{m^3}\right]$	$wb_t \left[\dfrac{m_{sg}^3}{m_t^3 \cdot s}\right]$
Skin	1085	0,43	3680	368,1	361,7
Fat	920	0,21	2300	368,4	76,7
Muscle	1085	0,51	3800	684,2	542
Core	1119	0,5	2679	2653	4155

Finally, the destroyed exergy rate over the lifespan of an individual was plotted for each of the groups, as well as the destroyed exergy rate per unit mass.

6. RESULTS AND DISCUSSION

Figure 3 presents the graph of the destroyed exergy rate as a function of lifespan for each of the three groups of individuals: control, moderately obese, and obese. It is evident that there is a significant increase in the destroyed exergy as the individual's mass also increases, reaching its maximum value for the obese group. Evaluating the destroyed exergy rate of individuals at the age of twenty, when metabolism reaches its peak, it can be observed that the moderately obese group destroys 8.08% more exergy than the control group, while the obese group shows a 15.17% increase in destroyed exergy compared to the moderately obese group. This increase in destroyed exergy is related to the higher exergy metabolism resulting from the individual's mass gain.
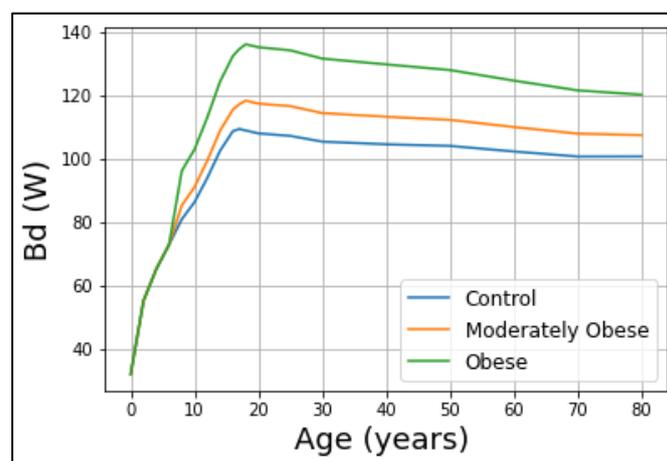

Figure 3. Rate of exergy destruction over the lifespan for each group of individuals - Authors (2023).

Now, constructing the plot of the destroyed exergy rate per unit mass, as presented in Figure 4, we have the opposite situation to what was shown in Figure 3, where the group of individuals with obesity shows a lower rate. When analyzing the exergy rate per unit mass of the obese group, it is observed that the obesity group has a rate that is 20.49% lower than the moderately obese group and 30.19% lower than the control group. These data suggest that as individuals gain weight, their expenditure on exergy is overshadowed by the increase in their mass. As evidenced by Garcia et al. (2018), obese individuals, who have a higher percentage of body fat, also have an increase in adipose tissue compared to muscle tissue, which has a higher metabolic rate, leading to this behavior. Thus, the percentage increase in an individual's metabolism is lower than their mass gain. Therefore, when analyzing the exergy metabolism per mass, it is lower for groups as their mass increases.
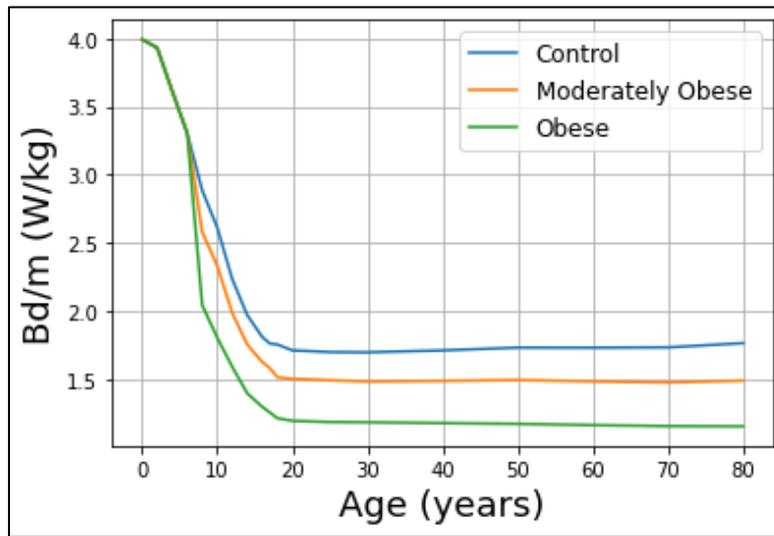

Figure 4. Rate of exergy destruction per unit mass over the lifespan for each group - Authors (2023).

These results are similar to those presented by Henriques (2018), indicating that the simulation conducted is consistent with the initial proposal, with a percentage error of less than 5%. That being said, applying the model to the following scenarios: an individual who is initially obese but, at the age of 40, aims to lose weight and reach the profile of the control group; and the opposite scenario, where an individual initially resembling the control group starts gaining weight until being diagnosed with obesity at the age of 40. After inputting this information into the program, the values of the total accumulated destroyed exergy and the destroyed exergy per unit mass for each individual are plotted, as shown in Figures 5 and 6.
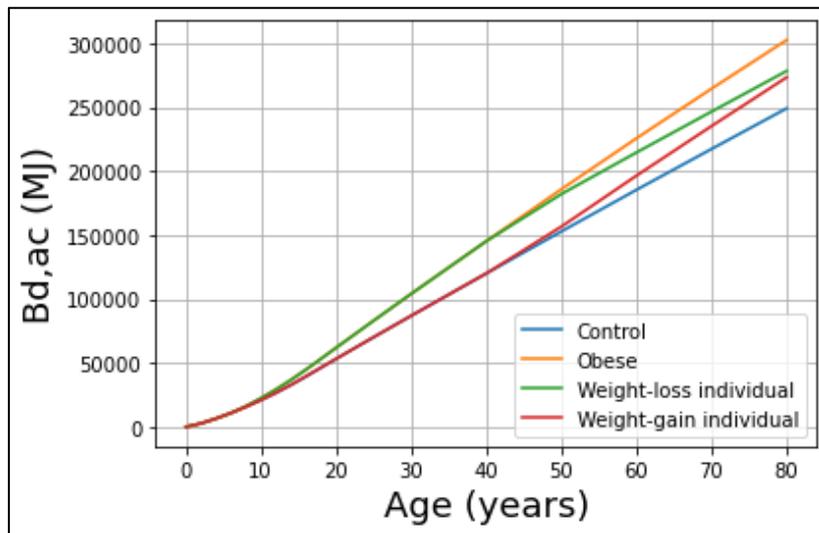

Figure 5: Accumulated exergy destruction over the lifespan for each group of individuals - Authors (2022).
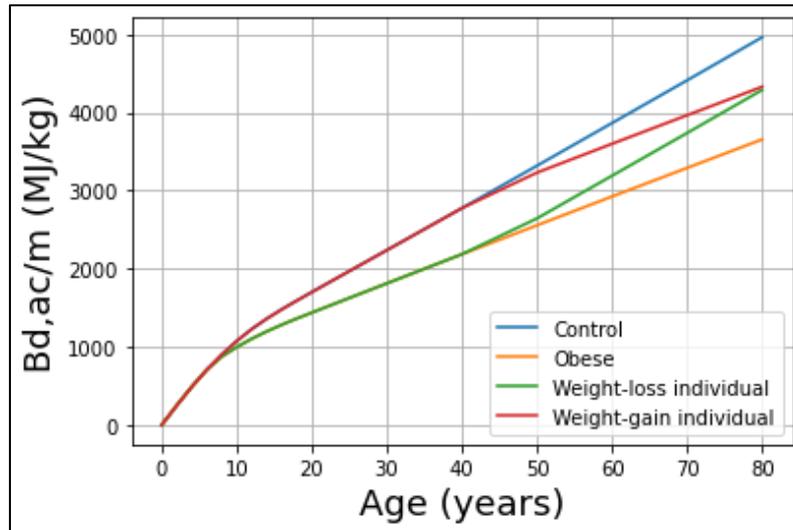
Figure 6: Accumulated exergy destruction per unit mass over the lifespan for each group of individuals - Authors

(2022).

Looking at the accumulated exergy curves for individuals who experienced changes in their morphological characteristics, it can be observed that both curves tend towards an intermediate value between the values for the control and obese groups. This is further emphasized when considering the accumulated exergy per unit mass. Taking into account the lifespan up to 80 years, individuals who gained weight accumulated 1.8% less accumulated exergy than those who were initially obese and subsequently lost weight. Considering the accumulated exergy per unit mass, this difference is only 0.94%. From these results, it can be concluded that the timing of morphological changes in each individual impacted their proportionate accumulation of destroyed exergy. This highlights the impact that remaining in an obese condition has on an individual, where the exergy analysis suggests a reduction or increase of up to 15 years in life expectancy.

Analyzing the curves of accumulated destroyed exergy in the two figures, it is possible to observe that, considering the value per unit of mass, obese individuals would take longer to reach the maximum limit of accumulated destroyed exergy, as proposed by the rate of living theory. This would suggest a higher life expectancy. However, real-life statistics indicate that the life expectancy of obese individuals is actually lower than that of non-obese individuals. Although, at first glance, the results obtained may appear contradictory to the actual behavior of the life expectancy of obese individuals, it is necessary to emphasize that in nature, larger animals live longer, as presented in Sperkman article (2005). Therefore, when considering the presence of metabolic syndrome in these patients, with obesity being a prominent symptom, the main factor contributing to the reduction in the life expectancy of individuals with this condition is the impact on the functioning of human physiological activities, such as blood circulation, and not obesity itself. It is important to note that the metabolic changes considered in the modeling are solely due to the increase in the mass of the individuals analyzed and do not take into account potential physiological alterations.

7. CONCLUSION

In order to analyze the effect of metabolic syndrome on life expectancy, three categories of individuals with different values of mass, percentage of body fat, and metabolism were divided into control, moderately obese, and obese groups. Exergoeconomic analysis was applied to each group, and it was observed that the rate of destroyed exergy increased with increasing mass. However, when considering the rate of destroyed exergy per unit mass, this relationship was reversed. Subsequently, a study was conducted to evaluate the effect of obesity on life expectancy in two scenarios: in the first scenario, individuals who had been obese since childhood were analyzed, and at the age of 40, they managed to lose weight and achieve healthy conditions; in the second scenario, the opposite case was evaluated, where initially healthy individuals gradually developed obesity until the same age.

When integrating the rate of destroyed exergy over the lifespan up to the age of 80, it was found that changes in individuals' morphological characteristics proportionately impacted their accumulation of destroyed exergy based on the timing of these changes. Furthermore, remaining in an obese condition can reduce life expectancy by up to 15 years, as obesity is a key component of metabolic syndrome. This highlights the importance of obesity prevention and treatment, as well as the management of other factors associated with metabolic syndrome, in promoting health and preventing cardiovascular diseases.

The accumulation of destroyed exergy in the group of individuals with obesity was also analyzed, and it was found that, when evaluated per unit mass, these individuals destroyed less exergy than the healthy group. This suggests that the progression of life is slower for those with obesity, which may result in a longer life expectancy for this group, despite mortality statistics indicating otherwise. This discrepancy suggests that the increased mortality in obese individuals is related to metabolic changes resulting from metabolic syndrome and its effects on the physiological functions of the human body.

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