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EXERGY ANALYSIS OF HUMAN BODY AND LIFESPAN: A FIRST APPROACH

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Abstract. *Exergy analysis is applied to assess the quality of the energy conversion processes that take place in the human body, aiming at developing indicators of health, performance and thermal comfort based on the concepts of exergy destroyed rate and exergy efficiency. Several authors in literature discuss about the lifespan entropy production or entropic age. This theory states that all humans have a maximum value of entropy generation during life, thus at a certain chronological age the entropy of the body is so high that it is no longer possible to sustain life. This kind of analysis may be used to compare two people at the same chronological age: the one with higher entropy production is the one with higher entropic age; a smoker has a higher entropy production than a non-smoker, therefore the first is heading towards a shorter life. To calculate this physical quantity it was proposed a thermal simplified model composed of 1 cylinder (easy to adapt for different anthropometric data) with circular cross section and four layers representing: skin, fat, muscle and core (composition of viscera, bones). From this model it was possible to calculate the energy and exergy flow rates to the environment associated with radiation, convection, vaporization and respiration. Finally, it was possible to calculate the total exergy destroyed for a Brazilian using mean anthropometric data. For basal conditions, the exergy destroyed in a lifespan was calculated as 3091MJ/kg (or entropy production of 10.2MJ/kgK), for a sedentary person this value is higher. The destroyed exergy per unit of surface area decreases as a function of aging as well as the exergy flow rate to environment and exergy efficiency. Moreover, the exergy efficiency of the life (for basal conditions) is 3.5%.*

Keywords: *Exergy Analysis;Destroyed Exergy;Lifespan*

1. INTRODUCTION

An overall study of human body behavior requires the use of the Second Law of Thermodynamics in order to assess the quality of the energy conversion processes that take place in its several organs and systems. Since the beginning of 1940 several authors tried to describe life as a function of the physical quantity named entropy. Schördinger (1944) compared it with the degree of order of the system, and established that the entropy of the body tends to a maximum while the biological system gets older. Later, Prigogine and Wiame (1946) proposed the principle of the minimum entropy production, therefore, all living things reaches a state of minimum production of this thermodynamic property. The relation between entropy and aging resulted in the designation of "arrow of time", since that physical quantity has the unique characteristic to establish a direction in a given process.

Over that past decades, several authors performed experimental and numerical studies attempting to confirm the "Prigogine's principle". Stoward (1962) studied the entropy production in bacterial culture. Zotin and Zotina (1967) examined different organism (from trout eggs to organism). Balmer (1982) studied the fish *Nothobranchius guentheri*, a species that lives in interment rivers of the East Africa and has the life cycle of 12 months. They all based the idea that most of entropy production is related to metabolism. Other authors, such as Aoki (1991), Rahman (2007), Silva and Annamalai (2008, 2009) analyzed the entropy generation over the lifespan and all their results confirmed the minimum entropy principle. Mady et al. (2012a) obtained that not only the entropy production decreases over time, but also the exergy efficiency decreases as a function of lifespan.

Rubner (1908) calculated lifetime energy expenditure of different mammals, and concluded that regardless the biological system which it is inserted, 1kg of cell generates the same amount of energy during lifespan (836kJ/kg tissue). According to Speakman (2005) while the mass of these biological systems varies by 50000, the energy expenditure varies approximately from 1.5 (if humans are not considered) to 5 (if humans are considered). From these analyses Hershey (2010) and Silva and Annamalai (2008, 2009) discussed that the entropy generated during lifespan may be a better indicator of physiological age or as the authors named "entropic age". The first author calculated the lifetime entropy generation as 10025 kJ/kgK and 10678kJ/kgK, for male and female, respectively. The last authors calculated this physical quantity as 11404kJ/kgK. This difference of magnitudes is caused by the metabolism adopted, Hershey (2010) used basal metabolism and Silva and Annamalai (2008, 2009) used the diet composition of American Society.

As Hershey (2010) analyzed, the biological system are out of equilibrium with the environment, therefore the body consumes energy from chemical bounds of macronutrients and the results are ordered phenomena such as growth, protein synthesis and locomotion (walking, running, any kind of performed work) . The order is achieved from the chemical reactions, which bring the biological system away from equilibrium with environment; nevertheless the irreversibilities of these same reactions are the responsible for the processes of aging, like the process of wear and tear (Speakman, 2005; Hershey, 2010). Therefore, there is a limited quantity of entropy that can be generated during lifetime from which the body is not able to sustain life. This point represents a maximum value of the body entropy (disorder achieve a maximum) and the entropy production achieves a minimum value. As examples of this kind of analysis the authors compared two people at the same chronological age: the one with higher entropy production is the one with higher entropic age; a smoker has a higher entropy production than a non-smoker, therefore the first is heading towards a shorter life.

All Second Law analyses of lifetime entropy production calculated it as a function of the metabolism (or thermodynamic properties of macronutrient) and body temperature. This analysis applies the exergy analysis on the model proposed by Mady et al. (2012) and Mady and Oliveira Junior (2013) which not only takes into account the metabolism on energy and exergy basis, but also the exergy transfer to environment and performed work.

2. MODEL DESCRIPTION

Figure 1 indicates a model with a schematic representation of the human body, previously published in Mady and Oliveira Junior (2013), where it is indicated the heat transfer rate and mass flow rates associated with radiation (Q_r), convection (Q_c), vaporization (H_e), respiration (H_{ex}–H_a), food intake, food wastes, water intake and urine. The term Q_M is the heat released to the body caused by the cellular metabolism. In this figure the human body is divided in two control volumes, CV1 and CV2. The first one represents the thermal system, circulatory system and respiratory system; and the second the cellular metabolism.

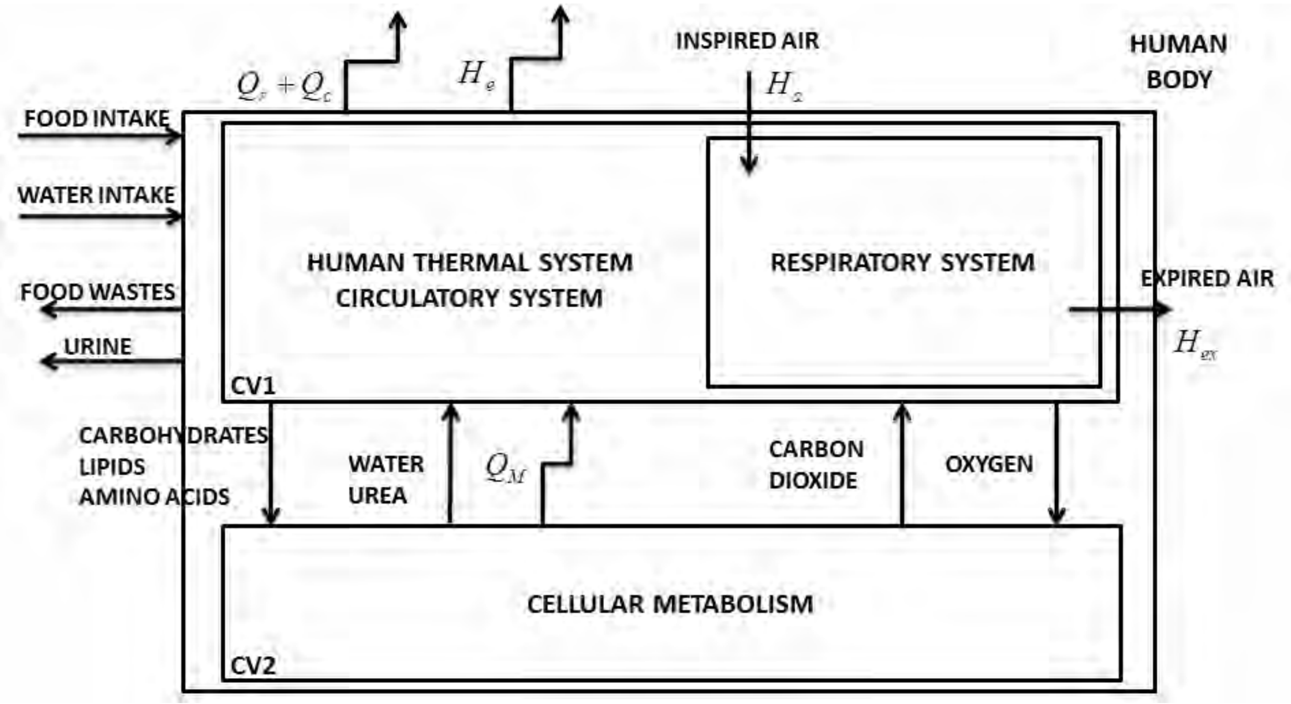

Figure 1. Schematic representation of the human body, with the intake of food, water and inspired air; and output of food, urine, expired air, vaporization trough skin and heat release due to radiation and convection (Mady and Oliveira Junior 2013)

According to Rahman (2007) in a period of one day the mass input (food, liquids and inspired gases) is equivalent to the mass output (food wastes, urine, expired gases and vaporization). In shorter periods of time this may not be verified. In this article, for the sake of simplicity, the variation of body mass due to food and water intake, wastes and accumulation are neglected.

The Energy and Exergy Analyses are applied to the control volume shown in Figure 1, with given environment and reference conditions such as temperature ($T_0 = T_a$), pressure ($P_0 = P_a$) and relative humidity ($\Phi_0 = \Phi_a$). Thus, Eq. (1) indicates a general equation of the exergy balance.

$$\frac{d\mathbf{B}}{dt} = \sum B_{in} - \sum B_{out} + \sum_k Q_k \left(1 - \frac{T_0}{T_k} \right) - W - B_{dest} \tag{1}$$

The energy (M) and exergy (B_M) metabolisms for the whole body are part of the total internal energy (dU/dt) and exergy ($d\mathbf{B}/dt$) variation of the body over time as in Eq. (2) and (3). Where, U is the internal energy of the body, $\mathbf{B}$ is the exergy of the body; $dU/dt\big|_{\Delta T}$ and $d\mathbf{B}/dt\big|_{\Delta T}$ are the internal energy and the exergy variation of the body due to a variation in environmental conditions, respectively. In these equations it is assumed that the variation of the volume of the body is negligible. The energy and exergy variation of the body over time due to transient conditions are considered only in CV1.

$$\frac{dU}{dt} = -M + \left.\frac{dU}{dt}\right|_{\Delta T} \tag{2}$$

$$\frac{d\mathbf{B}}{dt} = -B_M + \left.\frac{d\mathbf{B}}{dt}\right|_{\Delta T} = -B_M + \left(\left.\frac{dU}{dt}\right|_{\Delta T} - T_0 \left.\frac{dS}{dt}\right|_{\Delta T} \right) \tag{3}$$

The energy and exergy balances for CV1, and the exergy intake of this control volume are indicated in Eq. (4) to (6). In Eq. (4) the energy intake Q_M is the heat released to CV1 due to the metabolism. The terms Q_c, Q_r are the heat transfer rates to the environment associated with convection and radiation, H_e and ΔH_{res} are the enthalpy flow rate related to vaporization and respiration. The exergy rate B_{QM} is calculated by Eq. (6). It is the exergy transferred to CV1 caused by the exergy metabolism, T_0 is the environment/reference temperature and T_b the body temperature. The terms B_c, B_r, B_e and ΔB_{res} (B_{ex} - B_a) are the exergy rates and flow rates associated with convection, radiation, vaporization and respiration, previously determined in Mady et al. (2012).

$$\left.\frac{dU}{dt}\right|_{\Delta T} = Q_M - \left(Q_c + Q_r + H_e + \Delta H_{res} \right) \tag{4}$$

$$B_{dest}^{CV1} = B_{Q_M} - \left(B_c + B_r + B_e + \Delta B_{res} \right) - \left.\frac{d\mathbf{B}}{dt}\right|_{\Delta T} \tag{5}$$

$$B_{Q_M} = Q_M \left(1 - \frac{T_0}{T_b} \right) \tag{6}$$

The cellular metabolism is a representation of the human cells energetic behavior. In this control volume (CV2) the reactions of oxidation of the energy substrates, also called metabolism, take place. The Eq. (7) and (8) indicate the energy and exergy balances for CV2 where, H_{reac} is the enthalpy of the reactants (carbohydrates, lipids, amino acids and oxygen), H_{prod} is the enthalpy of the products (urea, liquid water and carbon dioxide), B_{reac} is the exergy content of the reactants, B_{prod} is the exergy content of the products and W is the performed work. A complete analysis of the cellular metabolism can be seen in Mady and Oliveira Junior (2013).

$$Q_M = H_{reac} - H_{prod} - W \tag{7}$$

$$B_{dest}^{CV2} = B_{reac} - B_{prod} - Q_M \left(1 - \frac{T_0}{T_b} \right) - W \tag{8}$$

The metabolisms on energy and exergy basis are defined according to Eqs (9) and (10). The analysis of the thermodynamics properties of the reactants and products as well as the equation to calculate the metabolism as a function of the consumption of carbohydrates, lipids and proteins (or from the oxygen consumption and carbon dioxide production in metabolism) are demonstrated in Mady and Oliveira Junior (2013)

$$M = H_{reac} - H_{prod} \tag{9}$$

$$B_M = B_{reac} - B_{prod} \tag{10}$$

Finally, Eqs. (11) and (12) indicate the energy and exergy analysis for the whole body. Equation (13) indicates the exergy efficiency of the body for $dU/dt\big|_{\Delta T}=0$.

$$\left.\frac{dU}{dt}\right|_{\Delta T} = (M - W) - (Q_c + Q_r + H_e + \Delta H_{res}) \tag{11}$$

$$B_{dest}^{body} = \left(B_M - W - \left.\frac{d\mathbf{B}}{dt}\right|_{\Delta T} \right) - (B_c + B_r + B_e + \Delta B_{res}) \tag{12}$$

$$\eta = \frac{B_M - B_d}{B_M} \tag{13}$$

Note that Eq. (5) takes into account only the thermal part of metabolism. Eq. (12) is similar to the analysis proposed by Batato et al. (1990). The difference between these two approaches is that all the exergy released to the body in CV2 is neglected if Eq. (6) is used as the metabolic exergy. Although, from the energy analysis for basal conditions, Eq. (4) is equal to Eq. (11), because $M=Q_M$.

2.1 ATP hydrolisis and maximum performable work

According to Nelson & Cox (2005) the degradation of carbohydrates, lipids and amino acids in human cells, occur gradually with the contributions of several enzymes to reduce the activation energy of the reactions. Thus, the energy is gradually captured with certain efficiency adding an inorganic phosphate group (P_i) to adenosine diphosphate (ADP) to form adenosine triphosphate (ATP) according to Eq. (14). The Gibbs free energy change in biochemical standard conditions ($\Delta g'^0$) is 30.5kJ/mol. As indicated by Lems (2009) the reversal reaction plays the key role in many cell processes by acting as an intermediate carrier of useful energy. So, to perform any kind of work, the human body obtains energy from the reversal reaction known as ATP hydrolysis.

$$\mathrm{ADP} + \mathrm{P_i} \leftrightarrow \mathrm{ATP} + \mathrm{H_2O} \tag{14}$$

Lems (2009), Alberty & Goldberg (1992), Alberty (1998) and Nelson & Cox (2005) affirm that the actual condition of the human body is different from biochemical standard conditions. These authors propound methods to take into account effects of reactants and products concentration, acid and base dissociation, free magnesium ion interaction, ionic interactions, effects of electrical potential, and so on. Based on these authors results, the actual free energy change of ATP formation (Δg_{ATP}) in Eq. (14) is 56kJ/mol.

Silva and Annamalai (2008, 2009) used the concept of metabolic efficiency (η_M) to calculate the maximum energy that is available on to perform work (Eq. 15). Where, ΔG_{oxi} is the Gibbs free energy of the complete oxidation of the nutrient.

$$\eta_M = \left| \frac{\Delta G_{ATP}}{\Delta G_{oxi}} \right| \tag{15}$$

After the complete oxidation of the nutrient in the cells certain quantity of ATP is formed. One mole of glucose forms 32 moles of ATP, one mole of palmitic acid forms 106 moles of ATP and 1 mol of amino acid forms 8 moles of ATP (this last result obtained by Silva and Annamalai (2008, 2009)). Hence, the maximum available power to the human body to perform any kind of physical activities, can be calculated from Eq. (16). Where the rate in which ATP is hydrolyzed (n_{ATP}) is obtained from Eq. (17).

$$W_{MAX} = -\Delta G_{ATP} = \sum_{i=1}^{3} (\eta_M \, \Delta G_{oxi})_i \tag{16}$$

$$n_{ATP} = 32\frac{m_{carb}}{M_{carb}} + 106\frac{m_{lip}}{M_{lip}} + 8\frac{m_{ami}}{M_{ami}} \tag{17}$$

The human body may use as work part of the free energy available in ATP. To the cells synthesize it from ADP and Pi, at least 40% of the exergy in macronutrients (carbohydrates, lipids and proteins) are destroyed as indicated by Mady and Oliveira Junior (2013); and calculated by Eq. (16). Nevertheless, 60% of the exergy content of nutrients is preserved in ATP.

$$Bd_{ATP} = B_M - W_{MAX} \tag{18}$$

The remain ($B_{d,r}$) of the destroyed exergy is related to how efficiently the body uses the energy in ATP, defined by $W_{MAX} - W$, and the exergy content in Q_M, or B_{QM}.

$$Bd_r = W_{MAX} - W - B_{Q_M} \tag{19}$$

If there is no performed work, all energy of ATP will be release as heat, $Q_M = M - W$ and then the destroyed exergy will be higher; otherwise, if the body performs any kind of work, protein synthesis, growth (organized phenomena), a minor portion will be released as heat. Therefore highest irreversiblities in human body are in the reactions of oxidation and in how the efficiently the body is able to use the energy in ATP. The term Q_M is transferred to the body and dissipated in the environment, however the objective of the body should be minimize it, because it indicates the percentage of energy of nutrients that are not used to perform work. From experimental analysis, if the person is at rest $M = Q_M$, therefore the vital functions does not absorb a significant amount of energy from the metabolism.

2.2 Human thermal model

In this work it was adopted a simplification of the human thermal model proposed by Ferreira and Yanagihara (2009), using one cylinder with circular cross sections and four tissues with its own metabolism (skin, fat, muscle and core). It was considered radial heat conduction, heat transfer between blood and tissue and metabolism as a function of nutrients consumption. To solve the differential equations the tissues were considered with uniform temperature and as initial value it was used the condition of thermal neutrality. The control system used was based on Ferreira and Yanagihara (2009). This model allows the determination of the energy and exergy transfer to environment associated with convection, radiation, vaporization and respiration. Moreover, because it consists of only one cylinder, it is possible to use different sets of anatomies (height, weight, and mass), being possible to represent the society from childhood to adulthood.

2.3 Antropometric data and metabolism

Table 1 indicates the anthropometric data of the male Brazilian society (IBGE, 2010), calculated metabolism (Harris e Benedict, 1918), calculated surface area (DuBois and DuBois, 1916) and calculated thermal neutrality temperature as a function of age. These data were used as an input for the exergy analysis. From these data it is possible to obtain the exergy transfer to the environment, destroyed exergy and exergy efficiency for each age group.

Table 1. Anthropometric data of Brazilian society (IBGE, 2010), calculated metabolism (Harris e Benedict, 1918), surface area and thermal neutrality temperature as a function of age

Idade	*h (cm)*	*w (kg)*	*M (W)*	*Ad* (m^2)	*M* (W/m^2)	T_{neut} (^oC)
0	67	8	29.1	0.4	79.1	28.0
2	92	14	37.0	0.6	63.6	28.9
4	106	18	41.8	0.7	58.0	29.4
6	118	22	46.1	0.9	54.1	29.7
8	130	28	50.7	1.0	50.7	30.0
10	139	33	56.0	1.1	49.1	30.0
12	151	42	63.9	1.3	47.9	29.8
14	164	52	73.3	1.6	47.1	29.6
16	170	60	79.2	1.7	46.8	29.5
17	172	63	81.4	1.7	46.7	29.4
18	173	65	82.7	1.8	46.7	29.3
20	173	69	84.9	1.8	46.6	29.2
25	173	73	85.4	1.9	46.0	29.2
30	172	74	84.5	1.9	45.3	29.3

40	171	75	81.3	1.9	43.6	29.6
50	170	75	77.8	1.9	41.9	30.0
60	168	73	73.1	1.8	40.0	30.4
70	167	70	67.6	1.8	37.9	30.8
80	166	67	61.9	1.7	35.6	31.3

Figure 2 indicates the ratio of the metabolism for sedentary person and for a person in basal conditions. The purpose of this comparison is to estimate the increment of the metabolism on the lifetime destroyed exergy until the person reaches 80 years old. The only case that was considered basal conditions was for a newborn (ratio equal to 1).

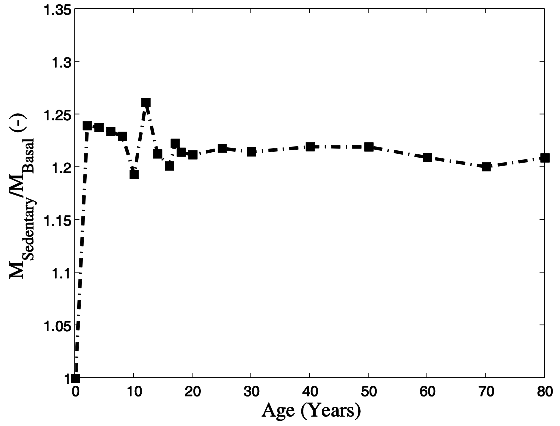

Figure 2. Ratio of metabolism for sedentary conditions and for basal conditions

2.4 Lifetime exergy destruction and performed work

From the destroyed exergy calculated from Eq. (12) it is possible to integrate using the trapezoidal numerical integration, from birth to 80 years as indicated by Eq. (13). Where $B_{d,life}$ is the destroyed exergy over life and $B_{d,age}$ is the destroyed exergy for each chronological age.

$$B_{d,life} = \int_{life} B_{d,age} dt \tag{13}$$

The performed work will be accounted as a percentage of W_{MAX}. As indicated in Mady et al. (2012b), there are series of physiological responses to physical exercise, but herein the objective is to analyze the effect of organize phenomena that uses a percentage W_{MAX} in lifetime exergy destruction (or entropy production) for the same condition or the same metabolism.

3. RESULTS AND DISCUSSIONS

Results in Figure 3 indicate the destroyed exergy and exergy efficiency as a function of aging. The maximum exergy efficiency and the minimum destroyed exergy occur close to the maximum metabolism. For ages above 20 years, the destroyed exergy and exergy efficiency decrease as a function of lifespan as indicated in Mady et al (2012). For different anatomies (during growth, for instance) it is necessary to compare the destroyed exergy and the other terms of the exergy balance divided by the surface area or by the body mass.

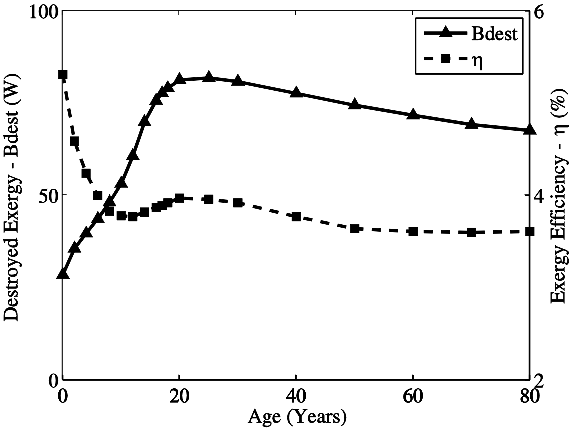

Figure 3. Destroyed exergy (B_{dest}) and exergy efficiency (η) as a function of aging

Figure 4 (a) and (b) indicate the destroyed exergy and exergy transfer to the environment per unit of area. From Fig. 4 (a) it is possible to conclude that the principle of Prigogine is valid from birth to an old age, therefore humans tend to a state of minimum entropy production. Moreover, the curve of exergy transfer to environment has the same slope of the destroyed exergy as a function of aging, but with one order of magnitude of difference as calculated in Mady et al (2012).

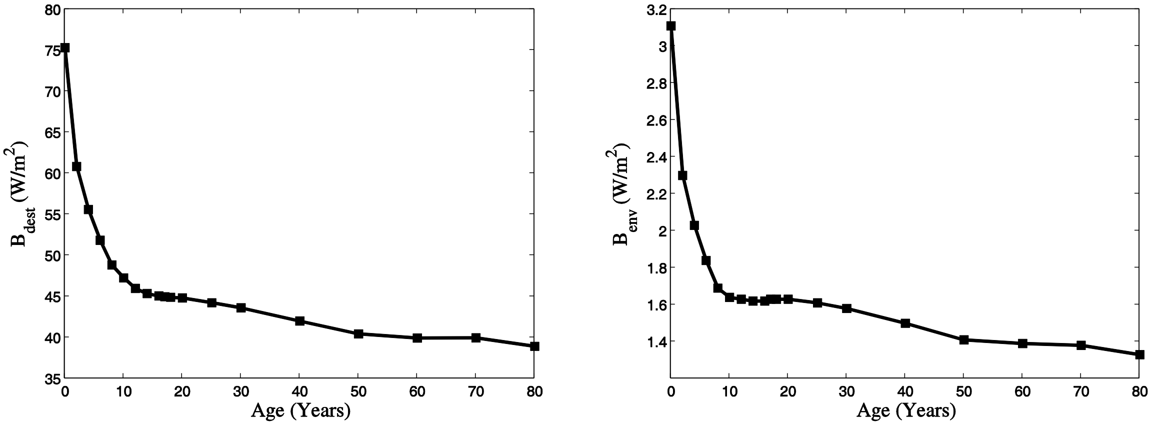

Figure 4. Destroyed exergy per unit of area (B_{dest}) and exergy transfer to environment per unit of area (B_{env}) as a function of chronological age

The destroyed exergy (or entropy generation) can be used to describe physiological age in a more appropriate manner than the metabolism or chronological age (Hershey, 2010), which can be explained by the directionality of this unique physical quantity. The entropy generation indicates that a process can occur only in one direction. Therefore, as demonstrated in Fig. 5 the accumulated destroyed exergy or, "exergy age" of a person with 80 years old is approximately 3037kJ/kg (10.023 kJ/kgK) for basal conditions and 3599 kJ/kg (11.872 kJ/kgK) for sedentary conditions. Table 2 indicates these values, the exergy efficiency, the metabolic exergy and exergy transfer to environment integrated until the person is 80. For basal conditions it was reproduced the results of Hershey (2010) and, for sedentary conditions, it was reproduced the results of Silva and Annamalai (2008, 2009). All results had the same order of magnitude of literature, but in this case it was used a model that takes into account the exergy transfer to environment and other physiological parameters. Hence, these values may indicate the maximum destroyed exergy and the rate of destruction that can no longer support life.

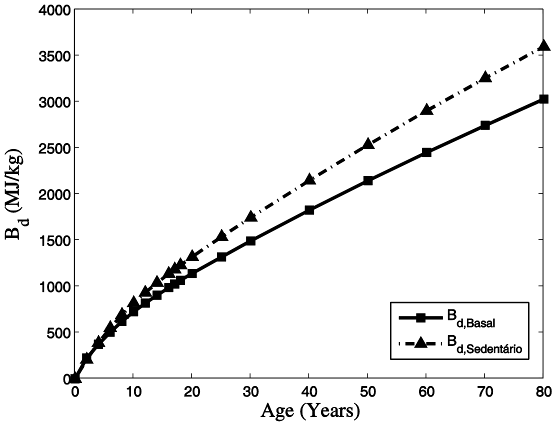

Figure 5. Destroyed exergy or *exergy age* (entropic age multiplied by T_0) integrated as a function of age

Table 2. Metabolic exergy, destroyed exergy exergy transfer to environment and exergy efficiency integrated to the age of 80

	Basal		Sedentary	
	(kJ/kg)	(%)	(kJ/kg)	(%)
B_M	3137	100	3752	100
B_d	3037	96.5	3599	95.9
B_{env}	106	3.5	155	4.1
η	3.5		4.1	

Figure 6 makes a comparison of the lifetime exergy destruction (Fig. 5(a)) and lifetime exergy transfer associated with Q_M (Fig. 5(b)) as a function of chronological age, but accounting for different proportions of the maximum available work (from 0 to 80%). It is important to detach that if the person performs this activities several body functions that control metabolism, sweat would change the metabolism. The purpose of this figure is to compare the effect of organized phenomena that uses ATP as performed work such as, protein synthesis, growth, and physical exercise. This Figure indicates that if the body uses the energy of ATP in organized phenomena, a smaller portion of the exergy in ATP will be dissipated as heat and therefore there will be less irreversibilities. Hence probably the biological system will live longer. Nevertheless, Mady et al. (2012b) and Rahman (2007) indicated that physical activities increases the metabolism and the entropy generation, Figure 5 also indicates that a more active person destroys more exergy. As indicated in Silva and Annamalai (2008,2009) exercises improve the capability of body organs (therefore they use ATP more efficiently), and there must be an optimum point between the improvement of physiological capacity and generation of entropy during physical activities. From Fig. 6(b) it is possible to conclude that the higher the exergy transfer to environment the lower is the exergy transfer to the rest of the body B_{QM}, furthermore, this transfer accounts of about 10% of the total destroyed exergy.

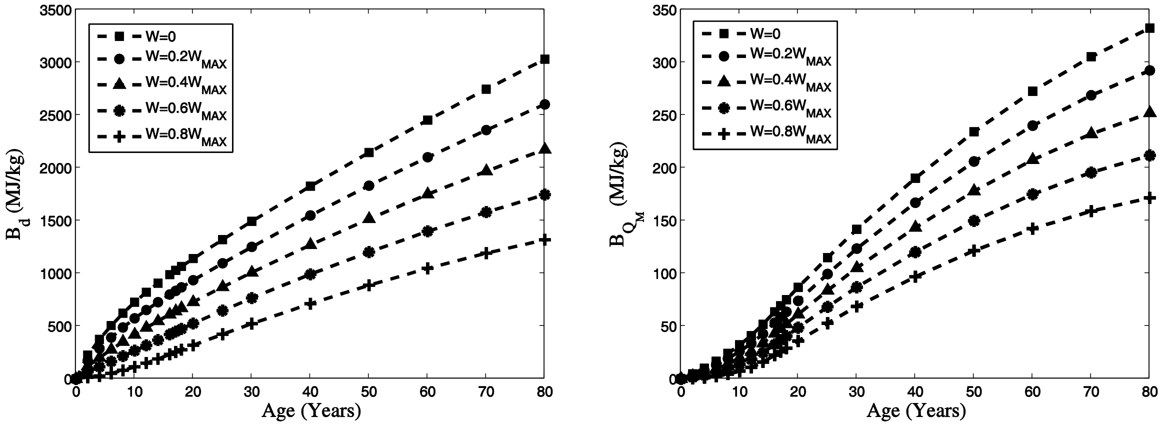

Figure 6. (a) Destroyed exergy or *exergy age* (entropic age multiplied by T_0) and (b) Exergy transfer associated with metabolism. Both integrated as a function of age for percentages of use of available work in ATP

4. CONCLUSIONS

Exergy analysis was applied to a simplified human thermal model, where it was possible to calculate the exergy transfer to environment, destroyed exergy and exergy efficiency of the Brazilian anthropometric data. From this range analyzed it was possible to conclude that the principle of Prigogine is valid for all ages, the slope of the curve of the exergy transfer to environment as a function of aging is similar to the destroyed exergy trend and the exergy efficiency also decreases as a function of the subject chronological age.

This work used a more complete model to estimate the total exergy destroyed in a lifetime (or entropy generation). The results were in the same order of magnitude. The organized phenomena in human body such as growth, protein synthesis, performed work, may increase the lifespan, if the same condition of metabolism is considered. Nevertheless, sedentary people destroy more exergy than subjects in basal conditions; therefore activities tend to increase the destroyed exergy. There must be an optimum point between the increase of exergy destruction during physical activities and the improvement in body functions because these activities.

5. ACKNOWLEDGEMENTS

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