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ENERGY AND EXERGY ANALYSIS OF HYPOTHERMIA AS A THERAPY USING COOLING PADS

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Abstract. *Due to the many unknown factors regarding the inducing of hypothermia in post-cardiac arrest patients, an energy and exergy analysis was performed in one of the techniques established in medical literature. Using a C++ code to simulate the body of an adult man under anesthesia, it was calculated the energy and exergy balance on different sections of the body for every time step during the procedure. Besides obtaining the global efficiency, an analysis of temperature profile and control was assessed, giving a special focus on the brain, target of the therapy. It was concluded that the cooling pads provide a response on the brain temperature well within acceptable values, although lowering the body temperatures to a possibly dangerous condition. The exergetic efficiency provided stable and of good values for the duration of the procedure.*

Keywords: *Therapeutic hypothermia, thermodynamics, exergy in biological tissues, simulation*.

1. INTRODUCTION

According to the American Heart Association (Benjamin et al. 2018), just in the United States of America, more than five hundred and sixty thousand people had a heart attack in 2016, and more than four hundred and sixty thousand died because of it. Similarly, it is stipulated that the survival rate of a heart attack in Europe is lower than 10% (Orban et al. 2012) and the use of localized hypothermia was the first treatment found to increase those odds. Unfortunately, the knowledge of how this treatment affects the biochemical workings of the body is limited. As a consequence, the ideal duration and even which techniques are more effective and why are not yet known. This culminates in inconstant and unreliable guidelines and a broad spectrum of tools that can be used to reduce the patient's body temperature.

Given this scenario, this research aims to evaluate the use of the cooling pads in a thermodynamic perspective, by use of the first and second laws. The results obtained are the first step to reduce animal experimentation on this field.

2. METHODOLOGY

2.1 Therapeutic Hypothermia

The neural tissue has the greatest demand for oxygen and glucose in the human body. Therefore, when the surplus is reduced in an ischemic event, such as a cardiac arrest, the lack of oxygen and consequential reduction on the energy production starts a chain of biochemical events that causes massive cellular death that debilitates and leads to the patient's death if perfusion is not restabilished within 20 minutes. Furthermore, the disbalanced environment created by the event can lead to a new period of massive cellular death several days after the cardiac ressussitation and little is known as to why this happens (Taoufik and Probert, 2008).

According to Karnatovskaia (2014), the therapeutic hypothermia provides neuroprotection in three phases: acute (minutes to hours after the event), subacute (hours to days after the event) and chronical (weeks to months after the event). The acute phase is characterised by the reduction of the metabolism proportional to the that of body temperature (6 to 7% of reduction per degree celcius). This causes the tissue to require less glucose and oxigen to maintain itself, therefore, reducing the initial damage done by the ischemia. Another effect is the reduction of blood flow, that provides protection against excessive increase of blood pressure after reperfusion is obtained.

Following up, the subacute phase is responsible for managing the imbalanced biochemical environment created by the event and may lead to swelling, cellular apoptosis and damage to the blood-brain barrier. Unfortunatelly, for the chronic phase no definitive evidences of possible effects of the treatment are known.

Although effective against brain insult, this therapy is accompanied by risks of its own. Not only it requires anesthesia to subdue shivering and pain sesation, which comes of risks of its own, but by reducing the temperature of the cardiac muscle the chances of a new ischemic event increases (Nolan et al, 2008).

Thus, the general accepted guidelines describes that the body must be reduced to a core temperature between 32 and 34°C for a duration of 12 to 24 hours. The treatment is divided into three periods for easiness of analysis. It initiates with the induction period, defined by a quick reduction of body temperature with duration no greater than 3 hours. Once the patient presents a core temperture lower than 34 °C, the maintenance period begins. It is defined by controlling the patient's temperature so it stays within the acceptable parameters in a stable manner. Lastly, the rewarming phase is defined by the slow increase of body temperature, reestablishing normothermia with indicated rate of 0.25 to 0.5 °C/hour. (Nolan et al, 2008).

2.2 Human Body Model

For this research, the human thermal model used was developed by Ferreira and Yanagihara (2009). It was made using average values for a 67 kg man of 1.76 m height and 14% of fat. The model is composed of fifteen separate elliptical cylinders with thermal properties (such as density, thermal conductivity, metabolic heat generation per unit of volume) varying according to the tissue distribution within the element. Each cylinder exchanges heat with the next through the blood flow, and with the environment through the lateral surface (through convection, radiation, breathing and evaporation). Note that this causes the model to not recognise any changes in the environment due to the body heat, therefor discarding the effects the position of a limb relative to the others. Figure (1) contains a schematics for the model.

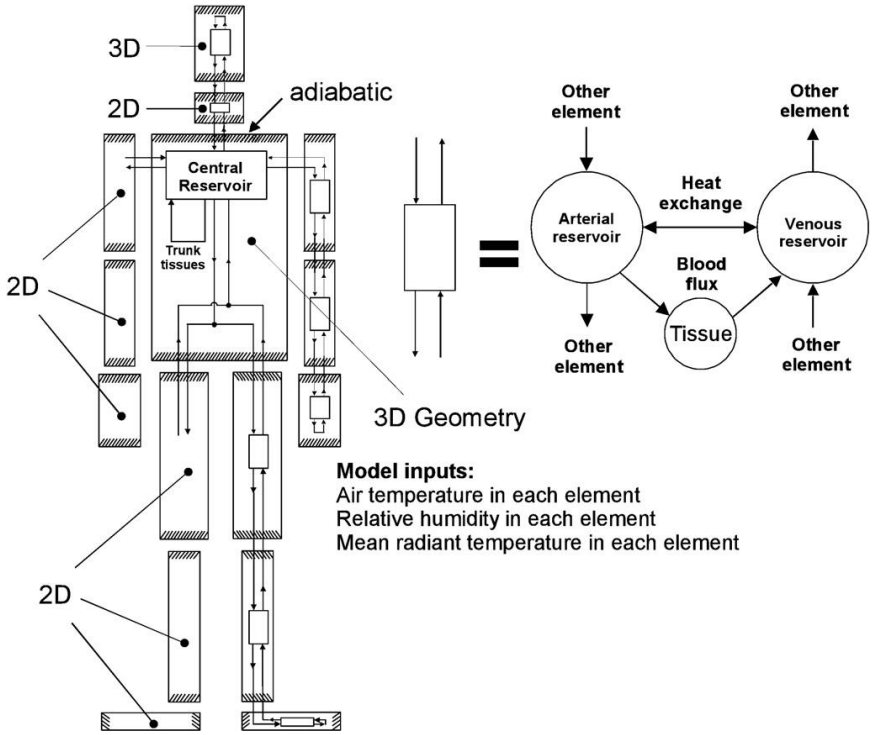

Figure 1. Overview of the passive system model, showing boundary conditions, geometry and circulatory system used in each segment (Ferreira, Yanagihara, 2009).

For the procedure, the environment was set at 24°C and 50% relative humidity according to healthcare facilities protocol (ANSI 2013). No clothing was applied, so any thermal resistance between the skin and the environment is due to the tools applied to induce hypothermia only. The patient remains under the effect of sedatives for the duration of the procedure, therefore, demonstrating no shivering nor sweating. The model starts in a state of equilibrium for a basal metabolism under those environmental conditions and, during the treatment, its temperature is measured directly in the hypothalamus.

After each time step, the laws of thermodynamics are applied to each cylinder and a new temperature profile is obtained. For the exergy analysis, any exergy associated with heat flow (B_{heat}) was calculated according to Eq. (1), the destroyed exergy (B_{des}) by Eq. (2) and the efficiency (η_b) using Eq. (3).

Equation (1) considers the positive heat flow (Q) exiting the system, the operative temperature (T_o) equal to the element's environment temperature and the surface temperature (T_{surf}) equal to the average skin temperature for that cylinder. Equations (2) and (3) take into consideration the heat generated by the metabolism (B_M) in the calculation of

the internal exergy variation of the body (dB/dt) (Mady, 2009). The subscript "env" refers to the environment, in this case, the heat exchanged with the air in the room, while the subscript "CP" refers to the cooling pads and the heat exchanged with them.

$$B_{heat} = Q(1 - T_o/T_{surf}) \tag{1}$$

$$B_{des} = -(dB/dt|_{\Delta T} - B_M) - B_{env} - B_{CP} \tag{2}$$

$$\eta_b = 1 - B_{des}/|(dB/dt|_{\Delta T} - B_M)| = (B_{env} + B_{CP})/(B_{env} + B_{CP} + B_{des}) \tag{3}$$

2.3 Cooling Pads Model

According to Vaity et al. (2015), surface cooling techniques work by circulating a cold fluid through pads or a blanket that are wrapped around the patient. The positioning of the tools varies with each product, ranging from covering only the torso and thighs to full body coverage. It was opted to place the cooling pads on the head, neck, trunk and thighs, for those are the most frequently used locations due to their greater blood flow close to the skin. For those elements, water was used in place of the environment, both for the convective heat transfer coefficient as well as the reference temperature for the exergy analysis. Therefore, the temperature of the elements under the influence of the cooling pads varies according the water temperature.

The surface of each pad was modeled as a thin layer of cotton that completely covers each element (due to the environment conditions) and has a thermal resistance (I_{clo}) calculated by Eq. (4) (ASHRAE, 2005). Using a thickness of 0.5 mm (average thickness of a cotton shirt), and a covered area (A_{cov}) equal to the total area (A_{total}), the resistance obtained is of 0.5 CLO (or 77.5 m² K /kW).

$$I_{clo} = (0.534 + 0135\, x_f)(A_{cov}/A_{total}) - 00549 \tag{4}$$

The temperature of the water is kept between 4 and 40 °C in order to keep in accordance to the values utilized by the products available in the market (Zoll, 2016). The procedure begins with the water at the lower end, with 4 °C, to ensure maximum cooling speed. When the hypothalamus' temperature reaches 33 °C, indicating that the patient is within the targeted temperature range, the fluid begins to warm, until it reaches 31 °C. This water temperature is capable of maintaining the patient within the desired conditions to simulate the maintenance period. For the rewarming phase, the fluid, once again, warms up in a rate of 0.1°C/s until reaching the maximum temperature of 40 °C, selected in order to evaluate the pads' maximum heat capacity. Once the patient reaches normothermia, the procedure ends.

3. RESULTS AND DISCUSSION

3.1 Temperature Analysis

Using the cooling blanket, the patient suffers a small period of increase in brain temperature, followed by a period of uniform decrease of approximately 3.3°C/hour, which leads to a delay of 65 minutes between the beginning of the procedure and the patient entering state of hypothermia. While in the maintenance period, after the increase in the water's temperature, the time required for the patient to stabilize is close to 20 minutes. This time frame can reflect the period required to adjust the patient's temperature in case it deviates from the desired range and can be the cause of medical complications.

It is worth noticing that, although delayed, slow changes of temperature provide for a more stable system, with no risks of overreactions due to changes in the environment. Thus, in case of malfunction of the water's temperature control, this same time frame reflects the period until those malfunctions affect the patient, preventing said complications.

Lastly, after 400 minutes of procedure, the rewarming phase was initiated, obtaining an average increase in temperature of 0.8°C/hour until normothermia. The complete profile can be observed in the graphics of Fig. (2), with the lowest temperature measured in the initial section of the maintenance phase with 32.2°C, well within the acceptable range.

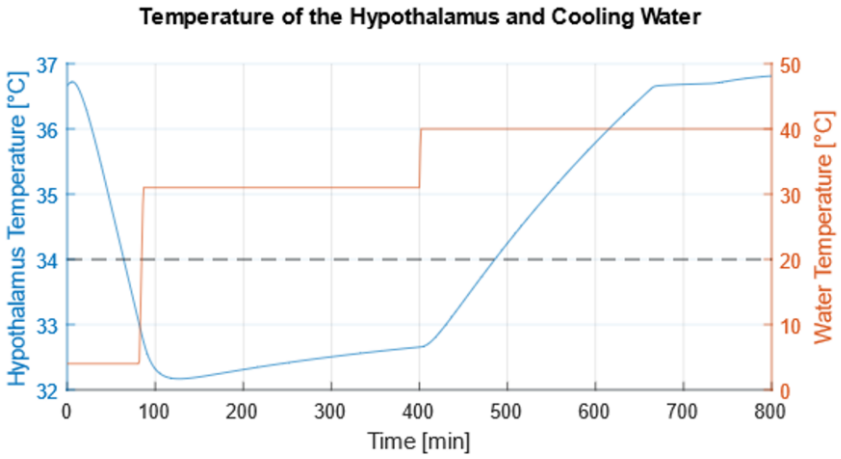

Figure 2: Variation of the hypothalamus and cooling water's temperature during the treatment.

Although the brain temperature was kept above 32°C, it is necessary to observe the temperature profile of the remaining elements in order to evaluate possible tissue damage due to excessive cooling, with a special focus on the cardiac tissue, as the chances of a heart attack increase drastically if it were to reach a more severe state of hypothermia. Taking the average tissue temperature for each element and assessing it throughout the procedure, the smallest value was recorded in Tab. (1) and compared to normothermic conditions.

Using 32°C as a threshold for possible damages, other than the head, only the heart and viscera were capable of maintaining good temperatures, whereas the remaining elements show different levels of a more severe hypothermia. This event is a direct result of the different tissue's basal metabolism. The brain, viscera and heart represent the tissues with greatest heat generation during rest, while the arms and legs are composed mostly of muscle tissue, with low basal metabolism, therefore, obtaining the lowest values observed.

Another explanation is due to the environment conditions. While the pads are kept only on the head, neck, trunk and thighs, the remaining elements are kept exposed to the environment, thus losing heat through convection with the air. As the blood flow to the extremities is reduced during hypothermia (vasoconstriction), the further from the torso, the more isolated the element gets, and the more expressive the heat loss becomes. This can be noticed on Tab. (1) as for the arms, the further from the trunk, the lower the minimum temperature, during both normothermia and hypothermia. Notice that, for the legs, although this rule follows for the normothermia state, during hypothermia, the thigs show slightly lower values than the leg due to the placement of the cooling blanket. Although under 32°C, those limbs are capable of sustaining little to no damage under these conditions, therefore, this treatment shows no unnecessary threat to the patient's life.

Table 1. Mean temperature in each element during normothermia and minimum values obtained during the procedure.

Element	Normothermia	Cooling Blanket
Head	36.7 °C	32.2 °C
Neck	34.7 °C	28.8 °C
Viscera	36.6 °C	32.1 °C
Heart	36.9 °C	32.3 °C
Arm	35.2 °C	29.3 °C
Forearm	34.3 °C	27.8 °C
Hand	33.1 °C	26.1 °C
Thigh	35.7 °C	28.3 °C
Leg	34.8 °C	28.6 °C
Foot	33.7 °C	26.9 °C
Skin	33.6 °C	24.0 °C

3.2 Exergy Analysis

The destroyed exergy is a tool used to quantify the irreversibilities of the process. Always positive, the lower the value, the closer to the ideal process it is. As the water's temperature was used as reference, instead of the air's, the system is limited to the model's body only, without taking into consideration any irreversibility originated on the cooling pads themselves.

Due to the transient characteristic of the adopted system, this value, much like the temperatures, varies with the time. Therefore, in order to provide a better analysis, it was opted to segment it between the inducing, maintenance and

rewarming periods, each separated by a moment of increase in the water's temperature and characterized by a constant value of the cooling water's temperature. Figure 3 contains the graphical visualization for that.

On the inducing period, as the heat is removed from the body, both the skin temperature and heat flux itself lower in different proportions, even on the elements not in contact with the pads. As it can be seen in Eq. (1), both lead to the decrease of the exergy removed and, according to Eq. (2), subsequent increase in the destroyed exergy. Simultaneously, as the body cools, the variation in the internal exergy and the metabolic exergy both decrease as well. While the first also contributes to the growth of the destroyed exergy, the later contributes for its reduction.

Observing Fig. (3), it is clear that the effects of the reduction in the removed exergy are mostly prominent in the initial fifteen minutes, as the destroyed exergy increases. Later, as the skin temperature and heat flux stabilizes, it is the reduction in the internal organs' temperature and its effect on the metabolism that outstands the effects of the removed exergy, inducing the reduction on the destroyed exergy in accordance to the remaining of the inducing period.

For the maintenance, the cooling pads now provide heat to the body while the exposed elements lose heat to the air. This creates not only stable internal temperatures, but also stable heat flows. Thus, the destroyed exergy remains stable.

The only noticeable shift occurs at the beginning and ending of said period. Both are marked by a rapid increase in the water's temperature, which, in this case, changes both the heat flow and the reference temperature for the elements in contact with the cooling pads. At the beginning of the period, this causes the heat flow to become negative and with lower absolute values, that, in accordance with Eq. (1), decreases rapidly the transported exergy, causing the consequential rapid increase of destroyed exergy. On the second increase in water temperature, the growth in the absolute value of heat flow causes an increase in transported exergy, which reflects as a decrease in the destroyed exergy.

Lastly, for the rewarming stage, an opposite event to the one observed during the inducing period takes place, where in increase in temperature causes a positive variation in the internal exergy and a growth of the exergy associated with the metabolism.

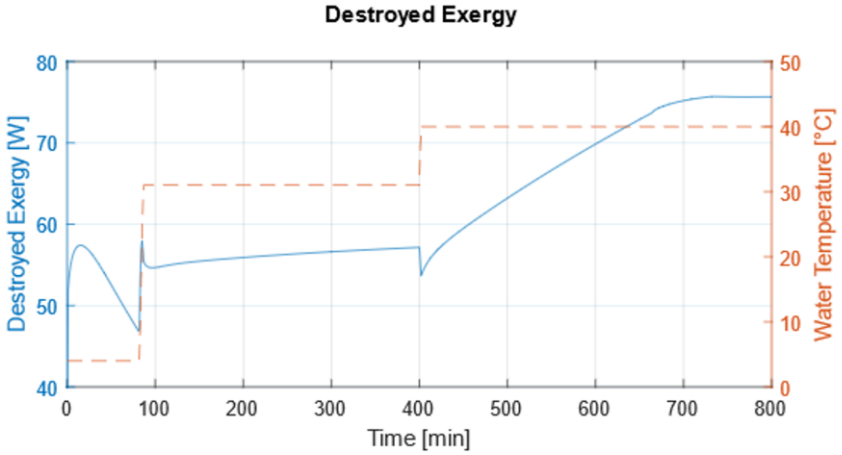

Figure 3. Exergy destroyed by the patient's body under the influence of the cooling pads.

Finally, Fig. (4) contains the calculated efficiency for the body subjected to this treatment. The profile it contains can be directly related to the exergy transported, B_{CP}, as it produces an initial high value that decreases over the induction period, a constant value during the maintenance and a quick growth at the beginning of the rewarming phase. This indicates that, among the components of Eq. (3) for the second form, not only the exergy transported by the environment is lower than that by the pads, but also the destroyed exergy contributes for stable values in each period.

During the induction, the initial high values of transported exergy, when added to the profile of destroyed exergy, create a steadily decreasing denominator that allows the numerator's tendency to be carried on to the efficiency, stabilizing at 21% efficiency before entering the maintenance.

For the duration of the maintenance phase, all transported values were held constant, thus coming forth in a constant value of average 3.9%, but the transitions from the induction and to the rewarming phases are marked by the abrupt changes of values. The first transition is marked by the reduction of transported exergy (due to the reduction of transported heat and proximity of reference temperature and skin temperature) and growth of destroyed exergy, while the opposite happens for the following transition. Therefore, during those moments, the denominator suffers little to no changes, adopting the shape of the numerator.

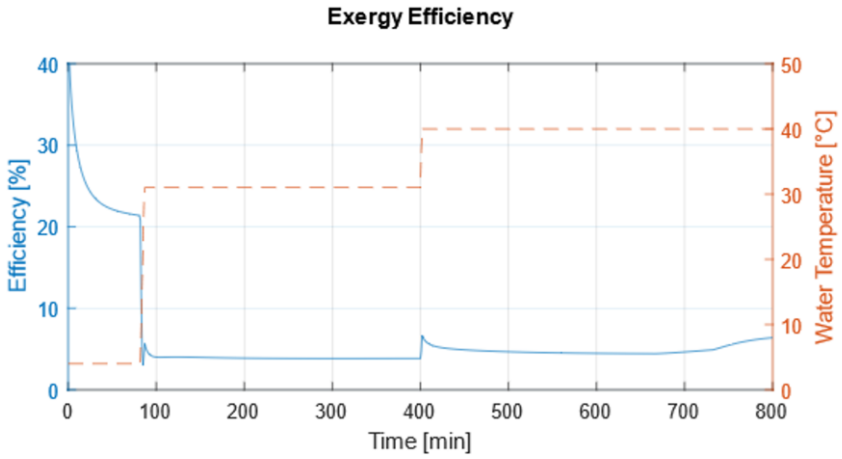

Figure 4: Exergetic efficiency of the model under the influence of the cooling pads.

Lastly, the rewarming phase is characterized by small temperature differences, providing small values of transported exergy with the environment with tendency to reduce further, and a growing destroyed exergy. This produces the steady profile observed on Fig. (4) with average value of 4.6 %. Notice that this profile presents a slight growth only after the patient enters normothermia. Although the rewarming is characterized by growth in the destroyed exergy, the increase in body temperature leads to an increase in the skin's temperature as well, boosting the heat flow with the air that creates the second threshold.

4. CONCLUSION

Regarding the capacity of the system to reduce the body temperature to therapeutic values, 65 minutes could be enough time for permanent damage to take place in the patient's brain. However, as it is within acceptable values, thermodynamically this method is capable of performing the task that is proposed. When taking into consideration the time it takes for the body to respond to the change in water temperature, the adjustment of the tool's setup according to the patient's body and response to the treatment can be complex, especially as the brain temperature is not commonly measured at these procedures. On the other hand, during the maintenance period, the system provided good stability for the body at a good temperature and for the last phase, the system rewarmed the patient in a rate greater than the acceptable, demonstrating good heat capacity. Therefore, although not deprived of its risks, this technique is capable of performing therapeutic hypothermia effectively.

Regarding the temperature profile on remaining elements, the procedure caused the extremities to be at lower temperatures, although the professionals applying the tools can manage possible damages.

For the exergy analysis of the body, although of various degrees of irreversibilities, with the rewarming period providing the greatest values, the efficiency is stable for the most part of the procedure. Taking into consideration that the mean basal efficiency of the human body is 7%, the inducing period managed to provide values far greater, while the remaining phases kept only slightly lower. Therefore, this procedure is both efficient and effective.

5. ACKNOWLEDGMENTS

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