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NUMERICAL SIMULATION OF THE HEAT TRANSFER IN CANINE KNEE JOINT DURING THE SITUATION OF THE THERAPEUTIC COOLING – AN ANALYSIS CONSIDERING VARIABLE BLOOD PERFUSION

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Abstract. *This study aimed to a heat transfer simulation in the canine knee, resulting from the application of therapeutic cooling. The two-dimensional computational domain was biult based on cross sectional photos of the canine knee in real dimensions. The temperature profile in the knee joint is modeled based on the heat diffusion equation published by Pennes considering the effects of blood perfusion and heat generated by metabolism. The simulation was performed considering the variable blood perfusion according to the tissues temperatures. The ANSYS-CFX® program was used to carry out the numerical simulation for a period of 30 minutes. The experimental value for temperature applied to the epidermis was considered as a boundary condition. The numerical results were compared with experimental data obtained from in vivo measurements. A maximum percentage difference of 44.10% was found between the numerical results and the experimental data, considering the internal tissues. The numerical simulation is a noninvasive method to determine the temperature profile in living tissues. However, it was noticed that the physiological properties and boundary conditions shall be improved.*

Keywords: *canine knee joint, bioheat transfer, variable blood perfusion, cryotherapy, thermal simulation*

1. INTRODUCTION

Studies on heat transfer in living tissues have grown considerably in recent decades, since temperature plays an important role in many processes in living things (Diller; Valvano; Pearce, 2000). Because cells are sensitive to temperature changes, heat transfer problems have a considerable impact on the biological sciences, with emphasis on pain relief, support for the healing process, and treatment and diagnosis of diseases (Acharya; Gurung; Saxena, 2014; Silva; Simon; Kosaka, 2001). The use of cold as a therapeutic resource also began in ancient civilizations. About 3000

B.C. the Egyptians applied cold compresses to treat patients with fractures of the skull and infected wounds. In ancient Greece, around 460 B.C., Hippocrates was aware of the analgesic and anti-inflammatory properties of the cold (Korpan, 2007; Cooper & Dawber, 2001). Currently, cryotherapy is widely used to impose a controlled exposure at low temperatures to the living tissues to induce physiological changes, without destroying the cells (Galiuto, 2016; Pasquali, 2015). Several methods are used for cooling the injured tissue such as ice packs, ice massage, ethyl chloride, inflatable splints with refrigerant gas and immersion in cold water (Meeusen; Lievens, 1986; White; Wells, 2013). Despite its applicability, cryotherapy may present tissue damage due to inappropriate application (Malone *et al*., 1992). Therefore, the success of the treatment depends on the prediction and control of the tissue temperature. Even though in vivo tissue temperature determination is possible, the procedures for the *in vivo* measurements during thermotherapeutic procedures present risks mainly due to the invasive nature, besides the imprecision in the control of the various parameters (Trobec *et al*., 2008). In this context, mathematical modeling emerged as an alternative for the calculation of living tissue temperature, and became a topic of interest to many physiologists, physicians and engineers (Charny, 1992).

The first mathematical model of biotransference of heat was proposed by Henry Pennes in 1948, as a result of the experiments conducted by the author himself where temperatures in a resting human forearm were measured. These results served as based for a mathematical model where the forearm was considered as a cylinder (Pennes, 1948). Although mathematical models have emerged as a reliable form of temperature monitoring, the nature of the biotransfer phenomenon can be complex to the point that it is not possible to solve the equations by analytical solutions. Numerical simulations are presented as an alternative for the non-invasive determination of the temperature profile of living tissues. However, numerical results need to corroborate with experimental values for its and boundaries condition validation. Thus, this study aimed at the simulation of the transient heat transfer taking place in the canine knee joint, resulting from the application of therapeutic cooling. Heat transfer was evaluated based on the bioheat transfer model proposed by Pennes, employing software based on the finite volume method.

2. MATERIALS AND METHODS

2.1 Mathematical and geometric model

The mathematical model proposed by Pennes (1948) was used to represent the process of bioheat transfer due to cryotherapy. The equation for calculating the temperature of the tissue may be written as:

$$\rho Cp\frac{\partial T}{\partial t} = \nabla(k\nabla T) + (\rho\omega)_b c_{pb}\left(T_{ref} - T\right) + q_{met} \qquad (1)$$

where k, ρ and cp correspond to the values of thermal conductivity [W/m·ºC], density [kg/m3] and specific heat [J/kg·ºC], respectively. The subcript b is in reference to blood properties, with w_b representing the blood perfusion [m3 s -1 m - 3]. q_{met} is the metabolic heat [W/m^3], T is the tissue temperature [ºC] and T_{ref} is the reference temperature (38.1ºC).

The proposal of this study is to simulate the variable blood perfusion according to an equation presented by Trobec *et al*. (2008), as in Eq. (2):

$$q_w'(T) = \rho_s c_{ps} 9{,}6x10^{-7} e^{0{,}1875T}\left(T_{ref} - T\right) \qquad (2)$$

where T is the temperature of the living tissue and T_{ref} represents the reference temperature.

The two-dimensional model of the canine knee was elaborated in a CAD tool (Computer Aided Design) based on an image of the knee cross section, shown in Fig.1. As numbered regions correspond to the layers whose temperature was analyzed (1 – Epidermis; 2 –Subcutaneous; 3 – Fat; 4 – Medial muscle; 5 – Lateral muscle; 6 – Pericapsular; 7 – Bone; 8 – Cruciate ligaments).

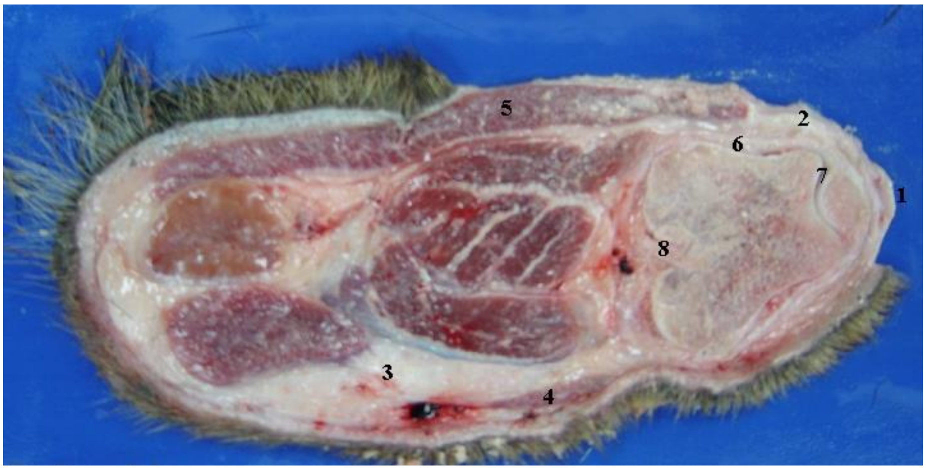

Figure 1 – Canine knee photography.

The physiological and thermo-physical properties were taken from the study from Araújo (2009), as well as the initial temperature values of each region, used as the initial condition for the transient numerical simulations of cryotherapy, as shown in Table 1.

Table 1. Physiological and thermo-physical properties of the layers and blood

LAYER	cp (Jkg-1oC-1)	ρ (kgm-3)	k (Wm-1oC-1)	qmet (Wm-3)	W (m³ s-1 m-3)	INITIAL TEMPERATURE (°C)
Epidermis	3593	1200	2.28x10-1	0	0	34.9
Subcutaneous	3365	1200	4.64x10-1	200	1.3x10 -3	35.5
Fat	2678	937	2.03x10-1	3,9	2.4 x 10-4	36.1
Muscle	3684	1097	5.29x10-1	716	5.8x10-4	36.5
Pericapsular region	3500	1051	4.98x10-1	0	1.8x10-3	35.2
Synovial fluid	4190	1000	6.10x10-1	0	0	37.1
Bone	1785	1585	7.35x10-1	368.3	4.0x10-4	37.1
Blood	3813	1038	-	-	-	38.5

2.2 Thermal simulation

The simulated boundary condition was the variable temperature, which corresponds to the surface temperature values of the epidermis equal to the values recorded in the same region during the experiments performed by Araújo (2009). The upper and lower surfaces of the model were considered adiabatic to establish heat transfer as bi dimensional. Moreover, for the several layers of living tissue that constitute the geometric model, the condition of interface between each of them was adopted. Thus, among the interfaces was assigned conservative heat flux.

The geometric model representative of the knee joint was discretized in an unstructured mesh composed of 29,002 elements and 68,442 nodes, as shown in Fig. 2. The mesh used was the result of successive refinement of assays performed by Silva *et al*. (2015) with the ANSYS Meshing program available in ANSYS Workbench® platform. The thermal simulation was performed using the finite volume method with the support of ANSYS-CFX program.

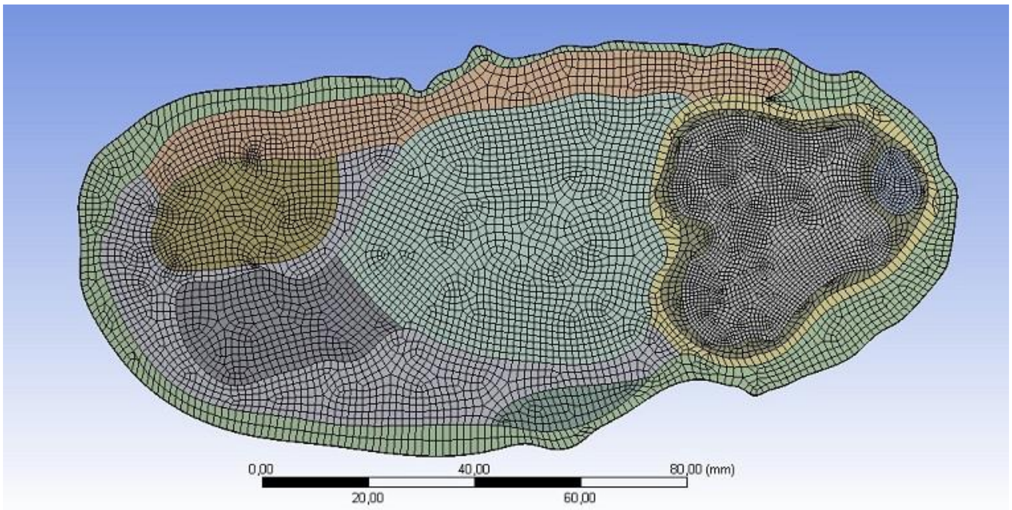

Figure 2 – Unstructured mesh.

3. RESULTS AND DISCUSSION

The graphs in Fig. 3 show the experimental and numerical results on each layer. The temperature field in the end of the cryotherapy process is shown in Fig. 4. It is possible to verify that the more internal layers, such as adipose tissue, medial and pericapsular muscle, presented numerical results high in relation to the experimental data. The other layers had simulated temperature values below the experimental values. Table 2 presents the mean percentage difference between the simulation and the experimental data. It was observed that, among the inner layers, the one that presented the smallest percentage difference was the lateral muscle, 3.60%. The medial muscle had the highest percentage difference value, 44.10%.

Table 2. Mean percentage difference between experimental and numerical temperature values for each layer

LAYER	EXPERIMENTAL TEMPERATURE [°C]	NUMERICAL TEMPERATURE[°C]	DIFFERENCE (%)
Epidermis	24,13	24,63	2,05
Subcutaneous	24,30	25,85	6,38
Fat	25,05	32,10	28,15
Medial muscle	19,08	27,50	44,10
Lateral muscle	29,94	28,86	3,60
Pericapsular	25,70	29,77	15,82
Bone	34,27	31,02	9,47
Cruciate ligaments	34,27	30,20	11,86

The study presented by Trobec *et al*. (2008) represented cryotherapy by applying ice packs for two hours in the human knee considering variable blood perfusion and metabolism. The present study showed the results of simulation of cryotherapy applied in canine knee for 30 minutes considering variable blood perfusion, as considered by Trobec *et al*. (2008) and constant metabolism. By the analysis of the graphs of Fig. 3, it can be observed that the layers corresponding to the epidermis and subcutaneous tissue suffered a reduction of about 10º. The medial and lateral muscle reduced by about 8º. The pericapsular layer and cross-linked ligaments showed a reduction of approximately 7 °C. The fat tissue is located in the outermost region of the knee joint, but presents a smaller difference between an initial and final temperature. This fact can be related to its low value of thermal conductivity in relation to the other layers, as in Table 3. In a thermal procedure, the fat tissue behaves like an insulating material which hinders the propagation of heat flow (Chudecka et al., 2014).

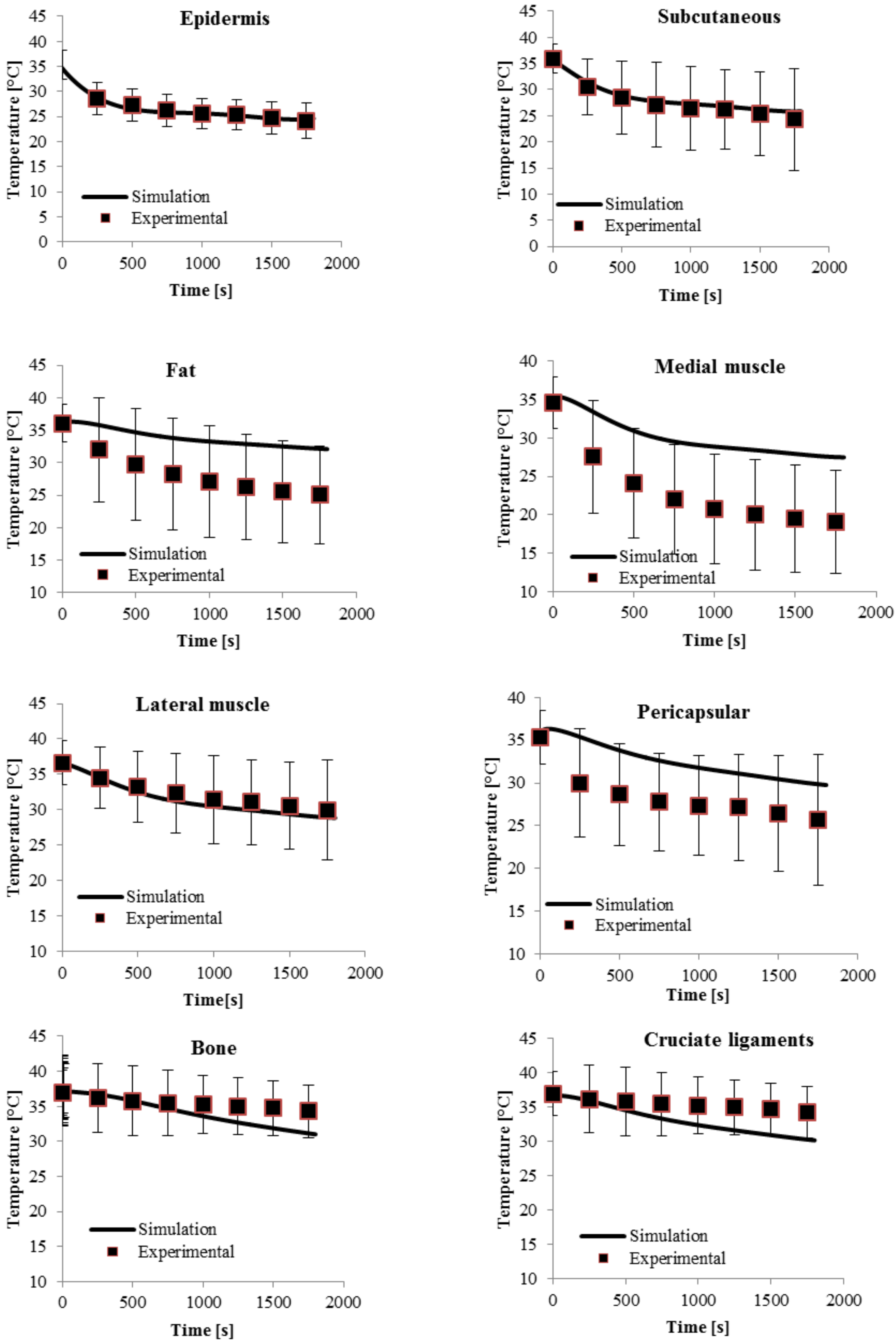

Figure 3. Experimental temperature with standard deviation and numerical temperature for each layer

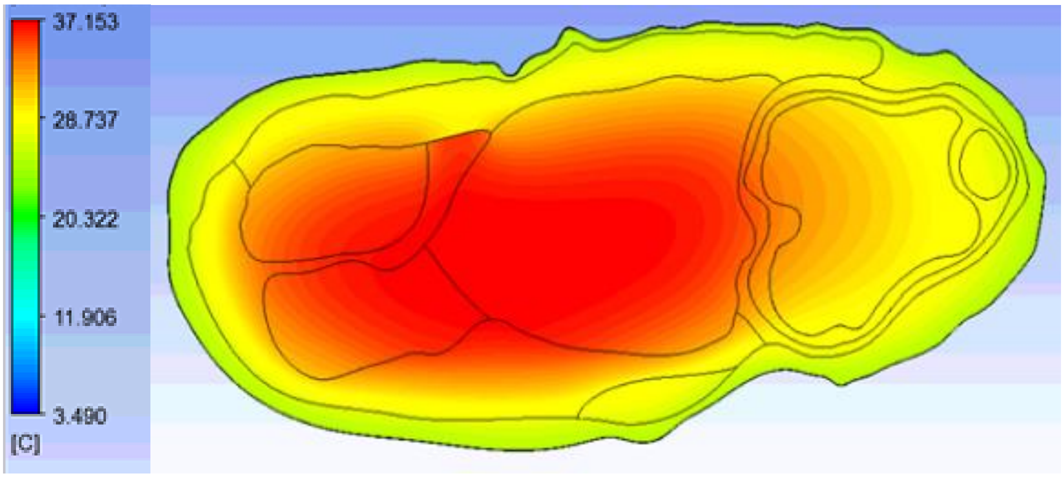

Figure 4. Temperature field in the end of the thermal simulation.

The discrepancy between the mean percentage difference values of the lateral muscle and the medial muscle may be related to the metabolic heat generation. The two layers have the same physiological and thermos-physical parameters, but they have different proportions. The medial muscle, of lower proportion, may have generated a high amount of metabolic heat, which made it difficult to reduce the temperature.

4. CONCLUSIONS

This study has presented the results of numerical simulations in the transient regime of cryotherapy applied in canine knee considering as boundary condition the experimental temperature of the epidermis, blood perfusion rate variable exponentially with tissue temperature and constant metabolism. The results showed that the medial muscle presents highest mean percentage difference between experimental and numerical temperature values. The numerical simulation of the bioheat transfer equation requires more studies and new proposals of mathematical models in order to better represent the cryotherapy process.

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6. RESPONSIBILITY NOTICE

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