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EVALUATION OF THE THERMAL PROFILE IN A CANINE KNEE JOINT BY THE VARIATION OF BLOOD PERFUSION VALUES

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Abstract. *This study aimed to assess the temperature behavior in the tissues that make up a canine knee joint considering different blood perfusion values found in the literature. The geometric model of the canine knee joint was created by the software SOLIDWORKS®, based on a photographic record of an anatomical piece. The heat diffusion equation was used to model the heat transfer phenomenon. The blood perfusion rate was considered constant in all tissues. The simulations were performed using the software ANSYS-CFX® 12.1. A percentage difference of 10 % was found between the numerical simulations and the experimental in vivo data. The results suggest that the numerical simulation can be an important tool to evaluate the biological tissue temperature profile during application of therapeutic heating. The tissues blood perfusion proved to be in the simulations a parameter which the temperature of the model is very sensitive, indicating that studies on its range of values should be done for a better understanding of the bioheat transfer behavior.*

Keywords: *bioheat transfer; Pennes equation; computational simulation; thermal resource; knee joint.*

1. INTRODUCTION

The knee is the largest and the most requested complex joint of the human body. It plays important roles for movement and maintenance of the bipedal stance, such as transmission and supporting of loads, body momentum conservation and stability during individual displacement (Hirokawa, 2001). Therefore, the knee joint is commonly affected by traumatic and/or degenerative lesions. It is one of the joints that receive the majority of therapeutic heating and cooling applications (Martin *et al*., 2001; Denegar, 2003; Levine *et al*., 2008), being considered an important matter of scientific research.

Thus, this study aims to understand the behavior of the tissues that composes the knee joint in thermal neutrality situation, considering different values of blood perfusion. The numerical simulations in thermal neutrality condition are the first step to better understand the thermal profile of the tissues by the variation of the blood perfusion values. A

proper understanding of this situation can serve as a basis for performing simulations in more complex systems, such as transient heating and cooling.

Currently, heat transfer has gained prominence in various health applications such as hyperthermia treatment of cancer (Huang and Liauh, 2011), cerebral hypothermia (Vanlandingham *et al*., 2015; Kirkman and Smith, 2014; Verco and Hockings, 2013), cryosurgery (Shi *et al*., 2009), cryopreservation (Rubinsky, 1987) and the realization of therapeutic treatments (Silva *et al*., 2011; Trobec *et al*., 2008; Araújo, 2009; Araújo, 2006). However, the success, the safety and the efficacy of the procedures involving heat transfer is highly dependent on understanding the thermal behavior of different biological tissues. Although *in vivo* determinations of tissues temperatures are employed for this purpose, there are still great difficulties and risks associated with carrying out these procedures, mainly due to the invasive nature, the inaccuracy in controlling the various parameters and the limitations of the measures (Trobec *et al*., 2008).

In the last two decades, the use of numerical simulations to solve complex health problems has become a reality due to the large spread of computer and the relative ease of numerical methods application (Maliska, 2004). Numerical simulations appear as a non-invasive and low cost alternative, enabling calculating, analyzing and displaying the temperature changes that occur with time at any point of the therapeutic target (Trobec *et al*., 2008).

Studies by Cui and Barbanel (1990) and Cui and Barbanel (1991) showed that the tissue properties, particularly blood perfusion, strongly influence the behavior and thermal responses of the tissue, both in neutral and in the transient thermal conditions. However, the estimated values of this physiological property are a major theoretical obstacle to the realization of any biological system model. In seeking work on bioheat transfer, it is possible to see that the blood perfusion values differ in some studies, particularly in bone and muscle layer. These differences show that there are still uncertainties in the experimental measurement of this property. Thus, the mistaken approach of blood perfusion value for tissue layers can influence on the results. In this context, this study aims to assess the temperature behavior in the tissues that make up a canine knee joint considering different blood perfusion values found in the literature.

MATERIAL AND METHODS

2.1 Geometric model and mesh generation

The geometric model of the canine knee joint was created based on a photographic record of a cross-section of an anatomical part and can be seen in Fig. 1a. The different tissues that comprise the canine knee joint were established by visual inspection. The geometric model was developed with the help of SolidWorks® software. For this study, it was developed a geometric model considering the epidermis, the subcutaneous, fat and muscle tissues, pericapsular and cruciate ligaments regions and bone. The geometric model was developed with a thickness of 0.5 mm, and can be seen in Fig. 1b.

After the development of computational domain, the meshes were built using ANSYS Meshing, a tool available in the ANSYS Workbench® platform. According to the literature, meshing is one of the most critical aspects of the simulation. A large number or very small elements can result in extensive simulation time or inaccurate results, respectively (Versteeg and Malalasekera, 2007). The simulations were started with less refined mesh (mesh 1), composed of prismatic quadrangular elements. Subsequently, the initial coarse meshes were gradually refined until the average changes in temperature results in tissues were lower than 1%. Refinements followed the criteria of the length value of mesh element described in literature (Celik, 2008). For the choice of the optimal mesh was considered that the solution is independent of the mesh with a lower percentage than 1% difference between the results obtained with coarse and subsequent refined mesh. Among the three evaluated meshes, the intermediate one (mesh 2) met the previously mentioned criteria and, therefore, was chosen to perform the simulations. The mesh chosen for the simulation of the heating can be seen in Fig. 2.

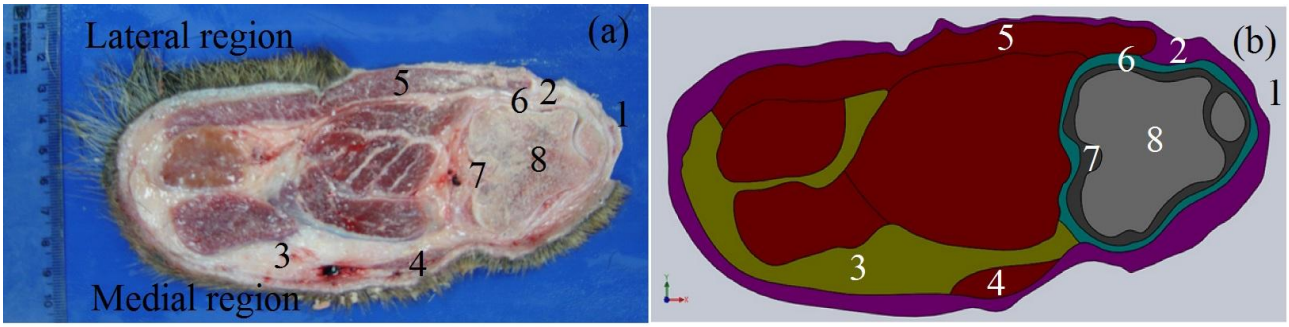

Figure1. (a) Cross-sectional and (b) Geometric model of the canine knee joint

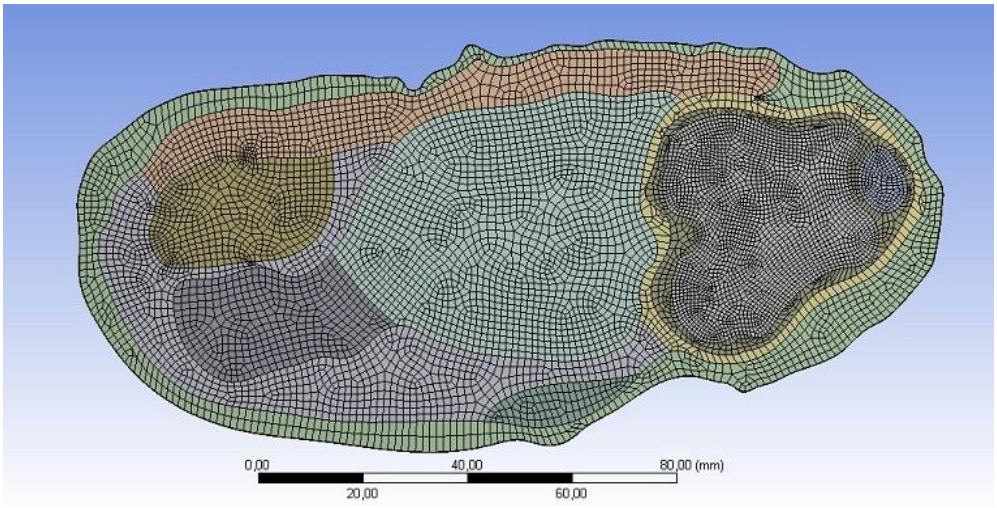

Figure 2. Mesh 2 generated on the geometric model

2.2 Mathematical model

The heat diffusion equation was used to model the heat transfer phenomenon in solid tissues during thermal neutrality condition. This equation can be described as:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q_m}+\dot{q_w}=0 \quad (1)$$

$$\dot{q_w}=w\rho_s c_{ps}(T_{ref}-T_{tec}) \quad (2)$$

where: k is the thermal conductivity of each tissue [$Wm^{-1}{}^{o}C^{-1}$]; $\dot{q_m}$ is metabolic heat rate [Wm^{-3}]; $\dot{q_w}$ is the blood perfusion rate of the tissue [Wm^{-3}]; w is the blood perfusion [m^3s^{-1} m^{-3}]; ρ_s corresponds to the blood specific mass [kgm^{-3}]; c_{ps} is the specific heat of blood [$Jkg^{-1}{}^{o}C^{-1}$] e T_{ref} e T_{tec} are rectal and tissue temperatures, respectively.

The rectal temperature T_{ref} (38.1 °C) and the temperatures used as initial condition of each tissue layer were taken from Araújo (2009) study. According to the author, the initial temperatures were considered to be equal to the average of the experimental temperatures obtained in thermal neutrality condition (24.7 ºC). The bone initial temperature was considered based on the innermost region in which the temperature was measured in this study (cruciate ligaments region).

In this study, the blood perfusion rate ($\dot{q_w}$) in each tissue was considered to be constant, not varying with the temperature of each tissue layer during the simulation.

2.3 Numerical simulation

The values of specific heat, density, thermal conductivity and metabolic heat adopted to perform the simulations were taken from Araújo (2009). The values of the variables used for each of the layers are shown in Tab. 1. All properties were considered constant for the implementation of the simulations.

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

Region	c_p ($Jkg^{-1}{}^{o}C^{-1}$)	ρ (kgm^{-3})	k ($Wm^{-1}{}^{o}C^{-1}$)	q_m (Wm^{-3})
Epidermis	3593	1200	$2.28x10^{-1}$	0
Subcutaneous	3365	1200	$4.64x10^{-1}$	200
Fat tissue	2678	937	$2.03x10^{-1}$	3.9
Muscle	3684	1097	$5.29x10^{-1}$	716
Pericapsular	3500	1051	$4.98x10^{-1}$	0

Cruciate ligaments	4190	1000	$6.10x10^{-1}$	0
Bone	1785	1585	$7.35x10^{-1}$	368.3
Blood	3800	1060	-	-

The simulations were performed considering the blood perfusion values most commonly cited in the literature (Liu *et al.*, 1999; Torvi and Dale, 1994; Jiang *et al.*, 2002; Gowrishankar *et al.*, 2004; Tzou, 1992; Ferreira and Yanagihara, 1999; Werner and Buse, 1988; Collins *et al.*, 2004) for each of the tissues and the average values described by Araújo (2009). Among tissues modeled, only the muscle and bone tissues showed different values of blood perfusion among the evaluated studies. Simulations were conducted by combining two and four blood perfusion values found for muscle and bone, respectively, and using the average values described by Araújo (2009). Thus, nine simulations were performed. In Table 2, it can be seen the blood perfusion values adopted to perform the simulations.

Table 2. Combinations simulated of blood perfusion values of muscle and bone tissue.

Combinations simulated	**w epiderme** ($m^3s^{-1}m^{-3}$ tecido)	**w subcutâneo** ($m^3s^{-1}m^{-3}$ tecido)	**w adiposo** ($m^3s^{-1}m^{-3}$ tecido)	**w músculo** ($m^3s^{-1}m^{-3}$ tecido)	**w pericapsular** ($m^3s^{-1}m^{-3}$ tecido)	**w osso** ($m^3s^{-1}m^{-3}$ tecido)
C1	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.04x10^{-4}$	$1.8x10^{-3}$	$3.06x10^{-4}$
C2	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.04x10^{-4}$	$1.8x10^{-3}$	$3.56x10^{-4}$
C3	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.04x10^{-4}$	$1.8x10^{-3}$	$4.75x10^{-4}$
C4	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.04x10^{-4}$	$1.8x10^{-3}$	$7.92x10^{-4}$
C5	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.95x10^{-4}$	$1.8x10^{-3}$	$3.06x10^{-4}$
C6	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.95x10^{-4}$	$1.8x10^{-3}$	$3.56x10^{-4}$
C7	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.95x10^{-4}$	$1.8x10^{-3}$	$4.75x10^{-4}$
C8	0	$1.25x10^{-3}$	$8.6x10^{-5}$	$6.95x10^{-4}$	$1.8x10^{-3}$	$7.92x10^{-4}$
Average values	0	$1.3x10^{-3}$	$2.9x10^{-4}$	$5.8x10^{-4}$	$1.8x10^{-3}$	$4.0x10^{-4}$

The simulation of the temperature profile of the canine knee joint was performed in thermal neutrality condition. To perform the simulation it was adopted at the upper and lower joint face a boundary condition of second kind, corresponding to a perfectly isolated or adiabatic surface. Thus, it was assured that the heat transfer occurs only in the two-dimensional cross sectional plane of the canine knee (although the real geometric model is three-dimensional). On the external surface of the geometric model was adopted a boundary condition of third kind, corresponding to the natural convection condition. To this end, a environmental temperature of 24.7ºC (Araújo, 2009) and a natural convection heat transfer coefficient (h) of 6 $Wm^{-2}K^{-1}$ (Dear *et al.*, 1997) were considered. Once the current model is composed of different tissue layers, it became necessary to define the interface conditions between the various tissues. Thus, it was assigned conservative heat flow between the tissue interfaces. Numerical simulations of the canine knee in thermal neutrality condition were performed using the ANSYS-CFX® 12.1 software.

The results of the simulations were evaluated and compared to the average values of temperature obtained from an experimental study *in vivo* (Araújo, 2009). The average percentage difference between the simulation and the experimental data was calculated for each of the tissue layers. A smaller or equal average percentage difference of 10% was considered acceptable.

3. RESULTS AND DISCUSSION

It is possible to visualize the percentage difference found between the experimental *in vivo* data and simulations performed in this study in Tab. 3. Among the simulations, only those considering the average values of blood perfusion

and combinations C1, C2, C3 and C5 showed temperatures lower than 10 % difference compared to the experimental data *in vivo*.

The combination C1 obtained the closest values of temperature when compared to the experimental data with an average percentage difference of 5.1%. The average percentage differences of combinations C2, C3 and C5 were 5.5%, 6.1% and 6.9 %, respectively. This fact can be explained by the increase in blood perfusion values between these combinations. The combinations C1, C2 and C3 only differ themselves between the bone tissue perfusion values, where C1 has the lowest value and C3 the highest. Therefore, it can be observed a proportional relation between the values of blood perfusion and temperature, since higher perfusion values generated higher temperatures in thermal neutrality. These data are consistent with the literature that says that blood flow is the key mechanism of controlling body temperature, working, depending on the body temperature, as a source or a heat sink (Zolfaghary and Maerefat, 2010). Temperatures of simulation based on the arithmetic average of perfusion values obtained an average percentage difference of 6.4%. Therefore, in a permanent regime condition, combinations C1, C2 and C3 values shown to be more consistent with the experimental data that the arithmetic average described by Araújo (2009).

The combination C5 showed temperatures with percentage difference lower than 10% while the C4 obtained difference up to 14% for bone region. This is due to the fact of combination C5 being considered an intermediate case. Although being modeled with a higher value of muscle blood perfusion that C4, it has a much lower value of bone blood perfusion in relation to C4, causing their temperatures to be lower and closer to the experimental data. The temperatures for the simulations of the combinations C4, C6, C7 and C8 were very high and were not considered satisfactory because they presented differences higher than 10% in at least one tissue.

Table 3. Percentage difference between experimental and simulated temperature values for each tissue and combinations.

Region	Average values	C1	C2	C3	C4	C5	C6	C7	C8
Epidermis	6%	5%	5%	6%	7%	6%	7%	7%	9%
Subcutaneous	5%	4%	5%	5%	6%	6%	6%	7%	9%
Fat tissue	7%	5%	5%	5%	6%	7%	7%	8%	9%
Lateral muscle	6%	5%	5%	6%	7%	7%	7%	8%	10%
Medial muscle	9%	7%	8%	8%	10%	10%	10%	10%	12%
Pericapsular	10%	9%	9%	10%	14%	10%	11%	12%	16%
Cruciate ligaments	4%	3%	3%	4%	8%	4%	5%	6%	9%
Bone	4%	3%	4%	5%	9%	5%	5%	7%	10%
Average percentage difference	6.4%	5.1%	5.5%	6.1%	8.4%	6.9%	7.3%	8.1%	10.5%

Table 4. Comparison between experimental and simulated temperature values (including the average values and combinations C1, C2, C3 and C5).

Region	Experimental temperature (°C)	Average values (°C)	C1 (°C)	C2 (°C)	C3 (°C)	C5 (°C)
Epidermis	34.9 ± 1.3	36.9	36.5	36.6	36.8	37.2
Subcutaneous	35.2 ± 0.6	37.1	36.7	36.8	37.1	37.4

Fat tissue	36.2 ± 0.5	38.6	37.9	38	38.1	38.8
Lateral muscle	36.5 ± 0.9	38.6	38.2	38.3	38.5	39.1
Medial muscle	35.0 ± 0.9	38.1	37.5	37.6	37.9	38.3
Pericapsular	35.0 ± 0.6	38.4	38.0	38.2	38.6	38.6
Cruciate ligaments	37.1 ± 1.0	38.5	38.0	38.2	38.7	38.7
Bone	37.1 ± 1.0	38.7	38.2	38.5	39.0	38.9

In Table 4, one can compare the temperature values measured in experiment with the temperatures obtained in the simulations considering the average blood perfusion values and combinations C1, C2, C3 and C5. Comparing the smallest simulated temperature values which were obtained with combination C1, with the experimentally measured values, it is clear that only the pericapsular region had simulated temperature value, 38.0°C, within the standard deviation range whose upper limit for this layer was 38.1°C.

It is possible to note that the highest temperature variation between simulations occurred in lateral muscle and fat tissue which presented a difference of 0.9°C between the C1 and C5 combinations. Also, the lowest difference was 0.6°C in the pericapsular region. This sensitivity of the lateral muscles was expected, considering that this layer presents different values of blood perfusion, which implies a direct change of the internal energy supply in this tissue, causing temperature variations. However, since the fat tissue was always simulated with the same blood perfusion value and it showed a significant temperature variation, it can be concluded that this layer in this model is the most sensitive tissue to variation of blood perfusion values. The opposite case occurs with pericapsular region, since it had the lowest temperature variation, indicating a smaller sensitivity of that tissue.

The numerical simulations performed on this study aimed to appraise the influence of different blood perfusion values adopted in the literature on the behavior of tissue temperature. The results show that tissue blood perfusion is a factor to which the temperature field within the canine knee joint is very sensitive. Thus, simulations that are based on overestimated blood perfusion values, which may be the case of the combinations C4, C6, C7 and C7, may present high temperature values that are not consistent with reality. Considering that the majority of studies have no experimental data as a reference for validation of the proposed models, the blood perfusion values presented in this study are best suited for performing numerical simulations of bioheat transfer.

Hence, it's possible to be concluded that inadequate determination of blood perfusion can greatly affect the results of the numerical simulations, leading to an erroneous interpretation of temperature behavior in biological tissues.

4. CONCLUSION

This study aimed to evaluate the sensitivity of the temperature distribution in a canine knee joint through the variation of blood perfusion values in thermal neutrality conditions. The blood perfusion of the tissues proved to be a very influential parameter on the temperature distribution of the model, making studies on their range of values necessary for a better understanding of the bio heat transfer behavior.

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