TWO-DIMENSIONAL SIMULATION OF THE TEMPERATURE PROFILES IN A CANINE KNEE JOINT DURING THERAPEUTIC HEATING AND COOLING

Fernanda Souza da Silva, nandasouzafisio@yahoo.com.br
Adriana Silva França, adriana@demec.ufmg.br
Marcos Pinotti, pinotti@ufmg.br
Mechanical Engineering Department
Universidade Federal de Minas Gerais – UFMG
DEMEC/UFMG – Av. Antônio Carlos, 6627. CEP: 31.270-901
Belo Horizonte, MG – Brasil.

Abstract. *The objective of the present study was to perform two-dimensional simulations of the heat transfer that occurs in the canine knee joint, resulting from the application of superficial thermotherapy (heating or cooling). Definition of the two-dimensional xy simulation domain, representing a transverse cut of a canine knee joint, was based on real dimensions extracted from a photographic image. Transient heat transfer was evaluated including the effects of blood perfusion and metabolic heat based on the model proposed by Pennes, employing a finite element based software (FEHT). Simulations were performed employing two types of boundary conditions at the external joint surface: 1- known temperature (heating/cooling) and 2- known heat flux (heating). There was good agreement with experimental data (average percent differences lower than 2%) for heating simulations based on known temperatures of the epidermis or known heat flux at the surface. In the case of therapeutic cooling, simulations based on the assumption that the external surface temperature was equivalent to that of the cooling device provided a satisfactory description of the experimental data (average percent difference of 3.1%). Our results indicate that computer simulation can be an important tool for assessing the effectiveness of thermal resources and that two-dimensional simulations can provide satisfactory estimates of average temperature values in the case of both heating and cooling therapies.*

Keywords: *bio heat transfer; Pennes equation; numerical simulation; thermal treatments; finite element method.*

1. INTRODUCTION

Heat in its various forms has been employed for therapeutic purposes since ancient times (Shitzer and Eberhart, 1985; Cameron, 2009). Therapeutic modalities such as superficial applications of heat use the body's natural thermoregulatory mechanisms to relieve pain or provide healing, being especially relevant to the treatment of lesions of the muscular and skeletal systems (Lin, 2003; Nadler *et al.*, 2004). However, for the benefits of this therapy to be achieved, it is necessary for the therapeutic target to be heated or cooled within specified temperature limits (Draper *et al.*, 1999; Kitchen, 2003). In the case of heating, it is recommended for the target tissue temperature to remain in the range of 40 to 45ºC for at least 5 minutes (Kitchen, 2003; Robertson *et al.*, 2005; Greenstein, 2007; Kennet *et al.*, 2007). During cooling procedures, target tissue temperatures must be in the range of 13 to 18.3 °C (Low and Reed, 2001). Furthermore, in either cooling or heating procedures, temperatures outside the required ranges are not sufficient for promoting the desired therapeutic effects, or can cause thermal damage to the tissue. Therefore, monitoring of these temperatures is an important strategy for safe and effective treatments.

Although in vivo tissue temperature determinations can be employed in order to better understand and improve therapeutic strategies, there are several difficulties associated with this type of experimental procedures (Trobec et al., 2008). Recent studies have shown that numerical simulations are an interesting non-invasive alternative for the assessment of temperature distribution in several tissue layers exposed to different thermotherapy interventions (Amini et al., 2005; Trobec et al., 2008; Araújo, 2009). Therefore, this study aimed at the simulation of transient heat transfer in the canine knee joint, resulting from the application of superficial thermotherapy. The knee joint dimensions in xy coordinates were defined based on real dimensions extracted from a photographic image of a transverse cut of a canine knee joint. The following regions were identified: epidermis; subcutaneous tissue; fat; muscle; pericapsular region; femorotibial region; cruciate ligaments and bone. Transient heat transfer in the xy direction was evaluated according to the model proposed by Pennes, during application of therapeutic heat and cold.

2. MATERIAL AND METHODS

Heat transfer in the canine knee joint, including the effects of blood perfusion and metabolic heat, was evaluated according to the model proposed by Pennes (1948). The corresponding governing equation can be written as:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + (\rho\omega)_b c_{pb}(T_a - T) + q_{met} \quad (1)$$

where k, ρ and c_p correspond to the values of thermal conductivity [W/m·ºC], density [kg/m^3] and specific heat [J/kg·ºC], respectively. The subcript b is in reference to blood properties, with w_b representing the blood perfusion [m^3 s^{-1} m^{-}3]. q_{met} is the metabolic heat [W/m^3], T is the tissue temperature [ºC] and T_a is the arterial temperature (37ºC).

All simulation studies were based on the finite element discretization method, employing the software FEHT (F-Chart Software, Madison, WI).

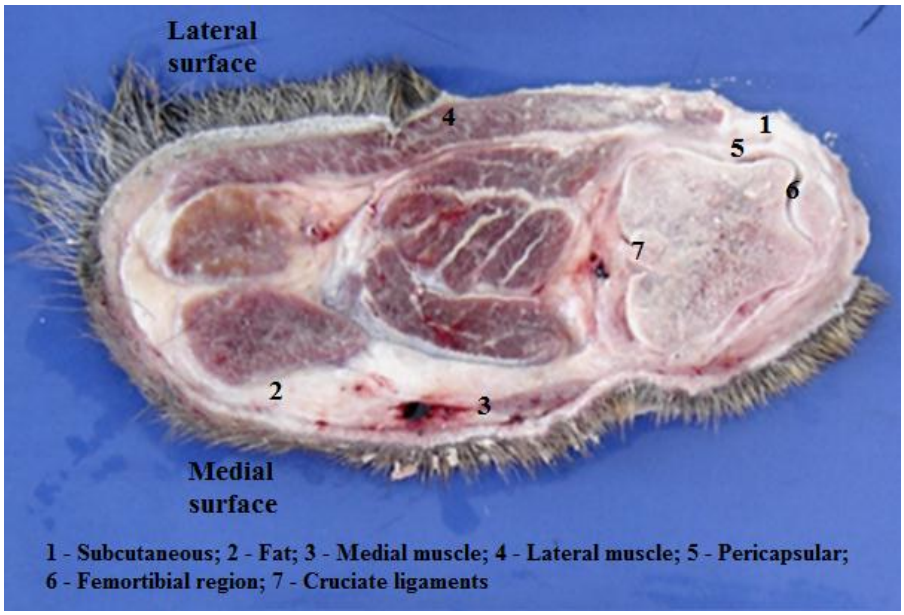
The two-dimensional simulation domain, representing a transverse cut of a canine knee joint, was based on real dimensions extracted from a photographic image (see Fig. 1a). Definition of the two-dimensional simulation domain (Fig. 1b) was accomplished with the aid of a CAD (Computer Aided Design) software. The numbers shown in Fig. 1 correspond to temperature measurement locations (Araújo, 2009). The corresponding thermo-physical properties and initial temperatures of each specific tissue are displayed in Table 1. Both the tibofemoral regions and cruciate ligaments are located inside the intra-articular cavity, and thus the corresponding thermophysical properties employed in the simulations were of the synovial fluid.

Table 1. Thermo-physical and physiological properties of tissues and blood.

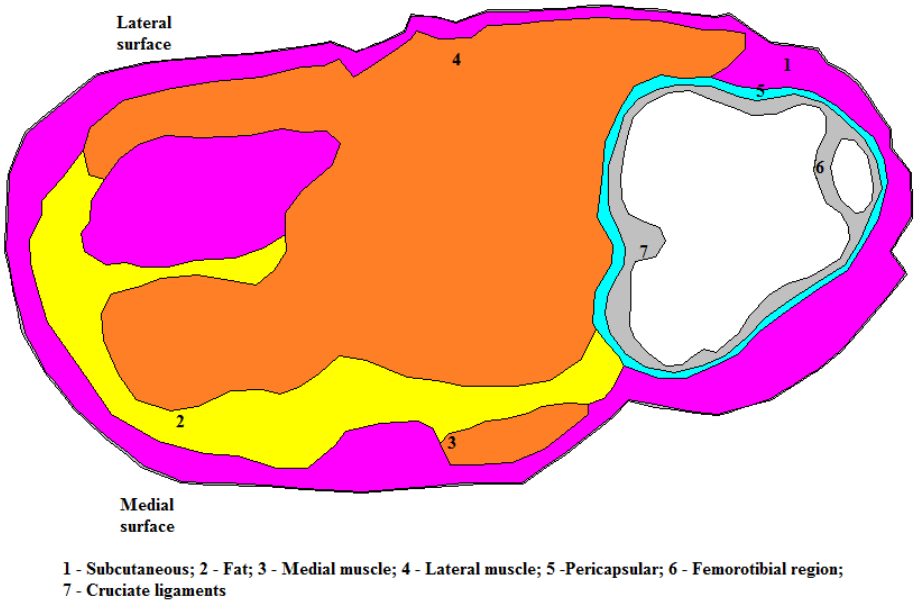
Tissue	**c_p ($Jkg^{-1}ºC^{-1}$)**	**ρ (kgm^{-3})**	**k ($Wm^{-1}ºC^{-1}$)**	**q_m (Wm^{-3})**	**W ($m^3s^{-1}m^{-3}$ tec)**	**Initial Temperature (ºC)**
Epidermis	3593	1200	$2.28x10^{-1}$	0	0	34.9
Subcutaneous tissue	3365	1200	$4.64x10^{-1}$	200	$1.3x10^{-3}$	35.5
Fat tissue	2678	937	$2.03x10^{-1}$	3.9	$2.9x10^{-4}$	36.1
Muscle	3684	1097	$5.29x10^{-1}$	716	$5.8x10^{-4}$	35.1 (medial) 36.5 (lateral)
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	-	-	-	37.0

Simulation parameters such as external heating/cooling device temperatures and heating times were established according to *in vivo* experimental data available in the literature (Araújo, 2009). The external layer of the epidermis was considered to be in perfect contact with the heating/cooling devices. The following boundary conditions were evaluated:

a) Temperature of the external layer of the epidermis equivalent to the average temperature of the heating/cooling device: simulation H1 (heating): T = 57.6ºC; simulation C1 (cooling): T = 4.5ºC.
b) Temperature of the external layer of the epidermis equivalent to the average value of the measured local temperatures: simulation H2 (heating): T = 40.7ºC; simulation C2 (cooling): T = 27.3ºC.
c) Heat flux at the external surface equivalent to the average heat flux provided by the heating device: simulation H3 (q = 215.7W m^{-2}).



(a)



(b)

Figure 1. Simulation domain: (a) original photograph and (b) FEHT domain definition.

3. RESULTS AND DISCUSSION

A discretization mesh comprised of 859 nodes and 1560 elements was employed in the simulations (Fig. 2). The calculated temperatures at specific locations (see numbers in Fig. 1) were compared to experimental data presented by Araújo (2009).

1 – Therapeutic heating

Percent differences between experimental and calculated time-averaged values of the temperatures at each measurement point (see Fig. 2) are displayed in Table 2. A significant difference between experiments and simulation was observed when the temperature of the external layer of the epidermis was considered to be equivalent to the average temperature of the heating device (simulation H1). The fact that the simulation provided an overestimation of temperature values is attributed to the resistance to heat transfer between the heating device and the epidermis not being taken into account. Such resistance to heat transfer is quite significant, for it represents a difference of 16.9^{o}C between the temperature of the heating device and the surface temperature of the epidermis. When the actual epidermis temperature was employed in the calculations (simulation H2), there was good agreement between experiments and simulation. There was also a significant reduction in differences between experiments and simulations when the boundary condition based on the known value of heat transfer at the surface was employed (simulation H3). In this case,

all the heat produced by the heating device was transferred to the tissues and no heat losses to the surroundings were considered.

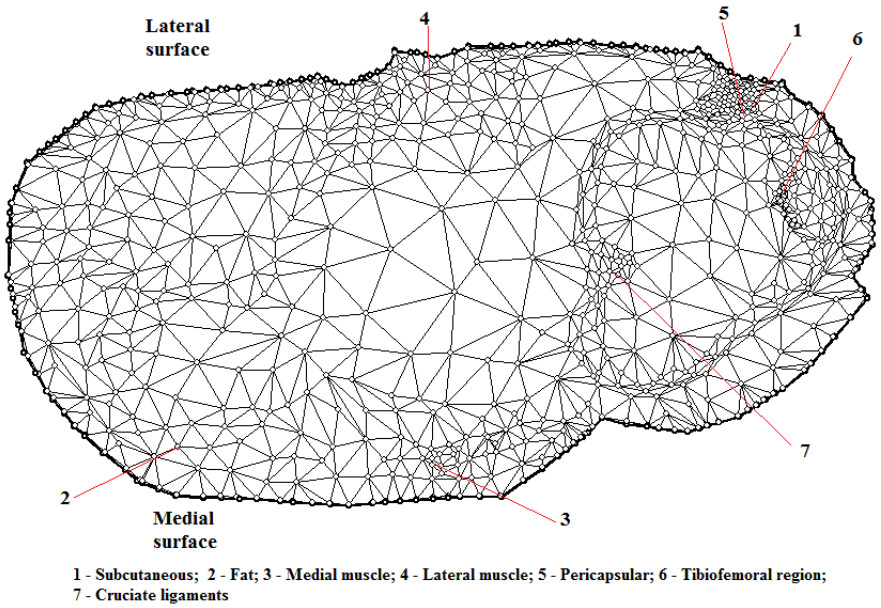


Figure 2. Finite element discretization mesh

Table 2. Differences between experimental and calculated values of the average temperature at each temperature measurement location during heating.

	Average percent difference (%)		
Location	**Simulation H1**	**Simulation H2**	**Simulation H3**
1-Subcutaneous tissue	18.7	0.8	0.3
2- Fat	16.6	0.8	0.4
3- Medial muscle	17.4	2.9	0.7
4- Lateral muscle	18.0	2.7	0.4
5-Pericapsular	14.6	2.3	0.6
6-Tibiofemoral region	16.0	2.7	0.7
7-Cruciate Ligaments	2.5	0.9	1.9
Average	14.8	1.9	0.7

Variations of the temperatures at each measurement point as a function of time are displayed in Fig. 3, in reference to simulation H2. It can be noticed in all temperature measurement locations, that the largest differences between experimental and simulation results occur during the first 20 minutes of heating. In most of the measurement locations the simulated temperatures increase faster than the experimental values at the beginning of heating. This could be related to variations in the thermo-physical and physiological properties of each tissue, mainly the thermal conductivity and blood perfusion (Cui and Barbanel, 1990; Cui and Barbanel, 1991) and to the body´s own thermoregulation system (Keller and Seiler, 1971; Mekjavic and Eiken, 2006). Heat transfer loss through the skin is counteracted by variations in the heat flux in both the epidermis and subcutaneous tissue, one of the major mechanisms employed by the body for temperature control (Keller and Seiler, 1971; Vanhoute et al., 2002). Thus, the difference between simulations and experiments can be attributed to the fact that the model does not take into account variations in the physiological parameters that take place as a consequence of heating. Also, the average temperature value employed as boundary condition did not take into account temperature fluctuations that took place during the first 10 minutes of heating.

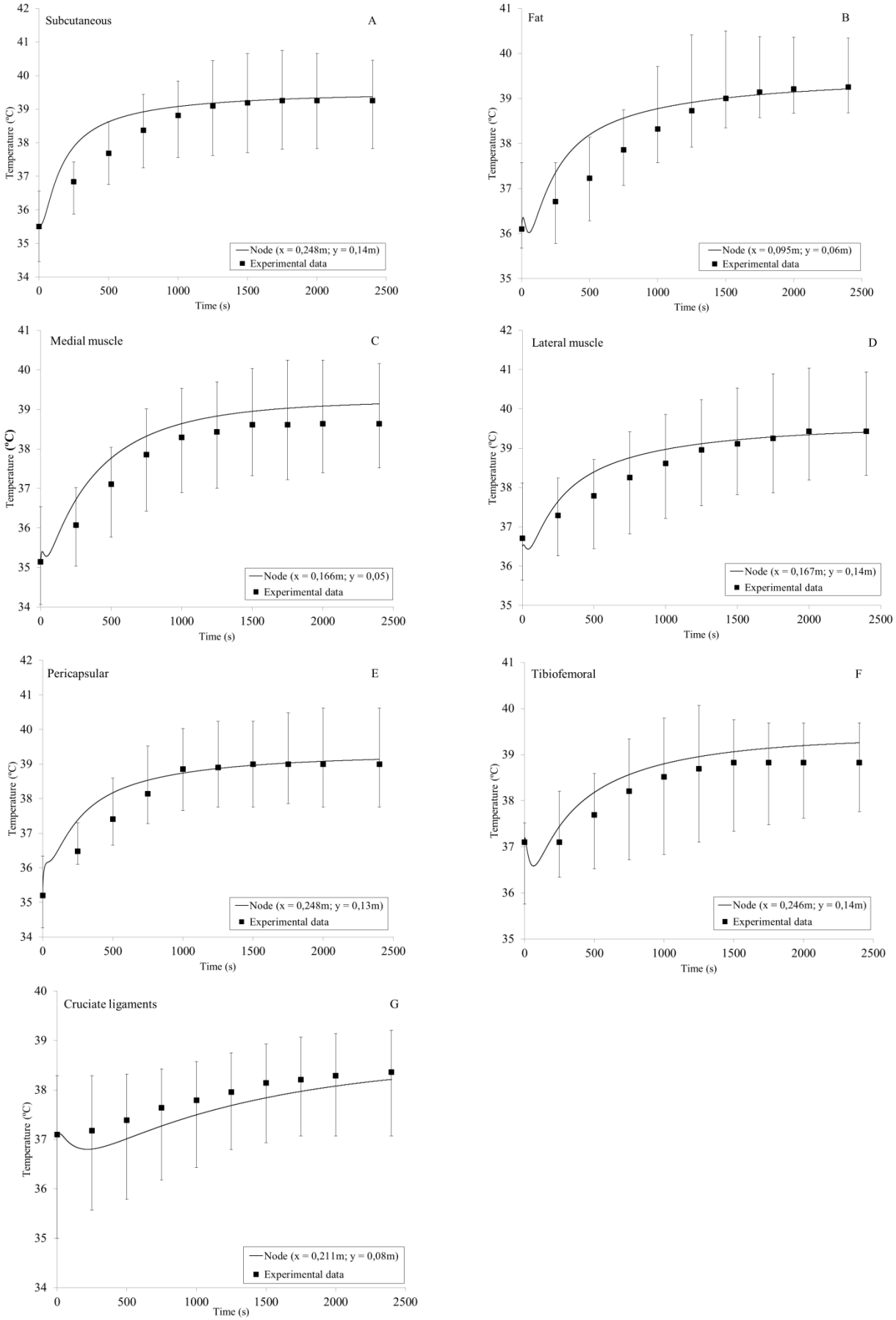


Figure 3. Variation of local tissue temperatures with time during heating: ■ experimental; —simulation H2.

Similar temperature profiles were obtained for simulation H3, but with smaller differences between experiments and calculations. Furthermore, the consideration of the heat flux at the external surface being equivalent to the average heat flux provided by the heating device is a more appropriate boundary condition, because it does not depend on the previous knowledge of the temperature value at the external surface. The small differences between experiments and simulations are attributed to heat losses to the ambient not being taken into account as well as variations in physiological parameters due to heating.

Temperature isolines at the end of the heating period (t = 2400s) are shown in Fig. 4. It can be seen that the increase in temperature is concentrated near the surface of the joint and that the internal muscle layers were only slightly affected by the heating procedure. This is expected for regions that are located far from the heat source.

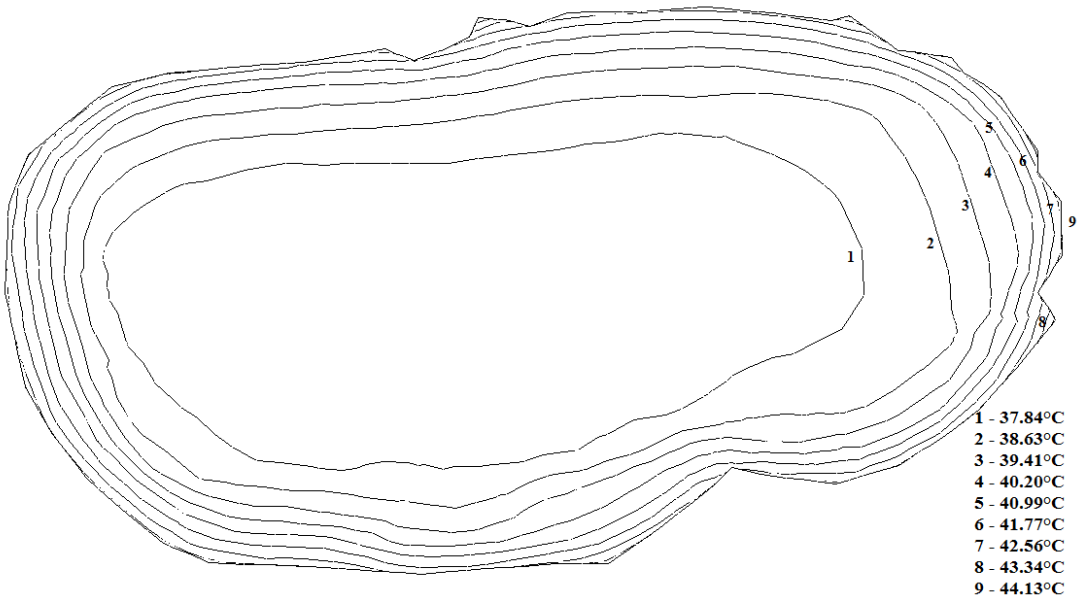


Figure 4. Temperature isolines after 2400s heating – simulation H3

2 – Therapeutic cooling

Table 3 displays the differences between experimental and calculated time-averaged values of the temperatures at each measurement point (see Fig. 2). A significant difference between experiments and simulation was observed when the average temperature of the external layer of the epidermis was assumed to be equal to the average value of the measured local temperature (simulation C2). The consideration of the temperature of the external layer of the epidermis being equivalent to the average temperature of the cooling device (simulation C1) provided a better description of the experimental data. In both simulations the calculated temperatures were higher than the experimental values. Variations of the temperatures at each measurement point as a function of time are displayed in Fig. 5, in reference to simulation C1.

Table 3. Differences between experimental and calculated values of the average temperature at each temperature measurement location during cooling.

	Average percent difference (%)	
Location	**Simulation C1**	**Simulation C2**
1-Subcutaneous tissue	3.1	18.5
2- Fat	4.1	16.7
3- Medial muscle	3.2	33.1
4- Lateral muscle	2.1	9.4
5-Pericapsular	3.5	18.7
6-Tibiofemoral region	5.0	8.8
7-Cruciate Ligaments	1.0	2.0
Average	3.1	15.3

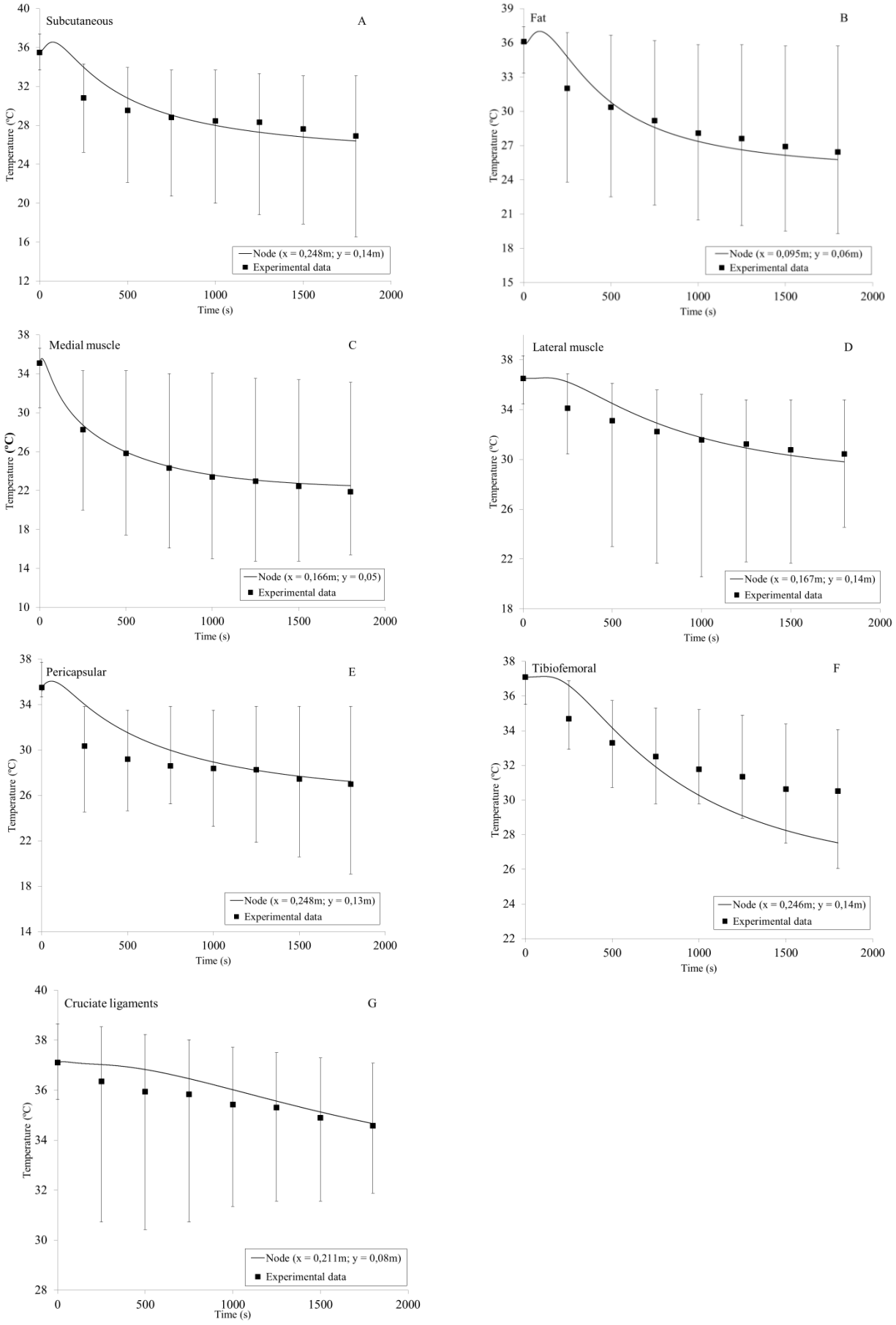


Figure 5. Variation of local tissue temperatures with time during heating: ■ experimental; —simulation C1.

An evaluation of the results presented in Fig. 5 shows that, in most of the temperature measurement locations, the largest differences between experimental and simulation results occur during the first 10 minutes of cooling. In all the measurement locations, except for the medial muscle, the simulated temperatures either remain constant (lateral muscle, tibiofemoral region and cruciate ligaments) or show a slight increase (subcutaneous, fat and pericapsular) at the beginning of cooling. This behavior was not expected, considering the proximity of the experimental measurement points to the surface (except the one corresponding to cruciate ligaments). According to the reviewed literature, the temperature of tissues close to the surface tend to decrease instantly as a response to criotherapy procedures (Palmer and Knight, 1996). However, according to Chaui-Berlinck *et al*. (2005), a small delay in the response of the tissue temperature to a thermal stimulus is characteristic of biological systems. Such behavior cannot be seen in the experimental curves because they correspond to average measurements performed in several animals. However, Araújo (2009) stated that some time delay, i.e., constant temperature during the beginning of the treatment, was observed for a few of the tested animals. Nonetheless, all the simulation results were within the experimental variations and the low values of average differences between experimental and simulation results presented in Table 3 indicate that simulation C1 provided a satisfactory description of the heat transfer phenomena.

Temperature isolines at the end of the cooling period (t = 1800s) are shown in Fig. 6, for simulation C1. It can be seen that the temperatures attained are above the recommended lower limit of 10°C (Low and Reed, 2001), except at the surface. However, given that the resistance to heat transfer between the cooling device and the epidermis was not taken into account, the actual temperature at the surface will be higher. It is noteworthy to mention that in a previous study (Silva *et al.,* 2011), one-dimensional simulations of the transient heat transfer taking place in the canine knee joint, resulting from the application of superficial thermotherapy were presented. Although that model was considered satisfactory for evaluation of the effect of superficial heating on the average temperature profiles, it did not perform well in the case of cooling. The two-dimensional simulations presented here were found to be satisfactory for both heating and cooling description.

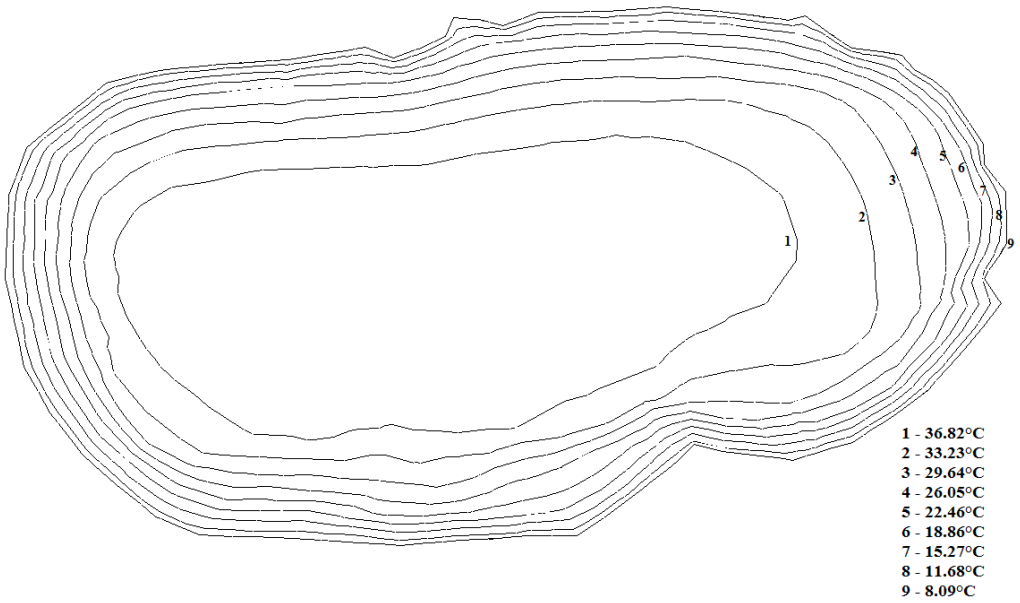


Figure 6. Temperature isolines after 1800s cooling – simulation C1

4. CONCLUSIONS

The results presented in this study showed that variations in tissue temperature arising from therapeutic heating and cooling of a canine joint can be satisfactorily predicted by a two-dimensional simulation of the transient bioheat transfer equation (Pennes Model). Among the evaluated boundary conditions, the consideration of heat flux at the external surface being equivalent to the average heat flux provided by the heating device was shown to be the most appropriate for simulation of therapeutic heating. In the case of cooling, the assumption that the external surface temperature was equivalent to that of the cooling device provided a satisfactory description of the experimental data. The results presented in this study confirm that simulations are an important step for non-invasive evaluation of thermal treatments.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding from CNPq.

6. REFERENCES

Amini, A.N., Ebbini, E.S. and Georgiou, T.T., 2005, "Noninvasive estimation of tissue temperature via high-resolution spectral analysis techniques". IEEE Transactions on Biomedical Engineering, Vol. 52, No. 2, pp. 221-228.

Araújo, A. R., 2009, "Formulação e validação de um modelo térmico para estimativa da temperatura intra-articular". Belo Horizonte, 166p. Tese – [Doutorado em engenharia mecânica]. Universidade Federal de Minas Gerais, Departamento de Engenharia Mecânica, UFMG.

Cameron, M.H., 2008, "Physical agents in rehabilitation: From research to practice". Ed. Saunders. 461 p.

Chaui-Berlinck, J.G., Navas, C.A., Monteiro, L.H. and Bicudo, J.E., 2005, "Control of metabolic rate is a hidden variable in the allometric scaling of homeotherms". The Journal of Experimental Biology, Vol. 208, pp. 1709-1716.

Cui, Z. F. and Barbenel, C. J., 1990, "The influence of model parameter values on the prediction of skin surface temperature: I. Resting and surface insulation". Physics in Medicine and Biology, Vol. 35, No.12, pp.1683-1697.

Cui, Z. F. and Barbenel, C. J., 1991, "The influence of model parameter values on the prediction of skin surface temperature: II. Contact problems". Physics in Medicine and Biology, Vol. 36, No.12, pp.1607-1620.

Draper, D.O., Knight, K., Fujiwara, T. And Castel, J.C., 1999, "Temperature change in human muscle during and after pulsed short-wave diathermy". Journal of Orthopaedic & Sports Physical Therapy, Vol. 29, No.1, pp. 13-22.

Greenstein, G., 2007, "Therapeutic efficacy of cold therapy after intraoral surgical procedures: a literature review". Journal of Periodontology, Vol. 78, No. 5, pp. 790-800.

Keller, K.H. and Seiler, L.J., 1971, "An analysis of peripheral heat transfer in man". Journal of Applied Physiology, Vol. 30, No. 5, pp. 779-786.

Kennet, J., Hardaker, N., Hobbs, S., and Selfe, J., 2007, "Cooling efficiency of 4 common cryotherapeutic agents". Journal of Athletic Training, Vol. 42, No.3, pp. 343-348.

Kitchen, S., 2003, "Eletroterapia: Prática baseada em evidências". Ed. Manole, São Paulo, Brasil, 339 p.

Lin, Y.H., 2003, "Effects of thermal therapy in improving the passive range of knee motion: comparison of cold and supercial heat applications." Clinical Rehabilitation, Vol.17, pp. 618-623.

Low, J. and Reed, A., 2001, "Eletroterapia explicada: princípios e prática". Ed. Manole, São Paulo, Brasil, 472 p.

Mekjavic, I.B and Eiken, O., 2006, "Contribution of thermal and nonthermal factors to the regulation of body temperature in humans". Journal of Applied Physiology, Vol. 100, No.6, pp. 2065-2072.

Nadler, A.F., Weingand, K. and Kruse, R.J., 2004, "The Physiologic Basis and Clinical Applications of Cryotherapy and Thermotherapy for the Pain Practitioner". Pain Physician, Vol. 7, pp. 395-399.

Palmer, J.E. and Knight, K.I., 1996, "Ankle and thigh skin surface temperature changes with repeated ice pack application". Journal Athletic Training, Vol. 31, pp. 319-323.

Pennes, H.H., 1948, "Analysis of tissue and arterial blood temperatures in the resting human forearm". Journal of Applied Physiology, Vol. 1, No. 2, pp. 93-122.

Robertson, V. J., Ward, A.R. and Jung, P., 2005, "The effect of heat on tissue extensibility: a comparison of deep and superficial heating". Archives of Physical Medicine & Rehabilitation, Vol. 86, pp. 819-825.

Shitzer, A. and Eberhart, R.C., 1985, "Heat transfer in medicine and biology. Analysis and applications". Ed. Plenum Press, New York, 435 p.

Silva, F.S.; Franca, A.S.; Pinotti, M. "One-dimensional simulation of heating and cooling of canine knee joints". Submitted for presentation at the 21st Brazilian Congress of Mechanical Engineering, 2011.

Trobec, R. Sterk, M., AlMawerd, S. and Veselko, M., 2008, "Computer simulation of topical knee cooling". Computers in Biology and Medicine, Vol. 38, pp. 1076-1083.

Vanhoutte, G. Verhoye, M. Raman, E., Roberts, M. and Van der Linden, A., 2002, "In vivo noninvasive study of the thermoregulatory function of the blood vessels in the rat tail using magnetic resonance angiography". NMR in Biomedicine, Vol. 15, pp. 263-269.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.