FORMULATION AND VALIDATION OF A MATEMATICAL MODEL FOR ESTIMATIVE INTRA-ARTICULAR TEMPERATURE: THE PASSIVE SYSTEM

Angélica Rodrigues de Araújo
Federal University of Minas Gerais. Av. Antônio Carlos, 6627 - Pampulha - 31.270-901 - Belo Horizonte / MG
angelica@bios.srv.br

Alexandre Gonçalves Teixeira
Bios Eletrônica e Informática. R. Castelo de Lisboa, 301C - Castelo - 31.330.340 - Belo Horizonte / MG
alexandre@bios.srv.br

Maria Elisa Jatobá Andrade
Federal University of Minas Gerais. Av. Antônio Carlos, 6627 - Pampulha - 31.270-901 - Belo Horizonte / MG
isajandrade@gmail.com

Rafael Resende Faleiros
Federal University of Minas Gerais. Av. Antônio Carlos, 6627 - Pampulha - 31.270-901 - Belo Horizonte / MG
faleiros@ufmg.br

Rudolf Huebner
Federal University of Minas Gerais. Av. Antônio Carlos, 6627 - Pampulha - 31.270-901 - Belo Horizonte / MG
rudolf@ufmg.br

Marcos Pinotti Barbosa
Federal University of Minas Gerais. Av. Antônio Carlos, 6627 - Pampulha - 31.270-901 - Belo Horizonte / MG
pinotti@ufmg.br

Abstract: *A mathematical model aimed at estimating canine knee intra-articular temperature under neutral thermal and transient conditions (articular heating and cooling) is being developed. This model will consist of two parts: one representing the passive system and the other representing the active system. The passive system will represent the heating exchange by conduction occurring between the devices used to heat and cool the knee and the impact of such exchanges on the layers of the joint, and will be used as support for the development of the active system. The active system will simulate the regulatory vasomotor and metabolic response of the joint under continuous and transient conditions. A pilot experiment was run during the first stage of the study so that the timing of the temperature behavior resulting from articular heating and cooling for the various areas of the canine knee could be determined. The methodology used in the pilot experiment and the results obtained with this study supported the experiment run with twenty canine knees distributed in two groups: heating (n = 10) and cooling (n = 10), aimed mainly at generating a database for future comparison between the behavior of the articular temperature in vivo and the behavior simulated by the mathematical model. This work presents the modelling of the passive system as analogous to the electrical system, considering the physiological characteristics and the physiothermal properties of the various tissues found in the canine knee. Computer models (PSpice; Simulink/Matlab)were used to solve the set of differential equations of the passive system while simulating the behavior of the articular temperature. The results of the simulation were compared to the data obtained experimentally and show that the passive model developed is suitable to represent the thermal exchanges which occur by conduction in canine knees.*

Keywords: *heat exchange, sinovial joint, passive system, mathematical modeling*

1. INTRODUCTION

The mathematical modeling of the thermal biological systems was first used around sixty years ago (Cooper, 2002). However, it was only in the past three decades that those models started considering the specificities and the individual physical and physiological characteristics of the various body tissues (Fiala *et al.*, 1999). One of the classical mathematical models of body thermal regulation was proposed by Stolwijk in 1971 (Stolwijk, 1971). Almost forty years later it is still considered a benchmark for the improvements and developments of new studies on the temperature control of biological systems (Gowrishankar *et al.*, 2004; Havenith, 2001; Fiala *et al.*, 2001), mainly in the areas of thermal comfort and diagnostic and therapeutic applications (Melodelina *et al.*, 2004; Telenkov *et al.*, 2004; Akkin *et al.*, 2003; Liu *et al.*, 1999).

However, specifically in the field of physiotherapy, research on heat exchange in living tissues is still rare, despite the wide application of therapeutic procedures with benefits and safety directly related to the magnitude of temperature variation (Chesterton *et al.*, 2002; Robertson *et al.*, 2005). As a result, the use of thermal treatment for physiotherapeutic rehabilitation is still devoid of any type of tissue temperature control. Analyses of the efficacy of thermotherapeutic and cryotherapeutic devices have been mainly developed by observation of the clinical findings obtained with the application of those devices (Swenson *et al.*, 1996; Draper *et al.*, 2004). Consequently, the risks of having unsatisfactory or damaging results are very high (Merrick *et al.*, 2003).

Traditionally, the modeling of heat transfer problems in living tissues has been made with the use of the classical Pennes' equation (Pennes, 1948), where the temperature variation rate in a given data is obtained from the difference between the amount of energy deposited in a certain volume and the amount of energy leaving that volume (Jiang *et al.*, 2002). In living organisms, the energy can be transferred by two main mechanisms: thermal conduction between adjacent tissue layers (Pikkula *et al.* 2003) and blood flow convection (Pardasani and Adlakha, 1995; Saidel *et al.*, 2001; Liu *et al.*, 2003). Heat removal is controlled 1) passively by the thermal characteristics and properties of the tissues and the capillary blood flow distribution, and 2) actively by mechanisms of physiothermal regulation (Fiala *et al.*, 1999; Fiala *et al.*, 2001). From the mathematical viewpoint, the biological systems can be represented by two distinct systems – passive and active – which jointly work to maintain the core temperature stable, free from external variations. The passive system represents the physical and models the heat transfer phenomena occurring internally (between the tissues) and on the outer surface of the body (between the skin and the external environment). The active system represents and reproduces the thermal regulation actions of the central nervous system which occur in response to the various forms of internal and external thermal stimuli (Winton and Linebarger, 1971; Fiala *et al.,* 1999; Fiala *et al.*, 2001).

This work presents a model of the canine knee passive system prepared by analogy with the electrical system, considering the physiological characteristics and the thermophysical properties of the various tissues and structures of the sinovial joint. The methodology and results of a pilot study completed during the first stage of this work (Araújo *et al.*, 2006) supported an *in vivo* experiment aimed at producing a database for further comparison between the behavior of the intra-articular temperature *in vivo* and the temperature simulated by the analogous electrical circuit model.

According to the literature, this type of model can be used to represent the transfer of heat which occurs by conduction and convection within both linear and non-linear systems. As the temperature behavior of such systems depends on perfusion variations in time and space, this type of model is largely used for the study of biology systems dynamics (Gowrishankar *et al.*, 2004). The literature registers the good correlation existing between the electrical system analogue modeling of thermal biological phenomena and the geometrical reality and spatial heterogeneity of heat transportation mechanisms within the cardiovascular, pulmonary, intestinal, urinary and thermal regulation systems (Reddy, 2003). The passive system model was used to represent the heat exchange by conduction between thermal devices and the cutaneous surface of the knee, and the impact of such exchanges on the temperature behavior of the core layers of the joint, as well as heat exchanges by conduction and convection occurring between the various layers of the knee. The results of the model simulation were compared to the experimental data during the heating and cooling procedures of canine knee.

2. MATERIALS AND METHODS

2.1. *In vivo* experiment

The study involved ten adult dogs (8 male and 2 female) from the Zoonosis Control Center of the Belo Horizonte Municipal Government/MG, healthy, with body mass reaching 25,1 ± 4,2 kg. The knees (n = 20) of the dogs selected were subjected to a single thermal treatment aimed at heating (n = 10) or cooling (n = 10) the joint. The thermotherapeutic and cryotherapeutic devices were first applied on the right knee with a minimum period of seven days between the applications. The experimental protocol used in the study was approved by the Animal Experimentation Ethics Committee (CETEA) of the Federal University of Minas Gerais (UFMG) (protocol 127/05) and processed in compliance with the ethical principles of the Brazilian College of Animal Experimentation (Cobea, 2001).

Flexible Teflon® isolated K-type thermopars (0,25 mm diameter, SALCAS) previously calibrated were used to measure the temperature. The thermopars were sterilized by incubation at 160°C during two hours and aseptically positioned on three external locations of the cutaneous surface of the knee (one before the joint, in the area of the knee cap, and two in the area of the joint interline, placed in the center and laterally); four placed internally: one in the subcutaneous region (subcutaneous tissue and dermis); one in the pericapsular area (interface of the subcutaneous tissue and the intra-articular cavity), and two in the intra-articular cavity (one in the front tibial-femural area and one in the cruciate ligaments area), where the temperature was to be monitored. To measure the body temperature, one thermopar was attached to the rectal mucosa.

Thermotherapeutic and cryotherapeutic devices were applied on canine knees in compliance with the recommendations of the Australian Physiotherapy Association (APA) (Robertson *et al.*, 2001). For both procedures the dogs were decubitus lateral position, with the limb receiving the thermal treatment kept elevated (30° abduction), so as to avoid interference during the thermal exchange due to contact between the physical device and the opposing limb. A 0,5 m x 0,29 m Biothermic, Bioset sectorial thermotherapy thermal pad with automatic temperature control between de 40°C a 66°C was programmed for 66°C and used as heating source. The pad covering the whole area of the knee was kept in place during 40 minutes and position. A protective gauze band kept the pad from directly contacting the cutaneous surface of the knee. The cooling of the knee was made with two frozen gauze compresses placed on the medial and lateral areas of cutaneous surface and covering the whole area of the joint during 30 minutes. Each compress was prepared with 1,0 kg of hand crushed ice wrapped in a previously wet towel [dry mass = 0,8 kg]. Gauze bands were used to secure the compresses and maintain the proper contact between the cryotherapeutic device and the articular surface. The thermal isolation of the system was made with the help of three dry towels placed over the ice compresses covering the whole set. During the articular heating and cooling process, the temperature of the Biothermic pad and the ice compresses was also monitored with K-type thermopars placed as follows: four on the thermal pad and two on each one of the ice compresses (one inside and one on the outer surface).

One duly calibrated data acquisition unit (NA4018-8, resolution 0,1°C, analogic) was used for collection and storage of the temperature values of the animals and thermal devices. The collection started ten minutes after positioning and fixing the thermopars in their respective locations and continued along the whole period of application of the thermal devices. The temperature values were recorded every one second in each channel. The thermal devices were applied ten minutes after the data collection started and the information obtained in the first ten minutes were used to determine the temperature values of the permanent system (thermal neutrality). By the end of the experimental period, the data collected were transferred to a Pentium Satellite® M45-S355, TOSHIBA computer for processing and further analysis.

Descriptive measures of central tendency and dispersion were used as support to the temperature behavior analysis under thermal and transient neutrality conditions. The paired *t*, Minimum Meaningful Difference, Leven, Games Howel, ANOVA and Kruskal-Wallis ANOVA tests were used to compare the parameters of two or more data groups. The Kolmogorov-Smirnov test was applied to confirm data normality. For all tests, *p*-value higher than the level of significance $\alpha = 5\%$ indicated that the null hypothesis of the test should not be rejected.

2.2. Construction of the model

The passive system model of the canine knee was developed with the support of information obtained from the literature and the experimental data collected *in vivo*. The model was prepared to represent the knees of adult dogs of medium built with body mass around 25,1 ± 4,2 kg optimal body conditions (Laflamme, 2005), subjected to transient and thermal neutrality conditions (articular heating and cooling).

For the purposes of model construction, the knee was geometrically represented by a single $H = 0{,}10$ m high cylinder, radius $r = 0{,}043$ m and volume $v = 5{,}81 \times 10^{-4} m^3$, consisting of four concentric annular layers, each one representing one area of the joint: epidermis, subcutaneuous (dermis and subcutaneous tissue), intra-articular cavity (capsule, meniscus, ligaments and sinovial liquid) and core (Fig. 1). The cylinder radius r and the volume v were estimated from the values of the articular circumference, obtained directly from the measures performed *in vivo* on twenty canine knees. The measures were performed in four spots of cutaneous surface of the joint (upper and lower edges of the patella and three cm above and below these edges) with the use of a measuring tape, and the average [(0,27 ± 0,03) m] was considered for calculation of the radius and total volume of the cylinder.

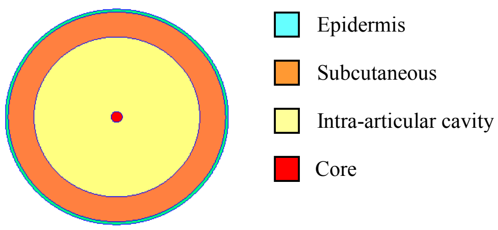

Figure 1. Schematic diagram of the passive system.

The number of layers of the model was determined by the similarities and differences observed between the physiological (blood perfusion and metabolic rate) and the thermophysical (density, thermal conductivity and specific heat) properties of the structures of the canine knee (Weinbaum *et al.*, 1984; Fiala *et al.*, 1999; Ferreira and Yanagihara, 1999). This information, as well as the data concerning the thickness of the tissues (except the thickness of the central layer and intra-articular cavity) were obtained in the literature (Fiala *et al.*, 1999; Torvi and Dale, 1994; Cui and Barbenel, 1990; Hodson *et al.*, 1989; Wilson and Spence, 1988; Tanasawa and Katsuda, 1972; Sejrsen, 1971 Mitchell *et al.*, 1970; Vendrick and Voss, 1957; Lipkin and Hardy, 1954; Henriques and Moritz, 1947), and the value average found for each area was used in the construction of the model.

The thickness of the core was defined to be identical to the radius of the innermost structure of the joint, that is, the bone, and estimated from the measurement performed in transverse anatomic cuts of a canine knee displaying physical characteristics similar to the knees used for *in vivo* data collection. The thickness of the intra-articular cavity was determined considering the cylinder radius and the thickness of the remaining layers of the model. Table 1 sums up all the information about the geometric characteristics and the thermal and physiological properties considered for the development of the passive model of the canine knee.

Table 1. Geometrical parameters and thermophysical and basal physiological properties for the layers of the passive system model of the canine knee.

Parameters	Epidermis (*ep*)	Subcutaneous (*sr*)	Intrarticular cavity (*ia*)	Core
Thickness (l)	0,2 x10^{-3} m	0,7 x10^{-2} m	2,1 x10^{-2} m	1,5 x10^{-3} m
Volume (v)	0,5 x 10^{-5} m^3	1,75 x $10^{-4}$$m^3$	4,02 x $10^{-4}$$m^3$	1 x $10^{-6}$$m^3$
Thermal conductivity (K)	2,4 x 10^{-1} Wm^{-1}°C^{-1}	0,35 Wm^{-1}°C^{-1}	0,63 Wm^{-1}°C^{-1}	_
Density (ρ)	1200 kgm^{-3}	1100 kgm^{-3}	1000 kgm^{-3}	_
Specific heat (c_p)	3589,3 Jkg^{-1}°C^{-1}	3103,3 Jkg^{-1}°C^{-1}	4000 Jkg^{-1}°C^{-1}	_
Perfusion rate (ω)	0 $m^3s^{-1}m^{-3}$ tecido	1,25 x 10^{-3} $m^3s^{-1}m^{-3}$ tecido	0 $m^3s^{-1}m^{-3}$ tecido	_
Metabolism rate (Q)	0 Wm^{-3}	200 Wm^{-3}	0 Wm^{-3}	_

For the passive model of thermal energy transport in the canine knee, the thermal properties and the physiological characteristics of the joint were represented as an electrical circuit analogue, as the one shown in Fig. 2. The electrical and thermal systems are governed by identical differential equations with a mathematical model prepared according to the Kirchhoff Laws (Wellstead, 1979; Vladimirescu, 1994). From the analogy between those two systems it is possible to identify an equivalence relation between the flow (electric current i) and effort (tension V) variables and the dissipative components (resistors R) and cumulative components (capacitors C) of those systems.

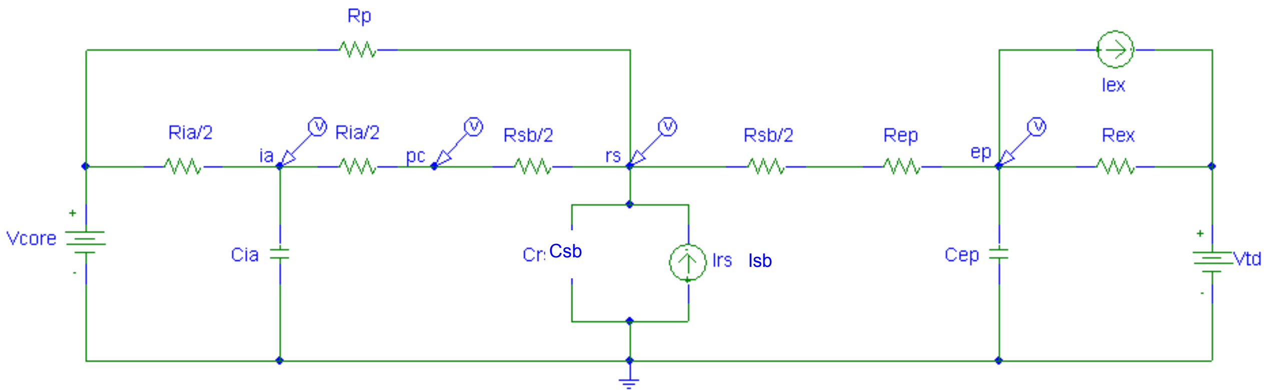

Figure 2. Eletric circuit analog representative of the thermal properties of layers of the canine knee.

For the specific case of the canine knee, the capacitors C_{ia}, C_{sb} and C_{ep} represent the thermal capacitance (J°C^{-1}) of the intra-articular cavity, subcutaneous and the epidermis. The tension V at the points *ia, pc, sb* and *ep* corresponds to the temperature of the intra-articular cavity (T_{ia}), pericapsular (T_{pc}), subcutaneous (T_{sb}) and the epidermis (T_{ep}). The heat flow q between the layers will occur by conduction through the resistors R_{ia}, R_{sb}, R_{ep} and by convection through the resistor R_p and are related to the temperature difference between the layers, the thermal conductance and capacitance of the tissues. The flow sources I_{sb} and I_{ex} represent, respectively, the heat generated by the metabolim of the subcutaneous – where $I_{sb} = Q.v$ – and the heat exchanges between the cutaneous surface of the knee and the environment; the sources of effort V_{core} and V_{td} represent the temperatures of the core (T_{core}), given by the average rectal temperature of the dogs, and the thermal devices used to heat (T_{heat}) and cool (T_{cool}) the knees, respectively. The values of the conductive (R_{ia}, R_{sb}, R_{ep}) and convective (R_p) resistance and of the thermal capacitance C_{ia}, C_{sb} and C_{ep} were calculated using the equations (1), (2) and (3) respectively, as shown in Table 2.

$$R = ln(r_e/r_i)\cdot(2\cdot\pi\cdot k\cdot l)^{-1} \tag{1}$$

$$Rp = \rho_b\cdot c_b\cdot\omega\cdot v \tag{2}$$

$$C = \rho \cdot c_p \cdot v \tag{3}$$

where r_e and r_i are the radius external and internal of the layers; l and v are the length (m) and the volume (m^3) of the cylinder; K, ρ, c_p e ω represent the thermal conductivity ($Wm^{-1o}C^{-1}$), the density (kgm^{-3}), the specific heat ($Jkg^{-1o}C^{-1}$) and the rate perfusion ($m^3s^{-1}m^{-3}$ tecido) of the layer; ρ_b and c_b represent the thermal conductivity ($Wm^{-1o}C^{-1}$) and the density (kgm^{-3}) of the blood, respectively.

Table 2. Resistence (conductive and convective) and thermal capacitance for the layers of the passive system model of the canine knee.

Parameter	Epidermis (ep)	Subcutaneous (sb)	Intra-articular cavity (ia)
Conductive resistance (R)	$3{,}1 \times 10^{-2}$ $^oCW^{-1}$	$8{,}1 \times 10^{-1}$ $^oCW^{-1}$	2,2 $^oCW^{-1}$
Convective resistance (R_p)	0^oCW^{-1}	$7{,}4 \times 10^{-1}$ $^oCW^{-1}$	0^oCW^{-1}
Thermal capacitance (C)	23,2 J^oC^{-1}	590,1 J^oC^{-1}	1335,8 J^oC^{-1}

The nodal analysis technique was used for resolution of the electrical circuit analogue, and the mathematical model of the thermal energy transport of the canine knee passive system, consisting of the differential equations, was simulated by the PSpice and Simulink/MATLAB® v 6.5.1 programs. For the simulations and analyses, the following conditions were considered:

1. temperature constant in the central layer of the model, independent of external conditions, while in the other layers, mainly in the epidermis, the temperature varies over time in response to different internal and external thermal stimuli.
2. spatial distribution of the temperature, generation of heat due to metabolic reactions and blood perfusion uniforme and constants in all the layers of the model.
3. heat flow by conduction only in the radial direction.
4. heat exchange between the model and the environment in the situation of thermal neutrality (room temperature between 18°C and 25°C and relative air humidity between 40% and 60%) only by free convection and radiation; the exchanges by evaporation being disregarded. The heat transferred by convection (q_{cv}) is proportional to the difference between the temperature of the epidermis and (T_{ep}) and room temperature (T_{rt}) (Eq. 4) (Ferreira and Yanagihara, 1999):

$$q_c = h_c \cdot A \cdot (T_{sk} - T_{rt}) \tag{4}$$

where h_c is the convection coefficient and A the surface area of the cylinder. For the calculation of h_c was used the correlation presented in Colin and Houdas (1967) (Eq. 5) and the speed air (v_{air}) was assumed equal to zero.

$$h_c = 2{,}7 + 6{,}5 \cdot v_{air}^{\;0{,}67} \tag{5}$$

To calculate the heat transferred by radiation (q_r) have assumed that the knee behaves itself as a gray area of emissivity $\varepsilon = 0{,}95$ and used the law of Stefan-Boltzmann (Eq. 6):

$$q_r = \varepsilon \cdot \sigma \cdot f \cdot A \cdot (T_{ep}^{\;4} - T_{rt}^{\;4}) \tag{6}$$

where $\sigma = 5{,}67 \times 10^{-8}$ $Wm^{-2o}C^{-4}$ is the Stefan-Boltzmann constant; $f = 0{,}90$ represents the ratio between the effective radiating area and the area externa of the knee (Fiala *et al.*, 2001).

5. heat exchange between the model and the thermal devices in the transient conditions only by convection only. In this case, a $0{,}5 \times 10^{-3}$m layer of air was added to the model to represent the thermal resistance existing between the cutaneous surface of the knee and the thermal devices. Equation 1 was used to calculate the resistance value of this layer ($R_{ex} = 0{,}7^oCW^{-1}$). For this calculation, the thermal conductivity of the air was considered equal to $2{,}63 \times 10^{-2}$ $Wm^{-1o}C^{-1}$.

For the simulations of the transient conditions, the model used the temperature values determined experimentally under thermal neutrality, and the temperature of the thermal devices was taken as external stimulus.

The adequacy of the passive system model of the knee for the representation of the data collected experimentally was determined under transient and thermal neutrality conditions (heating and cooling) by analisys of the curves temperature T (°C) along the time (s). The coefficients of determination (r^2) and correlation (r) and the standard error of the estimate were also determined to check the level of adjustment of the curves to the experimental data.

3. RESULTS AND DISCUSSION

3.1. *In vivo* experiment

To establish the profile of the temperature, the adoption of stable environmental experimental conditions and within the thermal neutrality zone it is important due to the large amount and complexity of factors influencing the temperature field of the tissues (Ferreira and Yanagihara, 1999). Within the thermal neutrality zone the generation of heat by tissue metabolism is lower and the central temperature of the animal tends to remain stable, without need for activation mechanisms of thermoregulation, which could impact the behavior of canine rectal and knee temperature. In this study, the temperature and relative air humidity was kept between $(24{,}7 \pm 0{,}4)^oC$ and $(53{,}6 \pm 0{,}21)\%$, respectively, all along the experiment. These values were considered adequate for the study of canine temperature behavior and used as reference for the simulations under thermal neutrality. Under those conditions, the differences observed between the temperature averages within one specific area were below $0{,}5^oC$ and did not reach limits of statistical significance.

Table 3 sums up the experimental data collected in the canine rectal and knee under thermal neutrality (articular pre-heating and pre-cooling) and transient (final stage of articular heating and cooling) conditions. The variability test between averages showed that, for the thermal neutrality condition, the temperatures of the regions evaluated were statistically different, and no statistically significant differences were present when the temperature averages of the various areas of the epidermis and the intra-articular cavity were compared. Because of that, the average temperature of the epidermis T_{ep} $[(34{,}8 \pm 1{,}5)^oC]$ and of the intra-articular cavity T_{ia} $[(36{,}8 \pm 0{,}9)^oC]$ were considered in the analysis and simulations of the passive model.

These results were in agreement with the literature which states that the temperature is not the same and will not be kept in different tissues of the body. In the most central tissues, represented in this study by the pericapsular and intra-articular cavity, the temperature is higher and more controlled while in the more superficial layers, the epidermis and the subcutaneous area it is lower and broadly varied, responding to the external conditions (Pardasani and Adlakha, 1995; Mainardi *et al.*, 1979; Hollander *et al.*, 1951).

Table 3. Mean and standard deviation of the rectal and the canine knee temperatures for thermal neutrality and transient (heating and cooling).

Condition	Region / Temperature (^oC)							
	Rectal	Epidermis			Subcutaneous	Pericapsular	Intra-articular cavity	
		Lateral region	Medial region	Anterior region			Femur-tibial	Cruciate ligament
Thermal neutrality	36,6±4,0	34,9±1,4	35,0±1,7	35,0±1,3	35,7±0,8	35,2±0,9	36,7±1,7	36,8±1,1
Heating(1)	37,0±4,7	40,0±0,7	40,8±0,6	40,9±0,7	39,2±0,9	39,1±1,0	38,8±0,5	38,3±0,6
Cooling(1)	37,4±0,8	25,8±4,3	25,4±5,0	26,8±4,7	27,1±5,4	27,1±4,5	30,6±2,7	34,7±1,1

(1): Mean and standart deviation of temperature of the last 60 s of heating and cooling of the knee.

The thermal pad [temperature $T_{heat} = (59{,}2 \pm 12{,}8)^oC$] and the ice compresses [temperature $T_{cool} = (8{,}9 \pm 3{,}3)^oC$] used for the heating and cooling respectively the canine knees were effective to produce statistically significant increase and reduction of the temperature in all regions evaluated, except in the rectal, where the variation observed was not statistically significant. Those findings comply with most of the works about thermotherapy and cryotherapy, which state that the effects of those devices – increase (Weinberger *et al.*, 1989; Draper *et al.*, 2004) or reduction (Dahlstedt *et al.*, 1996; Chesterton *et al.*, 2002) of tissue temperature in response to heating and cooling by conduction from the cutaneous surface – are restricted to the area where the thermal device is applied (Meeusen and Lievens, 1986; Halvorson, 1990).

3.2. Canine knee temperature behavior: experimental data x mathematical simulation

It is possible to observe in Figure 3 the behavior of the temperature T (^oC) along the time (s) for each of the tissue layers of the canine knee, under thermal neutrality [$T = (24{,}7 \pm 0{,}4)^oC$; air humidity $= (53{,}6 \pm 0{,}21)\%$]. The curves obtained from the experimental data indicated that the temperature of the epidermis, subcutaneous, pericapsular and and intra-articular cavity were stable all along the period previous to the use of the thermal devices, as expected. In the simulation of the model, the thermal stability temperature of each of those layers was different from that obtained experimentally, thus indicating that the model is not able to stabilize with the same values of the condition *in vivo*. The variability observed between the curves obtained experimentally and by simulation may have resulted from the uncertainties involved in the determination of the physiological and thermophysical parameters used in the elaboration of the model (Cui and Barbenel, 1990; Werner and Buse, 1988) considering that in the literature those parameters present great variation and the building of the model accounted for the average of the values obtained. Table 4 show the coefficients of determination (r^2) and correlation (r), as well as the standard error of the estimate for the curves obtained by the simulation of the model for each layer of the canine knee.

Table 4. Coefficients of determination (r^2) and correlation (r) and standad error of estimative for the passive system model curves for the canine knee: thermal neutrality.

Region	Coefficient of determination (r^2)	Coefficient of correlation (r)	Standard error
Epidermis	0,145	0,381	0,004
Subcutaneous	0,843	0,918	0,002
Pericapsular	0,452	0,672	0,002
Intra-articular cavity	0,601	0,775	0,002

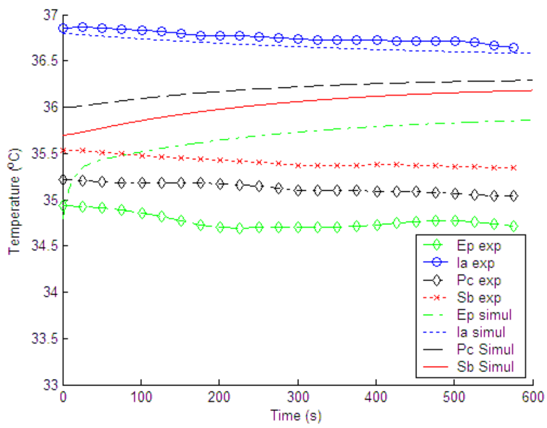

Figure 3. Temperatures of the canine knee for thermal neutrality [T = (24,7 ± 0,4)ºC; relative humity = (53,6 ± 0,21)%]. (Ep = epidermis; Ia = intra-articular cavity; Pc = pericapsular region; Sb = subcutaneous region; exp = experimental; simul = simulation)

Figures 4 to 7 show the temperature curves *T* (ºC) in function of the time (s), obtained from the data collected experimentally and simulation with the electrical circuit analogue under the articular heating and cooling conditions. The experimental data curves show that in all layers of the tissue the temperature displays exponential behavior in time and tends to reach a balance state by the end of the experiment. This behavior was observed in the curves resulting from the simulations as well and has been acknowledged by other authors who investigated the relations between the temperature of biological systems and the time (Liu *et al.*, 1999; Saidel *et al.*, 2001; Deng and Liu, 2002; Liu *et al.*, 2003). The curves resulting from the simulation showed proper adjustment to the experimental curves, with high values for the coefficients of determination and correlation, and low standard error for the estimate (Table 5).

Table 5. Coefficients of determination (r^2) and correlation (r) and standad error of estimative for the passive system model curves for the layers canine knee: transient (heating and cooling).

Region	Coefficients of determination (r^2)		Coefficients of correlation (r)		Standad error	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
Epidermis	0,812	0,878	0,901	0,937	0,541	0,510
Subcutaneous	0,894	0,962	0,945	0,981	0,559	0,336
Pericapsular	0,933	0,976	0,966	0,988	0,382	0,227
Intra-articular cavity	0,995	0,970	0,997	0,985	0,068	0,153

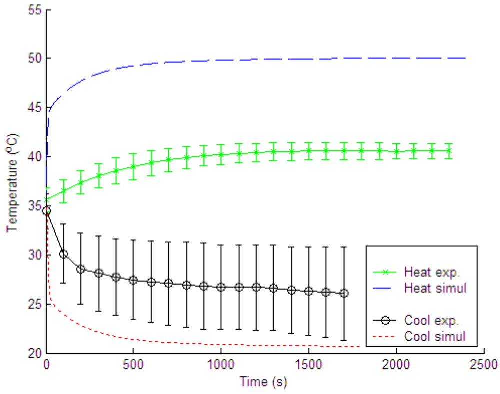

Figure 4. Temperature of the epidermis under the articular heating [T_{heat} = (59,2±12,8)^{o}C] and cooling [T_{cool} = (8,9±3,3)^{o}C] conditions. (exp = experimental; simul = simulation)

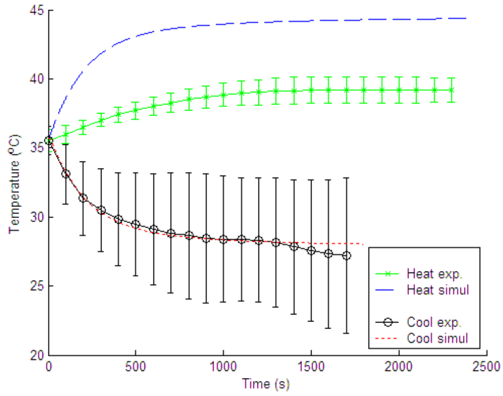

Figure 5. Temperature of the subcutaneous region under the articular heating [T_{heat} = (59,2±12,8)^{o}C] and cooling [T_{cool} = (8,9±3,3)^{o}C] conditions. (exp = experimental; simul = simulation)

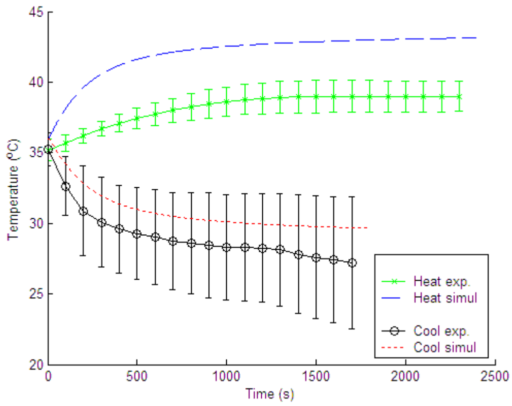

Figure 6. Temperature of the pericapsular region under the articular heating [T_{heat} = (59,2±12,8)^{o}C] and cooling [T_{cool} = (8,9±3,3)^{o}C] conditions. (exp = experimental; simul = simulation)

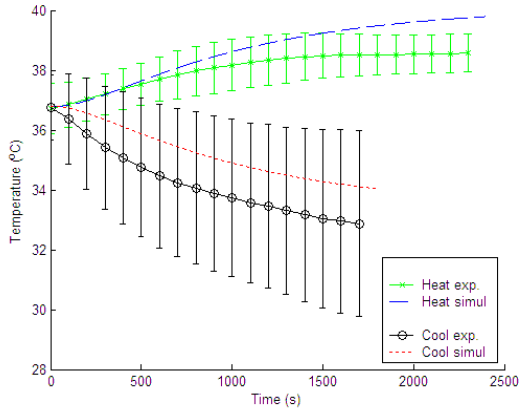

Figure 7. Temperature of the intra-articular cavity under the articular heating [T_{heat} = (59,2±12,8)^{o}C] and cooling [T_{cool} = (8,9±3,3)^{o}C] conditions. (exp = experimental; simul = simulation)

The thermal balance of the knee results from the interaction between the passive and active controls applied to each of the joint elements. The results of this study suggest that the pattern of temperature distribution in the epidermis, subcutaneous, pericapsular and intra-articular cavity is strongly affected by the vascular organization and blood flow distribution across the layers, under thermal neutrality but mainly during the heating and cooling processes. While the passive system does not cover the thermal regulation actions of the body, the variation observed between the curves obtained experimentally and the simulation may have been a consequence of the vasomotor reactions induced by the heating and cooling of the knee and their impact on the thermophysical properties of each joint layer.

The passive model proposed in this study highlights the importance of the thermoregulation system of the body for the temperature control of the tissues and the complexity of this phenomenon. The comparisons made with the data collected experimentally indicated that the model developed was suitable to adequately anticipate the temperatures of the internal layers of the canine knee under thermal neutrality and transient conditions. Therefore, this model provides a support for the active system to operate. Together, those systems can offer a more realistic anticipation of the canine knee temperature condition, particularly under heating and cooling conditions. The development and validation of the complete system is currently the subject of an ongoing work.

3. CONCLUSION

Considering the physiological characteristics and thermophysical properties of the various structures and tissues of the sinovial joint, the passive system modeling of canine knee, developed by analogy with the electrical system, proved suitable to anticipate the temperature behavior of the peripheral and core layers of the knee.

4. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from CNPq and CAPES.

5. REFERENCES

Akkin, T. *et al*., 2003, "Imaging tissue response to electrical and photothermal stimulation with nanometer sensitivity. Lasers in Surgery and Medicine", V. 33, pp. 219-225.

Altman, P. L., 1972, "Biology data book", 2d ed. Bethesda: Federation of American Societies for Experimental Biology, 2132 p.

Araújo, A. R. *et al.*, 2006, "Heat transfer in synovial joints during process of the heating articular: a study pilot", In: 11th Brazilian Congress of Thermal Sciences and Engineering, ENCIT 2006, Curitiba, Proceeding of the Congress of Thermal Sciences and Engineering, Braz. Soc. of Mechanical Sciences and Engineering, ABCM, Dec. 5-8, paper CIT06-0916.

Chesterton, L. S. *et al.*, 2002, "Skin temperature response to cryotherapy", Archives of Physical Medicine & Rehabilitation, V. 83, pp. 543-549.

Colégio Brasileiro de Experimentação Animal (COBEA), 1991, "Princípios éticos na experimentação animal", São Paulo: COBEA.

Cooper, K. E., 2002, "Molecular biology of thermoregulation. Some historical perspectives on thermorregulation", Journal Appl. Physiol, V. 92, pp. 1717-1724.

Colin, J.; Houdas, Y.; 1967, "Experimental determination of coefficient of heat exchanges by convection of human body", Journal Appl. Physiol, V. 22, pp. 31-38.

Cui, Z. F.; Barbenel, J. C., 1990, "The influence of model parameter values on the prediction of skin surface temperature: I. Resting and surface insulation", Phys. Med. Biol., V. 35, pp. 1683-1697.

Dahlstedt, L. *et al.*, 1996, "Cryotherapy after cruciate knee surgery", Acta Orthopaedica Scandinavica, V. 67, n. 3, pp. 255-257.

Deng, Z. S; Liu, J., 2002, "Analytical study on bioheat transfer problemas with spatial or transiente heating on skin surface or inside biological bodies", Journal of Biomechanical Engineering, V. 124, pp. 638-649.

Draper, D. O. *et al*., 2004, "Shortware diathermy and prolonged stretching increase hamstring flexibility more than prolonged stretching alone", Journal of Orthopaedic & Sports Physical Therapy, V. 34, n. 1, pp. 13-20.

Ferreira, M. S.; Yanagihara, J. I., 1999, "Um modelo do sistema termorregulador do corpo humano: exposição a ambientes quentes", Revista Brasileira de Engenharia Biomédica, V. 15, n. 1-2, pp. 87-96.

Fiala, D. *et al*., 1999, "A computer model of human thermoregulation for a wide range of environmental conditions: the passive system", Journal of Applied Physiology, V. 87, pp. 1957-1972.

Fiala, D. *et al*. 2001, "Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions", Int. Journal Biometeorol, V. 45, pp. 143-159.

Gowrishankar, T. R. *et al*., 2004, "Transport lattice models of heat transport in skin with spatially heterogeneous temperature-dependent perfusion", BioMedical Engineering OnLine, V. 3, n. 42. pp. 1-17. Download from: <www.biomedical-engineering-online.com/content/3/1/42>.

Halvorson, G. A., 1990, "Therapeutic heat and cold for athletic injuries", The Physician and Sports Medicine, V. 18, n. 5, pp. 87-92.

Havenith, G., 2001, "Individualized model of human thermoregulation for the simulation of heat stress response", Journal of Applied Physiology, V.90, pp.1943-1954.

Henriques, F. C.; Moritz, A R., 1947, "Studies of thermal injury, I. The conduction of heat to and through skin and the temperatures attained therein. A theorical and an experimental investigation" Amer. J. Pathol., V. 23, pp. 531-549.

Hilburn J. L. *et al.*, 1994, "Fundamentos de Análise de Circuitos Elétricos", 4.ed., Rio de Janeiro: LTC.

Hodson, D. A. *et al.*, 1989, "Modelling transient heat transfer through the skin and a contact material", Phys. Med. Biol., V. 34, pp. 1493-1507.

Hollander, J. L. *et al*., 1951, "Joint temperature measurement in the evaluation of anti-arthritic agents", Journal of Clinical Investigation, V. 30, n. 7, pp. 701-706.

Irwin, J. D., 2000, "Análise de Circuitos em Engenharia", 4.ed. São Paulo: Makron Books.

Jiang, S. C. *et al*., 2002, "Effects os thermal properties and geometrical dimensions on skin burn injuries", Burns, V. 28, pp. 713-717.

Kaminski, W., 1990, "Hyperbolic heat conduction equation for material with a nonhomogeneous inner structure", ASME Journal of Heat Trannsfer, V. 112, pp. 555-560.

Laflamme, D., 2005, "Nutrition for aging cats and dogs and the importance of body condition", Veterinary Clinics of North America: small snimal practice, V. 35 , n. 3, pp. 713-742.

Lipkin, M; Hardy, J.D., 1954, "Measurement of some thermal properties of human tissues" J. Appl. Physiol., V. 7, pp. 212-217.

Liu *et al*., 2003, "Model analysis of tissue responses to transient and chronic heating", Annals of Biomedical Engineering, V. 31, pp. 1007-1014.

Liu, J. *et al.*, 1999, "New thermal wave aspects on burn evaluation of skin subjected to instantaneous heating" IEEE Transactions on Biomedical Engineering, V. 46, n. 4, pp. 420-428.

Mainardi, C. L. *et al*., 1979, "Rheumatoid arthritis: failure of daily heat therapy to affect its progression", Archives of Physical Medicine and Rehabilitation, V. 60, pp. 390-392.

Meeusen, R.; Lievens, P., 1986, "The use of cryotherapy in sports injuries", Sports Medicine, V. 3, pp. 398-414.

Melodelima, D. *et al*., 2004, "Intraluminal ultrasound applicator compatible with magnetic resonance imaging *real-time* temperature mapping for the treatment of oesophageal tumours: an ex vivo study", Medical Physics, V. 31, n. 2, pp. 236-244.

Merrick, M. A. *et al*., 2003, "Identical 3-Mhz ultrasound treatments with different devices produce different intramuscular temperatures", Journal of Orthopeadic and Sports Physical Therapy, V. 33, n. 7, pp. 379-385.

Mitchell, J. W. *et al.*, 1970, "Thermal response of human legs during cooling", J. Appl. Physiol., V. 29, n 6, pp. 859-865.

Pardasani, K. R.; Adlakha, N., 1995, "Coaxial circular sector elements to study two dimensional heat distribuition problem in dermal regions of humam limbs", Mathematical and Computer Modelling, V. 22, n. 9, pp. 127-140.

Pennes, H. H., 1948, "Analysis of tissue and arterial blood temperatures in the resting human forearm" Journal of Applied Physiology, V. 1, n. 2, pp. 93-122.

Pikkula *et al*., 2003, "Methodology for characterizing heat removal mechanism in human skin during cryogen spray cooling", Annals of Biomedical Engineering, V. 31, pp. 493-504.

Reddy, N.P., 2003, "Modeling and simulation of biomedical systems - chapter 1", in Standard handbook of biomedical engineering & design. Editor Myer Kutz, McGraw Hill, N.Y., pp. 1.1-1.25, <www.digitalengineeringlibrary.com>.

Robertson, V. J. *et al*., 2001, "Guidelines for the clinical use of electrophysical agents", Australian Physiotherapy Association, pp. 1-21, <http://apa.advsol.com.au/static content/staticpages/guidelines/epags.pdf>.

Robertson, V. J. *et al*., 2005, "The effect of heat on tissue extensibility: a comparison of deep and superficial heating", Archives of Physical Medicine & Rehabilitation, V. 86, pp. 819-825.

Saidel, G. M. *et al*., 2001, "Temperature and perfusion responses of muscle and lung tissue during chronic heating *in vivo*", Medical and Biological Engineering and Computing, V. 39, pp. 126-133.

Sejrsen, P., 1971, "Measurement of cutaneous blood flow by freely-diffusible radioactive isotopes", Thesis, Copenhagen, Dan Med Bull (Suppl), V. 18, pp. 9–38.

Stolwijk, J. A. J., 1971, "A mathematical model of physiological temperature regulation in man". NASA contractor report CR-1855, NASA, Washington DC.

Swenson, C. *et al*., 1996, "Cryotherapy in sports medicine", Scandinavian Journal of Medicine and Science in Sports, V. 6, pp. 193-200.

Tanasawa, I.; Katsuda, T., 1972, "Measurement of thermophysical properties of biological system – part I", Seisan Kenkyu, V.24, pp. 404-406.

Telenkov, S. A. *et al*., 2004, "Differential phase optical coherence probe for depth-resolved detection of photothermal response in tissue", Physics Medicine and Biology, V. 49, pp. 111-119.

Torvi, D. A.; Dale, J. D., 1994, "A finite element model of skin subjected to a flash fire", Journal of Biomechanical Engineering, V. 116, pp. 250-255.

Vendrik, A. J. H.; Vos, J. J. A., 1957, "A method for the measurement of the thermal conductivity of the skin", J. Appl. Physiol., V. 11, pp. 211-215.

Vladimirescu, A., 1994, "The SPICE book", New York: John Wiley & Sons.

Weinbaum, S.; Jiji, L. M., 1985, "A new simplified bioheat equation for the effect of blood flow on local average tissue temperature", ASME Journal of Biomechanical Engineering, V. 107, n.2, pp. 131-139.

Weinberger, A. *et al*., 1989, "Intra-articular temperature measurements after superficial heating", Scandinavian Journal of Medicine and Science in Sports, v. 21, pp. 55-57.

Wellstead, P. E., 1979, "Introduction to physical system modelling", New York: Academic Press Inc.

Werner, J; Buse, M., 1988, "Temperature profiles with respect to inhomogeneity and geometry of the human", Journal of Applied Physiology, V. 65, pp. 1110-1118.

Wilson, S. B.; Spence, V. A., 1988, "A tissue heat transfer model for relating dynamic skin temperature changes to physiological parameters", Phys. Med. Biol., V. 33, pp. 895-912.

Winton, H.; Linebarger, R. N., 1970, "Computer simulation of human temperatura control", Simulation, V. 15, n. 5, pp. 213-221.

6. RESPONSABILITY NOTICE

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