ONE-DIMENSIONAL SIMULATION OF HEATING AND COOLING OF CANINE KNEE JOINTS

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Abstract. *This study aimed at the simulation of the transient heat transfer taking place in the canine knee joint, resulting from the application of superficial thermotherapy. The simulation domain (geometric model of the canine knee) was defined by a cylinder comprised of seven tissue layers, from the outside to the inside: epidermis; subcutaneous tissue; fat; muscle; pericapsular region; synovial fluid and bone. Transient heat transfer in the radial direction was evaluated, with the effects of blood perfusion and metabolic heat based on the model proposed by Pennes. To solve the problem, a software based on the finite element technique was used (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). Simulations based on the assumption that the external surface temperature was equivalent to that of the heating/cooling device did not present a satisfactory description of the experimental data, with average differences of 14.8 and 17.1 % for heating and cooling, respectively. There was good agreement with experimental data (average percent differences lower than 3%) for heating simulations based on known temperatures of the epidermis or known heat flux at the surface. Cooling simulations were not able to provide a good description of the heat transfer phenomena. Our results indicate that computer simulation can be an important tool for assessing the effectiveness of thermal resources and that one-dimensional simulations can provide satisfactory estimates of average temperature values in the case of heating.*

Keywords: *bio heat transfer; Pennes equation; computational simulation; thermal resources; finite element method.*

1. INTRODUCTION

Therapeutic application of heat and cold is commonly used in physical therapy, being especially relevant to the treatment of lesions of the muscular and skeletal systems, mostly in bones, ligaments, muscle and tendons (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). During cooling procedures, target tissue temperatures must be in the range of 13 to 18.3 °C in order to ensure attainment of therapeutic benefits (Low and Reed, 2001). Also, in order to maintain tissue integrity, the skin temperature should be kept between 10 and 15°C (Deal *et al.*, 2002). In the case of heating, it is recommended that the target tissue temperature be kept in the range of 40 to 45ºC for at least 5 minutes (Draper *et al.*, 1999; Kitchen, 2003; Robertson *et al*., 2005). Furthermore, in either cooling or heating procedures, local tissue temperature variations should be at most 6ºC in the case of deep (internal) tissue layers (Low and Reed, 2001). According to Andrews *et al.* (2010), temperatures outside the required ranges are not sufficient for promoting the desired therapeutic effects, or can cause thermal damage to the tissue, with consequent destruction of the cytoskeleton, cell membrane and micro vessels. Therefore, accurate knowledge of tissue temperature behavior as a consequence to the application of heat and cold is an important strategy for safe and effective treatments (Karaa *et al.*, 2005).

In vivo tissue temperature determinations have been employed in order to better understand and improve therapeutic strategies (Shrivastava and Vaughan, 2009). However, there are several difficulties associated with this type of experimental procedures, given its invasive nature and the lack in precision of several parameters in association to time constraints and the complexity of control mechanisms. Furthermore, such measurements are limited to a few locations in the tissue and do not provide a detailed description of the temperature distribution (Trobec *et al*., 2008). Given the aforementioned problems associated to *in vivo* temperature determinations, numerical simulations can be viewed as a promising alternative for the assessment of temperature distribution in several tissue layers exposed to different thermotherapy interventions. Therefore, this study aimed at the simulation of transient heat transfer in the canine knee joint, resulting from the application of superficial thermotherapy. The dog knee joint was approximated by a cylinder

comprised of seven tissue layers: epidermis; subcutaneous tissue; fat; muscle; pericapsular region; synovial fluid and bone. Transient heat transfer in the radial direction was evaluated according to the model proposed by Pennes, during application of therapeutic heat and cold.

2. MATERIAL AND METHODS

The canine knee joint was represented by a cylinder, considering transient heat transfer in the radial direction and including the effects of blood perfusion and metabolic heat, according to the model proposed by Pennes (1948). The corresponding governing equation can be written as:

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

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 dog knee joint was approximated by a cylinder comprised of seven tissue layers, from the outside to the inside: epidermis; subcutaneous tissue; fat; muscle; pericapsular region; synovial fluid and bone. The simulation domain is presented in Figure 1. The corresponding thermo-physical properties, initial temperatures and thickness of each layer are displayed in Table 1. Symmetry condition (q = 0) was assumed at the center of the joint.

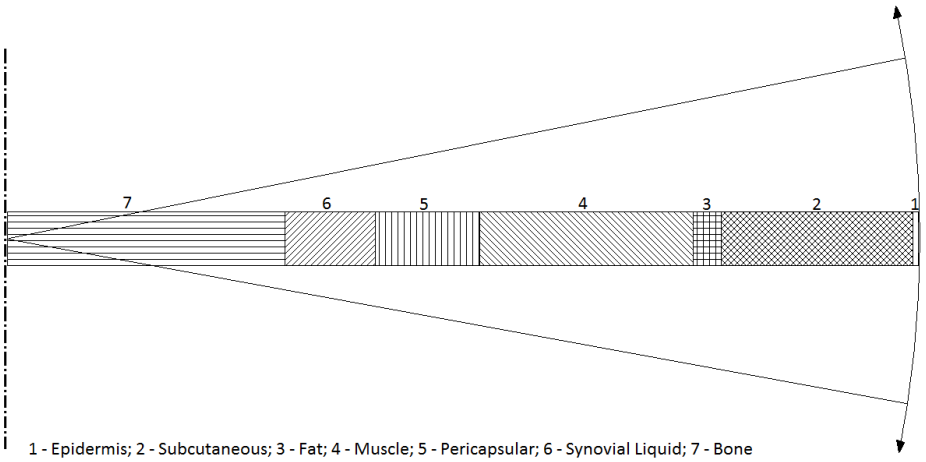

Figure 1. Geometric model of the canine knee joint used for one-dimensional simulations of heating and cooling treatments.

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

Tissue Layer	Thickness (m)	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	$8.0x10^{-5}$	3593	1200	$2.28x10^{-1}$	0	0	34.9
Subcutaneous tissue	$9.0x10^{-3}$	3365	1200	$4.64x10^{-1}$	200	$1.3x10^{-3}$	35.5
Fat tissue	$1.3x10^{-3}$	2678	937	$2.03x10^{-1}$	3.9	$2.9x10^{-4}$	36.1
Muscle tissue	$1.0x10^{-2}$	3684	1097	$5.29x10^{-1}$	716	$5.8x10^{-4}$	36.5
Pericapsular region	$4.9x10^{-3}$	3500	1051	$4.98x10^{-1}$	0	$1.8x10^{-3}$	35.2
Synovial fluid	$4.2x10^{-3}$	4190	1000	$6.10x10^{-1}$	0	0	37.1
Bone	$1.3x10^{-2}$	1785	1585	$7.35x10^{-1}$	368.3	$4.0x10^{-4}$	37.1
Blood	-	3813	1038	-	-	-	37.0

Simulations were performed for heating and cooling conditions, and the obtained results were compared to experimental data available in the literature (Araújo, 2009). The experimental protocol consisted of in vivo temperature measurements (10 K type thermocouples) of the peri- and intraarticular knee joints of ten dogs. Temperature readings were taken at pre-specified time intervals (250s) during 40 and 30 minutes for heating and cooling experiments, respectively. Simulation parameters such as external heating/cooling device temperatures and heating times were established according to the experimental data (Araújo, 2009). The external layer of the epidermis (re = 42.62 mm) 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 ($q = 215.7 W m^{-2}$).

3. RESULTS AND DISCUSSION

A discretization mesh comprised of 445 nodes and 704 elements was employed in the simulations. The average temperature of each tissue layer was compared to experimental data presented by Araújo (2009).

1 – Therapeutic heating

Average percent differences between experimental and calculated values of the average temperature of each tissue layer 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), with the differences being higher for the external layers (epidermis, subcutaneous and fat tissues). 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. When this resistance was considered and 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.

Table 2. Differences between experimental and calculated values of the average temperature of each tissue layer during heating.

	Average percent difference (%)		
Tissue Layer	**Simulation H1**	**Simulation H2**	**Simulation H3**
Epidermis	36.7	-	1.6
Subcutaneous tissue	27.3	1.8	2.4
Fat tissue	14.7	0.4	0.2
Muscle tissue	6.7	0.7	2.3
Pericapsular region	1.9	1.1	2.8
Synovial fluid	1.7	1.2	3.0
Average	14.8	1.0	2.1

Variations of the average temperatures of each tissue layer as a function of time are displayed in Fig. 2, in reference to simulation H2. An evaluation of Fig. 2 shows that, in the most external layers (epidermis, subcutaneous and fat tissues) the simulated temperatures increase faster than the experimental temperatures at the beginning of heating. This is attributed to the fact that the average temperature value employed as boundary condition (40.7ºC) did not take into account temperature fluctuations that took place during the first 10 minutes. During that time interval, the average external temperature increased from 34.9 to 39.6ºC (Araújo, 2009). According to the literature, 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 also be attributed to the fact that the model does not take into account real variations in the physiological parameters that take place as a consequence of heating. One example is the dilatation of blood vessels that occurs during heating. As a consequence, there will be an increase in blood flow that will cause a decrease in heating rate.

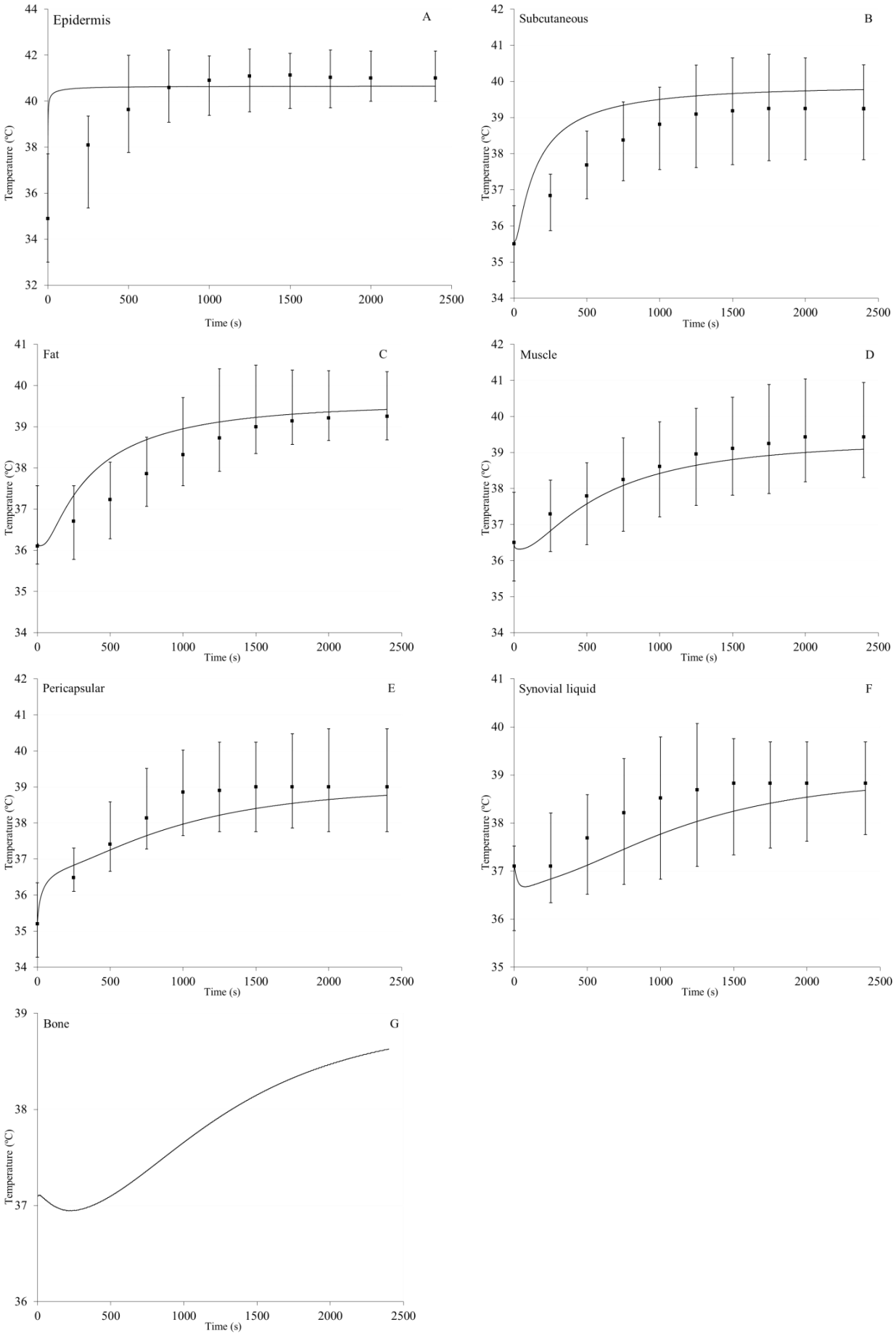

Figure 2. Variation of the average tissue temperature with time during heating: ■ experimental; ⎯ simulation H2.

An evaluation of the results presented in Fig. 2C shows that the temperature of the fat tissue remains constant during the first minutes of heating. Even though such behavior cannot be seen in the experimental curve, Araújo (2009) stated that it was observed for some of the tested animals. According to Chaui-Berlinck *et al.* (2005), such delay in the response of the tissue temperature to a thermal stimulus is characteristic of biological systems, becoming more evident as the tissues are located farther from the heating source. This is attributed to the skin, subcutaneous and fat tissues acting as thermal insulators and limiting heat transfer towards the interior (Pardasani and Adlakha, 1995; Ducharme and Tikuisis, 1991).

Simulation results based on consideration that the heat flux received by the knee joint was equivalent to the average heat flux (simulation H3) provided a better description of the experimental data than simulation H2, especially for the external layers (epidermis, subcutaneous and fat tissues). Furthermore, this type of boundary condition is more appropriate because it does not depend on the previous knowledge of the temperature value at the external surface. 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.

Local temperature profiles corresponding to simulation H3, at the beginning (60s) and end (2340s) of the therapeutic heating procedure are displayed in Fig. 3. A comparison of the two curves shows that the temperature increased in all evaluated tissues. However, such increase was more significant for the layers located closer to the heating source. Such behavior was expected, since the heat is applied at the surface and must cross all the external layers before attaining the internal tissue layers. Thus, the external layers (skin, subcutaneous and fat tissues) act as thermal insulators and limit the amount of heat that is transferred towards the interior (Pardasani and Adlakha, 1995; Low and Reed, 2001).

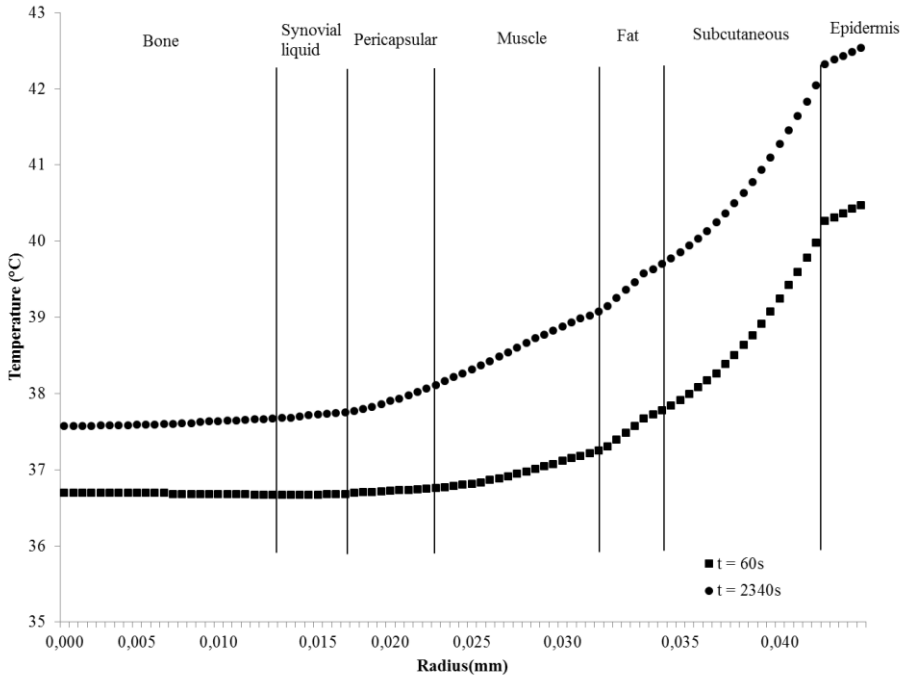

Figure 3. Local temperature profiles at the beginning (60s) and end (2340s) of the therapeutic heating procedure (simulation H3).

2 – Therapeutic cooling

Table 3 displays the average percent differences between experimental (Araújo, 2009) and calculated values of the average temperature of each tissue layer during cooling. Significant differences between experiments and simulation were obtained observed when the temperature of the external layer of the epidermis was considered to be equivalent to the average temperature of the cooling device (simulation C1) and also 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). In the case of simulation C1, the differences were higher for the external layers (epidermis, subcutaneous and fat tissues), given that the resistance to heat transfer between the cooling device and the epidermis was not taken into account and therefore the temperature value employed as boundary condition (4.5ºC) was much lower that its actual value (27.3ºC). However, when a more appropriate value of the epidermis external temperature was employed in the calculations (simulation C2), although the error decreased for the subcutaneous layer, it increased for the other layers that were located farther from the cooling device.

Table 3. Differences between experimental and calculated values of the average temperature of each tissue layer during cooling.

	Average percent difference (%)	
Tissue Layer	**Simulation C1**	**Simulation C2**
Epidermis	36.1	-
Subcutaneous tissue	27.5	7.3
Fat tissue	11.0	16.3
Muscle tissue	5.6	23.3
Pericapsular region	15.8	25.2
Synovial fluid	6.6	12.9
Average	17.1	17.0

Variations of the average temperatures of each tissue layer as a function of time are displayed in Fig. 4, in reference to simulation C1. It can be viewed that the temperatures corresponding to the most external layers (epidermis and subcutaneous tissue) are significantly underestimated in comparison to the experimental values. Also, although the differences between simulated and experimental temperatures for the remaining layers are within the experimental deviation, the description of the temperature behavior does not seem adequate. The average temperatures of the tissue layers nearer to the cooling device are lower than the value recomended for avoiding tissue damage (10°C). Also, a slight increase in simulation temperatures of the pericapsular region is observed, probably associated to the effect of metabolic heat that is not opposed by the cooling effect at the begining of the therapeutic cooling procedure.

Overall, considering the simulations presented in this study, the ones associated with therapeutic heating provided a better description of the experimental data. Among the evaluated boundary conditions, the one based on the heat flux was shown to be more appropriate to represent heat transfer in the canine knee joint, even though it did not take into account heat losses to the environment. It is also noteworthy to point out that the experimental measurements are subject to errors, and such errors are also affected by the intrinsic difficulties associated with *in vivo* experiments. According to Júnior and Sousa (2008), in order for such measurements to be error free it would be necessary: 1 – a perfect measurement system; 2 – a stable and controled environment; 3 – a perfect operator; and 4 – a unique, definite and stable measurement value. Values of thermophysical and physiological parameters are also quite discrepant in the literature. According to Cui and Barbenel (1990, 1991), blood perfusion and thermal conductivity are the ones that present the highest influence on the thermal response of biological tissues, affecting the thermal resistance of each tissue layer, the time necessary for attaining equilibrium, and the corresponding temperature (Lima *et al*., 2006).

The fact that variations in blood perfusion due to variations in temperature were not taken into account in the simulations may also account for some of the observed differences. The increase (dilatation) or decrease (contriction) of blood flow have a significant effect on the skin temperature given the respective variations in blood heat transfer (Arens and Zhang, 2006). During heating, an increase in blood flow and corresponding increase in heat transfer by the blood results on a decrease in tissue temperature. The opposite behavior occurs during cooling.

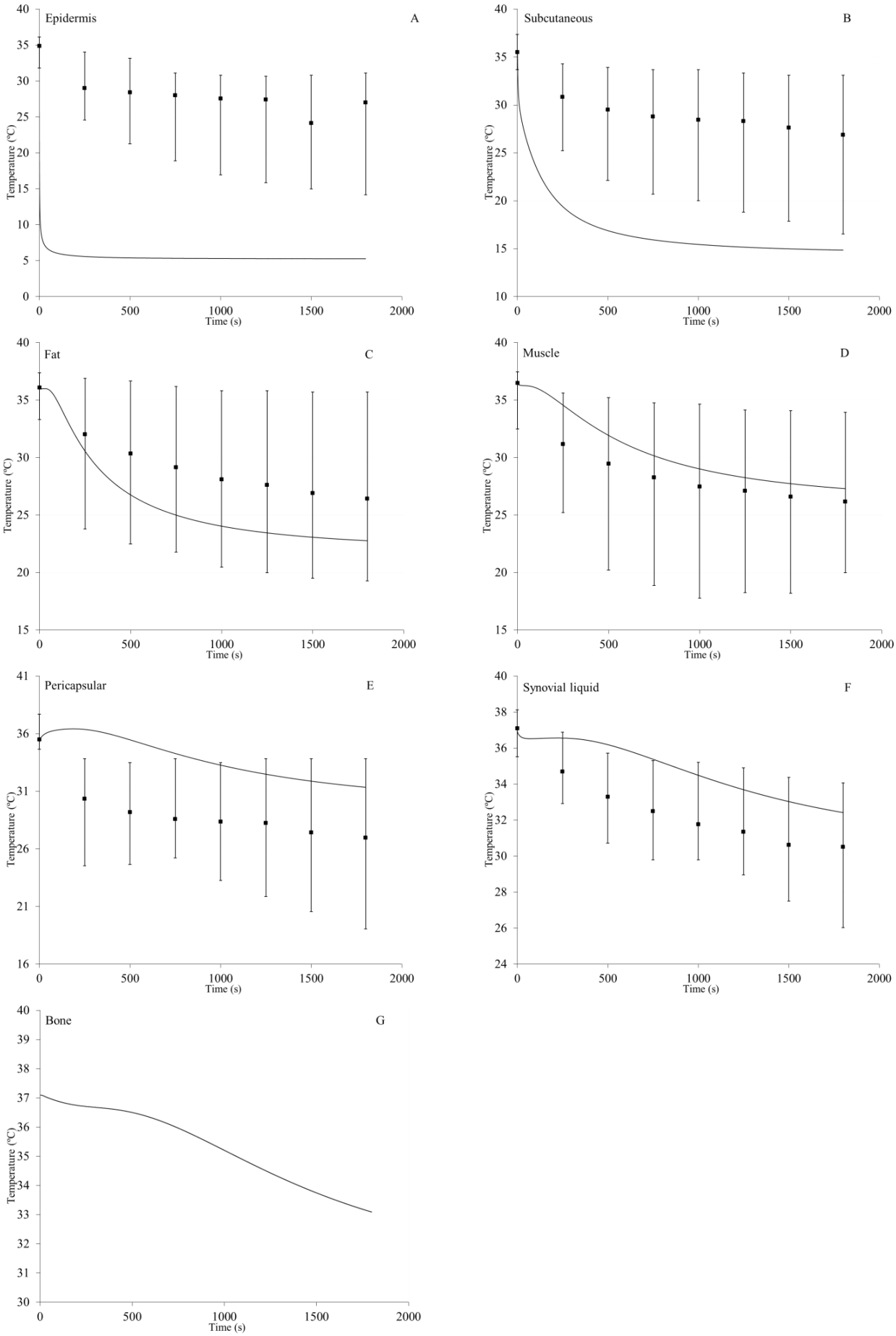

Figure 4. Variation of the average tissue temperature with time during cooling: ■ experimental; ⟶ simulation C1.

4. CONCLUSION

The results presented in this study showed that variations in tissue temperature arising from therapeutic heating of a canine joint can be satisfactorily predicted by a one-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 considered to be the most appropriate. Results obtained for cooling simulations presented significant differences in comparison to the experimental data. However, our results confirm that simulations are an important step for non-invasive evaluation of thermal treatments.

5. ACKNOWLEDGEMENTS

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