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SIMULATION OF HEAT TRANSFER IN THE KNEE JOINT IN CONDITIONS OF NEUTRALITY

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Abstract: *Therapeutic application of heat and cold is commonly used in physiotherapy, being especially relevant to musculoskeletal system lesions treatment.To achieve the therapy benefits, it is necessary heat or cool thetherapeutic targetwithin specified temperatures limits.Correct tissue temperature assessment is important to ensure safe and effective treatments, since temperatures outside the recommended range can either can be insufficient to promoting the desired therapeutic effect or it can cause thermal damage to the tissue.The computational numerical simulation become very important over the last few years to solve a lot of problems related to biologic tissue heat transfer.It is an alternative to analyze the heat transfer in biological tissues, resulting in a better understanding about the thermal behavior inside the human body parts.In this work, the computational numerical simulation was used to analyze the temperature distribution along the different dog knee tissues in thermal neutrality condition.A mathematical model base on heat diffusion equation was implemented, the simulations were performed usinga geometric model constructed from a dog knee's digital photos.The different knee's tissues, thermo-physical and physiological properties were determined based on literature values. The simulation results have been compared with the experimental data available on literature. The consistency between the numerical results and experimental data suggests that the computational model is a good approach.However, some mechanisms, like the heat transfer due the blood perfusion should be adjusted, especially when transient simulation takes place. Simulation seems to be a good way to estimate tissue temperature since no human being need to be involved, the cost is low, and there is a possibility to analyze the more internal tissues temperature.Therefore, therapeutics process effectiveness and safety, that involve heat transfer, could be determined through this method.*

Keywords: *Bioheat transfer, Simulation, Knee.*

1. INTRODUCTION

The therapeutic heating and cooling in its various forms has been employed for therapeutic purposes since ancient times (Shitzer and Eberhart, 1985; Cameron, 2008). However, just recently these modalities are being scientifically explored (Bissel,1999;Harztzell et al., 2012). This expansion is due to practicality, low cost, the benefits and minimum risks when correctly applied (Araújo, 2009). 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). According to Kitchen (2003), 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. These lesions can disrupt the reproductive cell cycle and local blood flow, which predisposes to tissue necrosis (Knight*et al.*, 2001). Therefore, monitoring theses temperatures is an important strategy for safe and effective treatments (Karaa*et al.*, 2005).

There are several devices that assist in body temperature evaluation. Due the ease surface structures access, many methods are available for temperature measurements of these structures, including thermografy (Shitzer and Eberhart, 1985) and mono and multi-frequency radiometric access (Chang*et al.*, 1998).

In contrast, the temperature measurements in tissues and deeper structures are generally more complex and difficult to achieve (Brajkovic andDucharme, 2005). In vivo tissue temperature determinations have been employed in order to better understand and improve therapeutic strategies. 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).

Other devices commonly used to measure the deeper tissues temperature are X-ray (Warkentin *et al.*, 2003), magnetic resonance imaging (Brat *et al.*, 1999; Seidell *et al.*, 1990; Parker, 1984; Hirsch *et al.*, 2003) and computed tomography (Crabtree*et al*., 2001; Kruger and Reinecke, 1999; Seidell *et al.*, 1990), but these methods are not used in clinical practice due the high cost. Given the aforementioned problems,numerical simulations can be viewed as a promising alternative for the assessment of temperature distribution in several tissue layers exposed to different thermal interventions (Silva, 2011). The numerical simulation is an non-invasive and inexpensive alternative, which it is possible calculate, analyze and display the temperature changes that occur with time at any therapeutic target point. Therefore, this study aimed simulates the temperature distribution over the different knee joint tissues in thermal neutrality condition.

2. MATERIALS AND METHODS

The bio heat transfer is a complex process and, therefore does not allow an analytical solution for the present study. Pryor to carrying out computer simulation to determine the temperature distribution in the canine knee joint is necessary create a geometry that really represents this joint. This geometric model must represent all canine knee layers and their thermophysical and physiological properties.

2.1 Geometric model

In this study, two geometrical models were created: 1- considering all tissues except the skin surface and 2 – with all tissues regions. These two models were creates to assess the effect of skin surface on joint temperature. Both geometric models were developed using the *software*SOLIDWORKS® and were based on a photographic image (fig 1 and fig 2).

The dog knee joint was represented for seven tissue layers, from the outside to the inside: Skin surface; subcutaneous tissue; adipose tissue; muscle tissue; pericapsular region; cruciate ligaments and bone. The correspondingthickness, thermo-physical and physiological properties of each layer are displayed in Table 1.

Figure 1.Knee joint photographic image.
Source: Araújo, 2009.

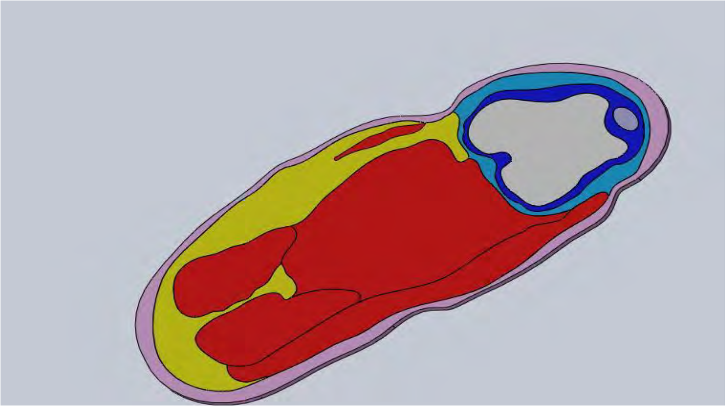

Figure 2.Geometry of the canine knee drawn in cross section in SOLIDWORKS ® representing all tissue layers except the skin surface.

Table 1.Physical, thermophysical and physiological parameters of tissues.

Region	Thickness (m)	c_p $(Jkg^{-1o}C^{-1})$	ρ (kgm^{-3})	k $(Wm^{-1o}C^{-1})$	q_m (Wm^{-3})	W $(m^3s^{-1}m^{-3}tec)$
Epidermis	$8,0 \text{ x } 10^{-5}$	3593	1200	$2,28 \text{ x } 10^{-1}$	0	0
Subcutaneous tissue	$9,0 \text{ x}10^{-3}$	3365	1200	$4,64 \text{ x } 10^{-1}$	200	$1.3\text{x}10^{-3}$
Adipose tissue	$1,3 \text{ x}10^{-3}$	2678	937	$2,03\text{x } 10^{-1}$	3.9	$2,9\text{x}10^{-4}$
Muscle tissue	$1,0 \text{ x } 10^{-2}$	3684	1097	$5,29\text{x } 10^{-1}$	716	$5,8\text{x}10^{-4}$
Pericapsular	$4,9 \text{ x } 10^{-3}$	3500	1051	$4,98\text{x } 10^{-1}$	0	$1,8 \text{ x } 10^{-3}$
Cruciate ligaments	$4,2 \text{ x}10^{-3}$	4190	1000	$6,10 \text{ x } 10^{-1}$	0	0
Bone	$1,3 \text{ x } 10^{-2}$	1785	1585	$7,35\text{x } 10^{-1}$	368,3	$4,0\text{x}10^{-4}$

Source**:** Araújo, 2009

2.2 Mathematical Model

The heat generated by metabolic processes is continuously circulated through the tissues due the existence of local temperature gradients.In living organisms, the energy can be transferred by two main mechanisms: thermal conduction between the adjacent layers tissue and by convectionthrough the blood flow.However, given the difficulty to represent the blood vessels in the geometric model, the heat received by each tissue was added to the knee term generation of metabolic energy from its layer, forming a term of energy generation. The heat transfer phenomenon is modeled using the heat diffusion equation simplified. The corresponding governing equation can be written as:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\dot{q}=0 \qquad (1)$$

$$\dot{q}=\dot{q_m}+\dot{q_w} \qquad (2)$$

where $\dot{q_w}$the rate released by blood perfusion and $\dot{q}_m$is the metabolic heat

$$\dot{q}_w = w\rho_s C_s\left(T_{ref}-T_{camada}\right)(3)$$

Where w representing the blood perfusion $[m^3\ s^{-1}\ m^{-}3]$, ρ_s blood specific heat [J/kg·°C], T_{ref} is the rectal temperature.

For the simulation the following values were considered $\rho s = 1060\ kgm^{-3}$;$cps = 3800\ Jkg^{-1o}C^{-1}$; T ref= 38,1°C (Araújo, 2009). The metabolic rateand blood perfusion were considered uniform and constant in all tissues layers.

Two simulations of the condition of thermal neutrality were performed: a) simulation-1 - geometric model without the skin surface and b) simulation 2 - using the full geometric model (with all tissue layers).In simulation 1, thevolumetric heat rates received due to blood perfusion were considered based on the literature (ARAÚJO, 2009). In the simulation 2, the heat volumetric rates received by perfusion were obtained using an iteration process of equation 3.

Initially it was assumed: $T_{layer} = 37°C$, obtaining a $T_{ref} - T_{layer} = 1$, since$T_{ref} = 38°C$. The convergence criterion used to finalize the iterations was a difference lower than 5% between T_{layer} (found with the simulations) and the temperature obtained experimentally in the study of Araujo (2009). The simulations results were evaluated and compared with average temperatures according to *in vivo* experimental data available in the literature (Araújo, 2009).For comparison the average temperatures obtained in both simulations were calculated.

2.3 Mesh and boundary condition

The construction of the mesh was performed using the ANYSY Workbench ® (Fig. 3) and the computer simulations were performed using ANSYS-CFX®.

Seven different domains were created to represent the seven canine knee layers, from the e outside to the inside: Skin surface; subcutaneous tissue; adipose tissue; muscle tissue; pericapsular region; cruciate ligaments and bone. Communication between the layers was performed for a single physical problem was considered by the program.The interfaces boundary conditions were defined between tissue layers. Symmetry conditionwas assumed at the upper and lower faces of the joint (fig.4). These ensure that the heat flow occur only bidimensionally. The external layer received a wall boundary condition, submitted to a natural convection coefficient of 6 $Wm^{-2}k^{-1}$ with an external temperature of 25 °C (Araújo, 2009).

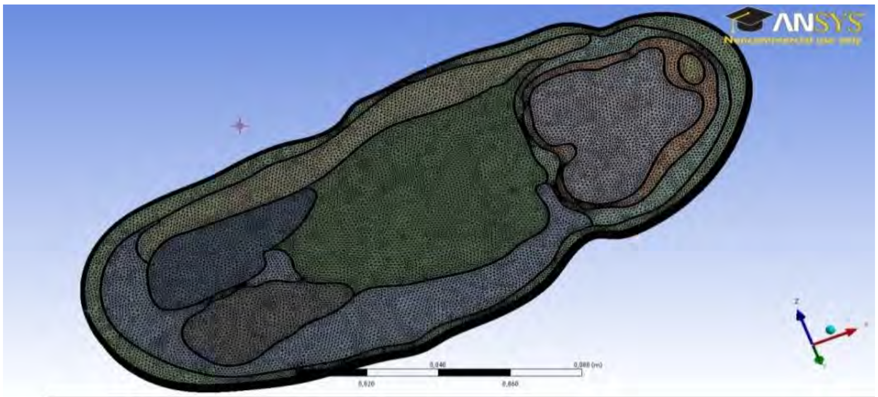

Figure 3.Mesh

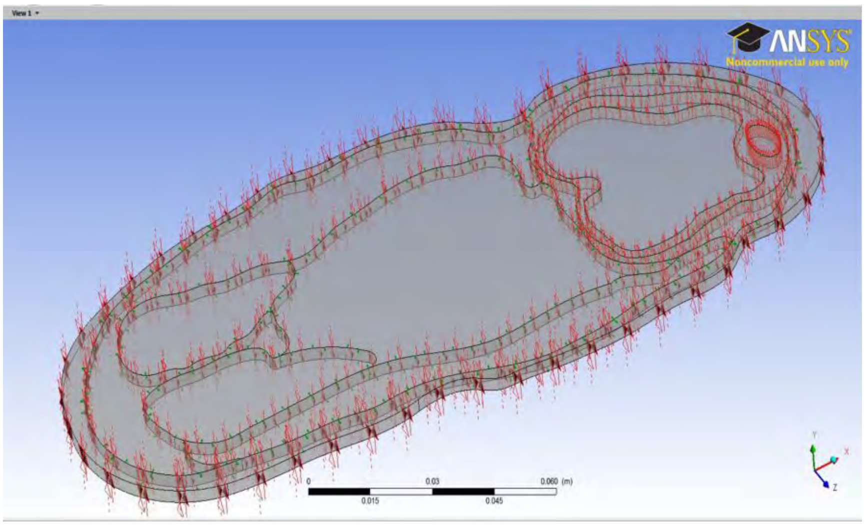

Figure 4. Interfaceboundary conditionsand symmetry.

3. RESULTS

Through numerical simulations it was possible to estimate the temperature field in thermal neutrality state in different canine knee layers. The Table 2 shows the simulation 1 results, with all tissue layers and without iterative process.Note that with the exception of regions pericapsular and cruciate ligaments the difference between simulated and experimental temperature was lower than 6%.The percentage difference for bone area was not estimated by unavailability of experimental data for this layer.

The temperature profile of canine knee in symmetry plane (first iteration) is shown in Figure 3.

Table 2. Simulation1 results of neutrality without skin surface and without iterative process, compared with results of experimental study (Araújo, 2009).

Region	Temperature (C°) Simulation	Temperature (C°) Experiment	Diference %
Subcutaneous tissue	37,2	35,2	5,8
Adipose tissue	40,4	36,2	11,7
Muscle tissue	41,6	35,8	6,5
Pericapsular	36,2	35	3,5
Cruciates ligaments	36,6	37	0,9
Bone	36,3	*	*

Source: Research data.

*Temperature not estimated in the experimental study.

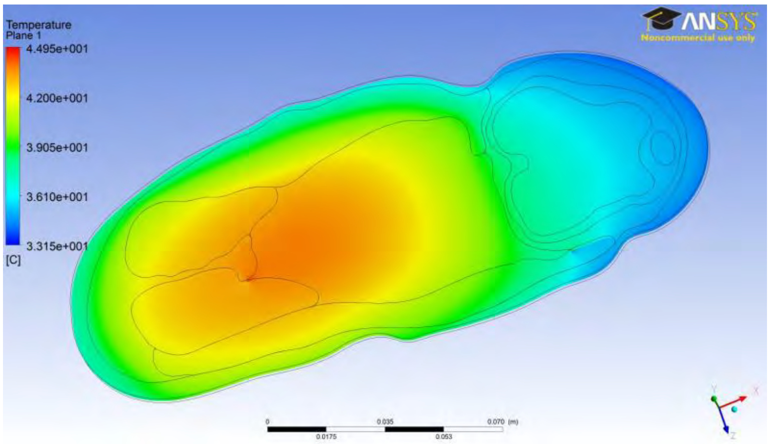

Figure 5.Temperature profile in symmetry plane for the simulation without epidermis and the iterative process.

The second numerical simulation (simulation 2) included the skin surface layer and iterative processes. In tables 3, 4 and 5 are the results for first, second and third iteration respectively.

Table 3.Simulation results of neutrality with skin surface and first iteration compared with the experimental study results (Araújo, 2009).

Region	Temperature (C°) Simulation2	Temperature (C°) Experiment	Diference %
Skin surface	32,8	34,8	5,7
Subcutaneous tissue	33,1	35,2	5,9
Adipose tissue	34,5	36,2	4,8
Muscle tissue	35,2	35,8	1,6
Pericapsular	32,5	37	12,1
Cruciates ligaments	32,6	35	6,7
Bone	32,3	*	*

Source: Research data.

*Temperature not estimated in the experimental study.

Table 4. Simulation results of neutrality with epidermis and second iteration compared with the experimental study results (Araújo, 2009).

Region	Temperature (C°) Simulation2	Temperature (C°) Experiment	Diference %
Skin surface	42,4	34,8	-21,9
Subcutaneous tissue	42,9	35,2	-21,8
Adipose tissue	44,7	36,2	-23,4
Muscle tissue	44,9	35,8	-25,6
Pericapsular	40,7	37	-10,1
Cruciates ligaments	41	35	-17,1
Bone	40,4	*	*

Source: Research data.

*Temperature not estimated in the experimental study.

Table 5.Simulation results of neutrality with epidermis and third iteration compared with the experimental study results (Araújo, 2009).

Region	Temperature (C°) Simulation2	Temperature (C°) Experiment	Diference %
Skin surface	22,3	34,8	36,0
Subcutaneous tissue	22,5	35,2	36,2
Adipose tissue	23,4	36,2	35,3
Muscle tissue	25	35,8	30,1
Pericapsular	24,6	37	33,6
Cruciates ligaments	24,5	35	30,1
Bone	24,6	*	*

Source: Research data.

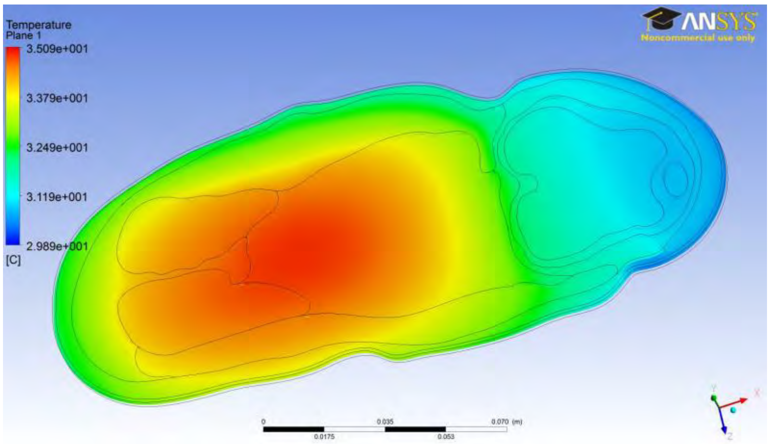

Figure 6.Temperature profile in symmetry plane for simulation with the epidermis- first iteration.

4. DISCUSSION

The lack of studies on thermal behavior of biological tissuesis a challenge for the realization of safe and effective physiotherapy treatments.In this context, computational numerical simulation emerges as solution, innovative and interdisciplinary, to assist in the scientific basis of Physiotherapy.

The results from simulations showed that with the exception of regions adipose and muscle tissues, the difference between simulated and experimental temperature were lower than 6%. This may be related tothe difficulty in determine adequately the parameters used in simulation, mainlyonvascularized tissues such as muscles. Since there is no consensus onliterature about blood perfusion values in different biological tissues for thermal neutrality this variable can be dimensioned up or below its real value.

As a solution to problem iterations were proposed to adjust the blood perfusion influence in heat exchange on each canine knee layer. In tables 3, 4 and 5 it is noted that the second and third iterations are not converged, with unacceptable error (less than 5%) when compared with data from an experimental study. It´s necessary to elucidate why the temperature values have not converged, and determining the amount of heat that transfers to each layer the adjacent tissue.

It was also found that the presence of skin surface layer has not significant improvements in simulated temperature values of canine knee.This can be explained by the small thickness of this layer relative to the other, and the low thermal conductivity, the lowest among all tissues.

Another important point to be considered is to investigate the value of convective coefficient of geometric model by correlations of natural convection, bringing the knee canine as a cylinder.

5. CONCLUSION

The simulation results show that the model represents the process of heat transfer canine knee satisfactorily. However, some iterations did not fit within the margin of error expected (less than 5%).Setting some parameters of mathematical model, such as the convergence of iterations to adjust the influence of blood perfusion in the heat exchange, is expected to find better results in the future. It is clear, therefore, to further study the importance of simulations in the condition of heating and cooling.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Araújo, A.R. 2009. “Formulação e validação de um modelo térmico para estimativa da temperatura intra-articular.”Ph.Dthesis, Universidade Federal de Minas Gerais, Belo Horizonte.

Brajkovic, D. andDucharme, M.B. 2005.“Confounding factors in the use of the zero-heat-flow method for non-invasive muscle temperature measurement”.*European Journal of Applied Physiology,* vol. 94, p. 386–391.

Brat, H.J., Renton, P., Sandison, A. and Cannon, S.1999.“Chondromyxoid fibroma of the sacrum”. *European Radiology*, vol. 9, p.1800-1803.

Bissel, J.H. 1999. “Therapeutic Modalities in Hand Surgery”.*The Journal of Hand Surgery,* vol. 24, p. 435-448.

Cameron, M.H. 2008.*Physical agents in rehabilitation: From research to pratice*. Saunders, 3st edition.

Chang, J. T. Paulsen, K. Meaney, P. and Fanning, M. 1998.“Non-invasive thermal assessment of tissue phantoms using an active near field microwave imaging technique”.*International Journal of Hyperthermia*, vol. 14, p. 513-534.

Crabtree, N., Loveridge, N. Parker, M., Rushton, N., Power, J., Bell, K.L., Beck, T.J. and Reeve, J. 2001. “Intracapsular Hip Fracture and the Region-Specific Loss of Cortical Bone: Analysis by Peripheral Quantitative Computed Tomography”. *Journal of Boneand Mineral Research*, vol. 16, p. 1318-1328.

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, p. 13-22.

Harztzell ,T.L., Rubinstein, R. and Herman, M. 2012. “Therapeutic Modalities - An Updated Review for the Hand Surgeon”.*Journal of Hand Surgery,* vol. 37, p.597-621.

Hirsch, L.R., Stafford, R. J., Bankson, J.A., Sershen, S.R., Rivera, B., Price, R.E., Hazle, J.D., Halas, N.J., and West, J.L. 2003. “Nanoshell-mediated near-infrared thermal therapy of tumors under magnetic resonance guidance”. *Proceedings of the National Academy of Sciences of the United States of America,* vol. 100, p.13549-13554.

Karaa, S., Zhang, J. and Yang, F.A. 2005.“Numerical study of a 3D bioheat transfer problem with different spatial heating”.*Mathematics and Computers in Simulation.*vol. 68, p.375–388.

Kitchen, S. 2003.*Eletroterapia: Prática baseada em evidências.*Manole, São Paulo, 11st edition.

Knight, C.A.,Rutledge, C.R., Cox, M.E., Acosta, M. and Hall, S.J.2001.“Effect of superficial heat, deep heat, and active exercise warm-up on the extensibility of the plantar flexors”.*Physical Therapy,* vol. 81, p. 1206-1214.

Kruger, R.A.Reinecke, D.R. and Kruger, G.A., 1999. “Thermoacoustic computed tomography–technical considerations”.*American Association of Physicists in Medicine*, vol. 26, p. 1832-1837.

Parker, D.L. 1984. “Applications of NMR Imaging in Hyperthermia: An Evaluation of the Potential for Localized Tissue Heating and Noninvasive Temperature Monitoring”.*Ieee transactions on biomedical engineering*, vol. BME 31, p. 161-167.

Seidell, J.C., Akker, C.J.G. and Kooy, K.V.D. 1990.“Imaging techniques formeasuring adipose-tissue distribution-a comparison between computed tomography and 1 .5-T magnetic resonance”.*TheAmericanJournal ofCIinical Nutrition*, vol. 51, p.953-957.

Silva, F.S.,2011. *Simulação da transferência de calor na articulação do joelho em modelo animal para condições de aquecimento e resfriamento.*Masters dissertation, Universidade Federal de Minas Gerais, Belo Horizonte.

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.

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

Warkentin, B., Steciw, S., Rathee, S. and Fallone, B.G. 2003.“Dosimetric IMRT verification with a flat-panel EPID”.*American Association of Physicists in Medicine*, vol. 30, p. 3143-3155.

7. RESPONSIBILITY NOTICE