THRESHOLD OF PERMANENT CORNEA THERMAL DAMAGE DUE TO INCIDENTAL CONTINUOUS WAVE CO_2 LASER IRRADIATION

by

Mayada M. TAHIR
Department of Laser and Optoelectronics Engineering,
University of Technology, Baghdad, Iraq

Original scientific paper
UDC: 544.032.65:617.7-001.15/.17:517.96
DOI: 10.2298/TSCI1002459T

Cornea thermal damage due to incidental continuous wave CO_2 laser irradiation is studied numerically based on bio-heat equation .The interaction of laser with tissue leads to a rapid temperature increased in target and the nearby tissue. As the temperature of the eye surface reaches 44 °C, a sensation of pain will cause aversion response of the reflex blink and/or shifting away from the source of pain. The aim of the work is to predict numerically the threshold limit of incidental laser power that causes damage to the anterior part of the cornea, which can be healed within 2-5 days as long as damage is not exceeding the outer part of the eye (epithelium). A finite element analysis is used to predict temperature distribution through the cornea where the necroses region can be obtained using thermal dose equation. The thermal dose that required for damaging the cornea is predicted from previously published experimental data on rhesus monkeys and used later as a limit for shrinkage to human cornea. The result of this work is compared by international standard of safety and a good nearby result is obtained which verified the result of this work.

Key words: *cornea thermal damage, laser safety, incidental laser accident, continuous wave CO_2 laser, finite element analysis*

Introduction

The wide use of laser system in every aspect of technology may lead to an incidental exposure to laser beam [1], which can be either intra, reflected or diffused laser beam. The laser beam may cause a harmful effect to users who deal with those types of systems especially at a high laser power [2]. The eye and skin are the most susceptible parts of the body to accidental laser irradiation and due to the importance of vision to the quality of life, the eye hazards are the more important consideration for safety.

Typical continuous far IR laser is the CO_2 laser. It is of special concern for eye and skin burns because of its capability to produce high power also it can be highly absorbed in tissue and has low reflectivity as it interacts with tissue. In contrast, for visible and near infrared lasers, the absorption occurs over a more extended depth, so that heating effects will be less severe. Due to

* Author's e-mail: stary5@yahoo.com

the harmful effect of damage caused by lasers on human, a well established standard of safety has been established during the last decades.

So far almost researches focus their attention in studying laser safety on the permanent damage caused by the intended or accidental laser exposure. In this work, a special important case is studied; an intra continuous wave CO_2 laser beam of Gaussian distribution suddenly strikes the eye where it may be absorbed very superficially. The front part of the eye (cornea) will receive the major part of the energy that is converted from the photons of light to heat. A rapid increasing in the temperature of the cornea surface may follow this interaction till it reaches 44 °C. The temperature of 44 °C is known as the threshold limit of pain [1]. Due to the intensive nervous end that concentrate in cornea [3], a human response with a time delay of 0.25 s [3, 4] may follow this event so as to close the eyelid and/or move away from the source of pain. During this period, a damage of the outer surface of cornea (epithelium) may occur.

Here the threshold limit of the incidental combined laser power with aversion response that caused total damage to epithelium is the aim of this work. An axis-symmetry finite element analysis is used to solve the bio-heat equation which describes this case. Temperature distribution is the first aim of this work from which an experimental predicted thermal dose value is used to recognize the necroses zone in an accident of intra continuous wave of CO_2 laser having Gaussian beam distribution during and after the event.

Due to a high absorption of CO_2 laser photons in tissue, comparing with lasers having less wavelength then cornea, damage caused by CO_2 laser is maximal. Damage caused by CO_2 laser will show the maximum *corneal damage* that may occur, if it is accidentally hited by laser beam. Laser of less wavelength may also cause damage in the in depth eye tissue rather than in cornea.

Human eye modeling

Eye is a very complex optical system, although it is relatively a small organ in the human body. Its typical dimensions are about 24 mm in length (along pupillary axis) and 23 mm in diameter. In modeling the eye, it is assumed that it has a solid structure of given dimensions, consisting of eight homogeneous tissues, namely, cornea (the clear outer covering of the eye), aqueous humour (a liquid sits behind cornea), cilliary body (tissue that holds the lens to the sclera), lens (it focuses light to the back of the eye), vitreous humour (clear gel lies between lens and retina), retina (light-sensitive back of the eye), choroids (layer between retina and sclera), and sclera (white part of the eye), see fig. 1. To simplify the solution and due to almost symmetrical nature of the eye only one half zone is shown, assuming the entire laser photons are absorbed within the cornea, then only the cornea and the near adjusting tissue are considered in the mathematical solution of the eye which is indicated as the selected region in fig.1. Blood flow occurs only in the back of the eye, in the sclera and retina region.

A deep insight into the structure of cornea is necessary to understand the thermal behavior and the threshold limit of damage when laser beam incidentally hits an eye. Briefly it consists of epithelium (50 μm), Bowman's membrane, stroma, descemet membrane, and endothelium. The typical thickness of the cornea is about 500 μm at the center of the optical axis. The upper part of cornea (*i. e*. epithelium) can regenerate itself within 2-5 days [4], however lesions which penetrate deeper can be accompanied by edema and collagen shrinkage, which result in significant permanent vision impairment [4].

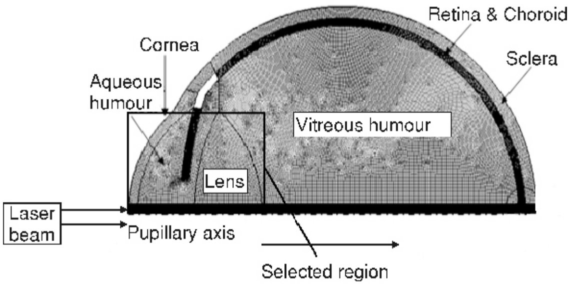

Figure 1. Eye axis symmetry model

Theory

Mechanism

The aim of the work is to predict the power level at which epithelium damage may occur where an incident of intra continuous wave of CO_2 laser strikes the eye resulting in increasing of cornea temperature so that a sensation of pain is started. The elevation in the temperature of cornea will cause aversion reflex by closing eyelid and/or moving away from the stimuli. For the simulation proposed at both cases above, laser beam on the tissue will terminate after 0.25 s from the time of pain sensation, but its effect still exists till the cornea temperature goes below 37 °C again. The model is tested to show at which power level of continuous wave CO_2 laser can damage only the epithelium with aversion human response.

Partial differential equation and boundary conditions

Beyond 2.5 m of laser beam wavelength, the absorption coefficient in tissue is high enough such that the cornea is the structure primarily at risk where a thermal damage mechanism may occur [4]. The partial differential equation that covers the heat transfer inside biological tissue is proposed by Pennes which is till now proved to well model the thermal behavior in living tissue [5]. To simplify the solution, an axis-symmetry form about pupillary axis is used. This assumption is almost the case for dealing with the front part of the eye, then:

$$\rho c \frac{\partial T}{\partial t} \quad \frac{1}{r} k \frac{\partial}{\partial r} \quad r \frac{\partial T}{\partial t} \qquad \frac{\partial^2 T}{\partial z^2} \quad W c_{\mathrm{b}} (T_{\mathrm{B}} \quad T) \quad \dot{Q} \quad \dot{Q}_{\mathrm{m}} \tag{1}$$

IR laser beam such as CO_2 laser is absorbed very superficially in the cornea and only the front part of the eye is necessary to model the situation. Laser beam, evaporation, convection, and radiation are assumed at the vulnerable part of the eye. Convection, evaporation, and radiation heat transfer between the outer part of cornea (which is covered by tear layer) and the environment is modeled as:

$$k \frac{\partial T}{\partial n} \quad h(T \quad T_\infty) \quad E \tag{2}$$

where

$$h = h_{\mathrm{co}} + h_{\mathrm{r}} \tag{2a}$$

and

$$h_{\mathrm{co}} \text{ (convection heat transfer coefficient)} = 10 \text{ Wm}^{-2}\text{K}^{-1} \text{ [6]} \tag{2b}$$

also

$$h_{\mathrm{r}} \text{ (radiation heat transfer coefficient)} \quad 4\sigma\varepsilon \quad \frac{T_{\mathrm{s}} \quad T_\infty}{2}^{3} \text{ [7]} \tag{2c}$$

The heat loss due to evaporation of tears (E) is assumed to be 40 W/m^2 [6] , the environmental temperature (T_∞) is 25 °C, while the emissivity (ε) of the cornea is taken to be 0.975 [6]. Evaporation, convection, and radiation boundary conditions are applied in an open eye model while only convection to environmental temperature of 37 °C is applied when eyelid is closed. This boundary condition must be applied through the solution simultaneously as the eyelids are closed [3]. An adiabatic boundary condition is applied through the axis of pupillary due to symmetrical nature of the problem. In the relative far in-depths boundaries, insulated boundaries are applied (see fig. 2). The fact of that the in-depth temperature distribution will not be affected by instantaneous localized induced heat resulting by striking of accidental laser beam, is confirmed by relatively low thermal conductivity, high specific heat of the eye tissue.

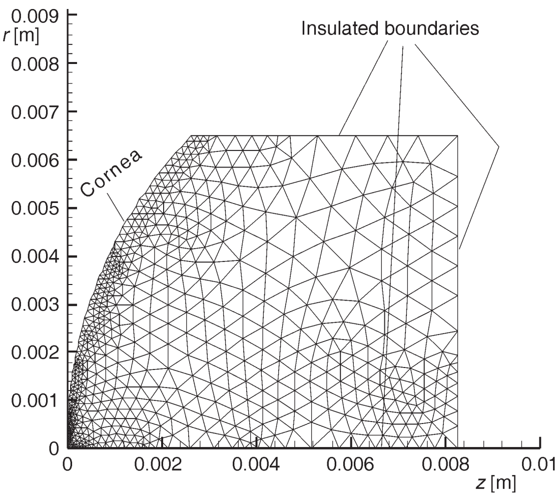

Figure 2. Dimensions of the selected region and mesh for finite element solution

It is assumed that a tear layer of 7 μm is covered the cornea and the other vulnerable part of the eye [8]. Due to a small amount of metabolic heat comparing with heat generated due to laser accident then it can be neglected. Also the perfusion rate at the selected region is almost zero because of the absence of blood vessel in cornea and the adjusting tissue [9].

A good starting is to impose the initial temperature distribution taken from other well established works where the surface temperature of cornea at the pupillary axis is almost equal to 33.7 °C and is approximately increased linearly toward 36 °C as the depth reaches 0.008 m [10]. Finally, the thermal properties of the ocular tissues are taken from Waddell *et al*. [11], while the thermal properties of tear layer are taken to be that of water.

Laser as heat source

The heat generation at any depth due to laser-tissue interaction depends mainly on absorption coefficient and light intensity at that depth. If absorption dominates the scattering, which is the case for interaction of CO_2 laser with tissue, then heat generation through the tissue due to laser of Gaussian beam distribution is written as [12]:

$$\dot{Q}\quad \mu(1\quad rf)\frac{2p}{\pi w_0^2}\exp(\quad \mu z)\exp\quad \frac{2r^2}{w_0^2} \tag{3}$$

The reflectivity of tissue (rf) at high wave length (*i. e*. 10.6 m) is almost zero, the absorption coefficient of cornea (μ) is equal to 950 cm^{-1} [4] and waist diameter ($2w_0$) is taken to be 1 mm to standardize the model.

Finite element formulation

Equation (1) is discredited in axis-symmetry spatial dimensions and solved using the weak formulation and Galerkin procedure [13]. A total number of 1272 triangular elements and 2300 nodes are generated follow a special grid model, see fig. 1. A finer element is used in the region of highly expected temperature gradient and a courser mesh elsewhere. A computer program is created using VB6 coding to follow the procedure of predicting the temperature distribution through the domain and the subsequent thermal damage zone.

Thermal dose equation

The effect of the elevated temperature on tissue depends on the temperature and the duration of the heating. A mathematical technique describing this effect is written as [14-19]:

$$TD = \int_{t_0}^{t_f} R^{(T-43)} \mathrm{d}t = \sum_{t=0}^{t\ final} R^{(T-43)} \mathrm{d}t \qquad (4)$$

where TD is thermal dose in minutes.

$$R(\text{Iso-dose constant}) \quad \begin{matrix} 2 \text{ for } T \geq 43\ ^\circ\text{C and} & (4a) \\ 4 \text{ for } 37\ ^\circ\text{C} < T < 43\ ^\circ\text{C} & (4b) \end{matrix}$$

This technique used the numerical integration to calculate the time that would give an equivalent thermal dose at a reference temperature (43 °C) for different temperature profiles. The thermal dose calculation is used to estimate the necroses tissue volume. The thermal dose value required for the total necrosis ranges from 25 to 240 minutes for brain to muscle tissues [18, 19]. This term is calculated continuously through the transient solution to predict the thermal dose as long as there is damage.

Result and discussion

Figure 2 represents the domain dimensions and the using mesh. Only one-half of the cross-section is shown because of symmetry. A detailed mesh is used so as to create a finer mesh in the region where thermal effect may be more severe (*i. e.* epithelium) and a courser mesh elsewhere, this strategy will increase the efficiency of the computer program.

The transient finite element solution is used to predict temperature distribution through the model. An example of far-IR laser is the continuous wave CO_2 laser having a wavelength of 10.6 μm where the main part of laser photons energy is absorbed by the tissue and is converted to heat. The damage thresholds are mostly derived from animal experiments, but the small amount of data from human exposure (accidental exposure and volunteers) has indicated that the threshold values are relevant for the establishment of safety standards [2].

Based on thermal dose equation and depending on experimental data, the threshold limit of cornea damage is obtained numerically comparing with that of irhuses monkey (*i. e.* a limit at which the power induced and time required to reach damage is meeting) which is found to be in order of 240 minutes. The comparison between the result from the current model and an experimental data for rhesus monkey is shown in fig. 3.

The predicted thermal dose is used as a guide to determine the damage zone on human cornea due to incidental CW CO_2 laser strike where the aim is to predict the intensity at which

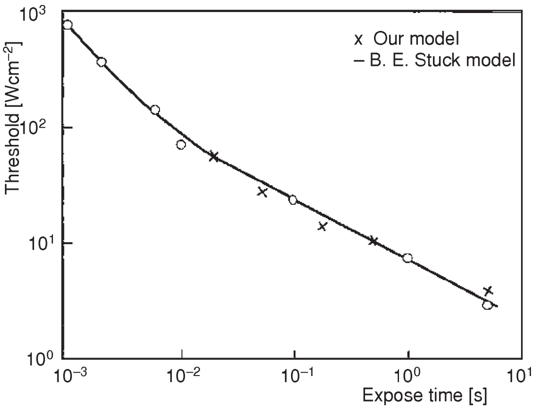

Figure 3. Threshold CO_2 laser irradiance needed to cause minimal damage to the cornea of rhesus monkeys as a function of expose duration data due to B. E. Stuck, Frankford Arsenal, adapted from reference [2]. The cross point indicates the predicted value, using the current model so that a thermal dose is found to be equal to 240 minutes

the damage of cornea do not exceed the previously mentioned 50 μm thickness layer that contains the epithelium.

Some good agreement can test the accuracy of the model compared with the standard curve for the maximum permissible exposure (MPE), which means the highest power or energy density of a light source that is considered safe, *i. e.* that has a negligible probability for creating damage. The MPE is usually about 10% of the dose that has a 50% chance of creating damage under worst-case. According to this rule, the predicted power from the finite element solution of this model that may start cornea damage must be divided by 10 to obtain the corresponding MPE, if the result of the model is said to be in agreement with the national standard of safety. The high safety factor is because of that some observations have indicated that the microscopic histological changes may occur at the lower levels than the burn threshold so safety standard is usually incorporated some reduction below the burn threshold.

After the threshold limit of the cornea is obtained then the minimum power level of an intra Gaussian continues wave CO_2 laser beam that may cause damage to the entire epithelium layer can be obtained. A several power level is tested to show at what depth the damage may reach. The result shows that a power of 0.0971 W having a power intensity of 12.387 W/cm^2 will take 0.061 s to reach the limit of pain sensation (*i. e.* when maximum temperature exceed 44 °C) and for 0.25 s for aversion reflex then the total time is 0.311 s for completely removing from the laser beam as aversion response. In this case, the maximum depth is found to be 57 μm (7 μm for tear layer and 50 μm for epithelium layer of cornea). As the eyelids are closed then only convection is applied where only the environmental temperature is changed to 37 °C which is assumed to be the temperature of the inside eyelid temperature. This thermal boundary condition is imposed on the outer edge of the tear layer following the path of closing the eyelid. This procedure is followed by ref. [3] and is used here. The temperature distribution at a response time is shown in fig. 4. The change in temperature due to laser accidental strike is not exceeding 1.5 mm in radial direction while only 1 mm in-depth direction is affected. The affected region may expand laterally more than in-depth, especially at a high temperature; this is because of high absorption coefficient of cornea. Figure 5 indicates the boundary of the damage zone which will increase rapidly as laser beam interact with tissue, then it may progress slowly when the laser is terminated. Finally the progress is stopped as the temperature decreases below 37 °C which is called relief condition .The fast and slow progress of the damage zone are shown in fig. 5.

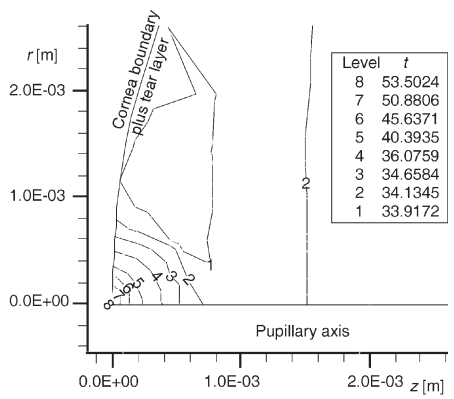

Figure 4. Enlarged view of temperature distribution at response time (0.31 s) to incidental laser strike

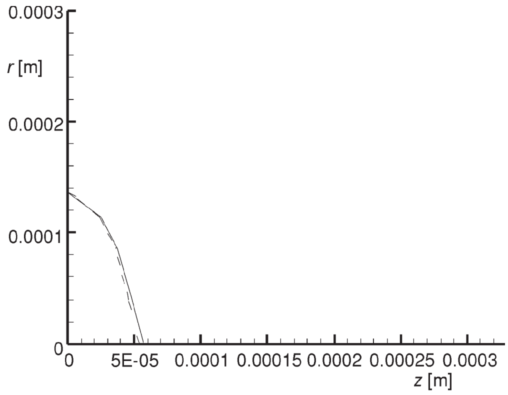

Figure 5. Damage zone at response time (dash line) and relief time (solid line)

The depth at a maximum expected damage region is predicted to be 57m which theoretically indicates the thickness of Epithelium plus tear layer.

Figure 6 indicates a comparison between the MPE as determined from the national standard of safety (solid line) and the result of this work (cross point) after imposing the safety factor. The nearby result may verify the result of this work. The reason of the small difference between the national standard and the result of this work are due to the increasing in the environmental temperature (inside eyelid temperature) which is closed to 37 °C. This means that the cooling rate will be reduced, also radiation and evaporation cooling may disappear while closing eyelid simultaneously so the cooling agents will be less effective and the tissue will hold in high temperature more than in the open eye model. Assume the usual analysis methods don't take into account the aversion response while computing threshold limit of damage.

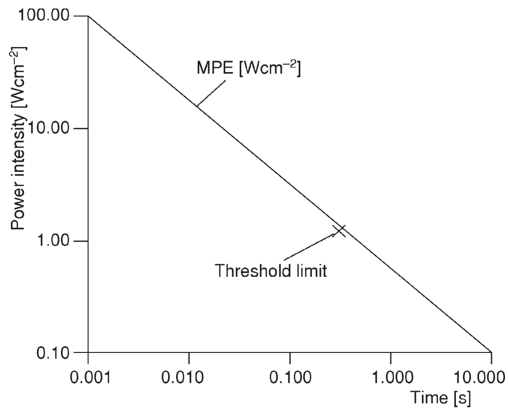

Figure 6. Comparison between result of this work (cross point) and international standard of safety (solid line)

Conclusions

From this work one can conclude that:

- the finite element solution of bio-heat equation is used to predict the temperature distribution through the cornea subjected to incidental laser exposure where the threshold limit of damage is obtained and successfully compared with the international standard of safety;
- the threshold levels for skin burns are similar to that of cornea; the cornea is not particularly more sensitive to damage by a CO_2 laser than the other portions of the skin, but it is known

that a small burn on the cornea may be more troublesome than a similar small burn elsewhere on the skin;
– cornea thermal dose is predicted from experiments on rhesus monkey where it is used successfully to determine the threshold limit of permanent irreversible damage due to incidental continuous wave CO_2 laser in human eye; due to high absorption of CO_2 laser photons in cornea then the cornea damage caused by this wavelength may be the maximum damage that can be occurred comparing with lasers of less wavelengths.

Nomenclature

c – specific heat, [$Jkg^{-1}K^{-1}$]
E – the heat loss due to evaporation of tears, [Wm^{-2}]
h – heat transfer coefficient, [$Wm^{-2}K^{-1}$]
k – thermal conductivity, [$Wm^{-1}K^{-1}$]
n – vector normal to surface, [–]
p – power, [W]
$\dot{Q}$ – heat generation, (Wm^{-3})
R – iso-dose constant, [–]
r – radial dimension, [m]
rf – reflectivity, [–]
T – temperature, [°C]
TD – thermal dose, [minutes]
t – time, [s]
W – perfusion rate of tissue, [$kgs^{-1}m^{-3}$]
w_0 – waist radius, [m]
z – axial dimension, [m]

Greek letters

ε – emissivity, [–]
μ – absorption coefficient, [m^{-1}]
ρ – density, [kgm^{-3}]
σ – Stefan-Boltzmann constant, [$Wm^{-2}K^{-4}$]

Subscripts

B – basal
b – blood
co – convection
f – final
m – metabolic
o – initial
r – radiation
s – surface
∞ – environmental

References

[1] Hamed, M., Nadeau, V., Dickinson, M. R., A Novel Modeling and Experimental Technique to Predict and Measure Tissue Temperature During CO_2 Laser Stimuli for Human Pain Studies, *J. Lasers Med. Sci, 21* (2006), 2, pp. 95-100
[2] Ready, J. F., Industrial Applications of Lasers, 2nd ed., Academic Press, San Diego, Cal., USA, 1997
[3] Cicekli, U., Computational Model for Heat Transfer in the Human Eye Using the Finite Element Method, M. Sc. thesis, Louisiana State University, Baton Rouge, La., USA, 2003
[4] Mihran, R. T., Interaction of Laser Radiation with Structure of the Eye, *IEEE Transactions on Education, 34* (1991), 3, pp. 250-257
[5] Minkowycz, W. I., Sparrow, E. M., Murthy, J. Y., Handbook of Numerical Heat Transfer, 2nd ed., John Willey & Sons, Inc., New York, USA, 2006
[6] Ooi, E., Ang, W., Ng, E., Bioheat Transfer in the Human Eye: A Boundary Element Approach, *Engineering Analysis with Boundary Elements, 31* (2007), 6, pp. 494-500
[7] Mcquistion, F. C., *et. al*. Heating, Ventilating, and Air Conditioning, 5th ed., John Wiley & Sons, Inc., New York, USA, 2000
[8] Mishima, S., Some Physiological Aspect of the Personal Tear Film, *Arch. Ophthalmol, 73* (1965), pp. 233-241
[9] Niemz, M. H., Laser-Tissue Interactions, Springer-Verlag, Berlin, Heidelberg, Germany, 1996
[10] Amara, E. H., Numerical Investigation on Thermal Effects of Laser Ocular Media Interaction, *International Journal of Heat and Mass Transfer, 38* (1995), 13, pp. 2479-2488
[11] Waddell, H. G., *et al*., Advance in Biological Heat and Mass Transfer (Ed. J. J . McGrath), ASME HTD, New York, USA, 1992
[12] Chen, B., Experimental and Modeling Study of Thermal Response of Skin and Cornea Wavelengths Laser Irradiation, Ph. D. thises, The University of Texas at Austin, Tex., USA, 2007

[13] Lewis, R. W., *et. al*., The Finite Element Method in Heat Transfer Analysis, John Wiley & Sons Ltd., Chichester, UK, 1996
[14] Sapareto, S. A., Dewey, W. C., Thermal Dose Determination in Cancer Therapy, *Int. J. Radiat. Oncol. Biol. Phys., 10* (1984), 6, pp. 787-800
[15] Chato, J. C., Fundamentals of Bioheat Transfer, in: Thermal Dosimetry Planning (Ed. M. Gautherie), Springer-Verlag, Berlin, 1990
[16] Roemer, R. B., Thermal Dosimetry, in: Thermal Dosimetry Planning (Ed. M. Gautherie), Berlin, Springer-Verlag, 1990
[17] Arkin, H., Xu, X., Holmes, K. R., Recent Developments in Modeling Heat Transfer in Blood Perfusion Tissues, *IEEE Trans. Biomed. Eng., 41* (1994), 2, pp. 97-107
[18] Dewey, W. C., Arrhenius Relationships from the Molecules and Cell to the Clinic, *Int. J. Hyperthermia, 10* (1994), 4, pp. 457-483
[19] Damianou, C. A., Hynynen, K., Fan, X., Evaluation of Accuracy of a Theoretical Model for Predicting the Necroses Tissue Volume during Focused Ultrasound Surgery, *IEEE Trans. Ultrason. Ferroelect. Freq. Contr., 42* (1995), 2, pp. 182-187

Paper submitted: December 3, 2009
Paper revised: January 4, 2010
Paper accepted: January 6, 2010