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Thermal Analysis of Muscle Tissues Exposed to Electromagnetic Fields

Elektromanyetik Alana Maruz Kalmış Kas Dokusunun Termal Analizi

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Abstract

The interaction between electromagnetic fields and biological masses is increasing day by day. There are thousands of studies in the literature on this interaction. Until now, most of the studies on bio heat transfer have focused on damage caused by electromagnetic fields. However, the therapeutic side of electromagnetic fields has been neglected. This study aimed to bring a new perspective. Using the bio heat transfer equation, the temperature effect of different parameters due to the electromagnetic field was investigated. In the present study, the analytical solution of Pennes' bioheat transfer equation was evaluated together with real muscle tissue parameters. By trying different parameter variations, the effect of parameters such as perfusion constant and thermal conductivity coefficient on tissue warming was observed. In the light of this study, device designs for magnetic heating processes applied in physiotherapy will be possible. After entering the tissue parameters and electromagnetic field values, it was possible to find out what kind of temperature change can be observed as a result of the formulation obtained in this study. The effects of thermal conductivity coefficient, blood perfusion value and heat transfer coefficient on temperature distribution were graphically analyzed. Effect of randomly selected thermal parameters are evaluated within the study. This study has shown to what extent the increasing thermal parameters of the tissue will be affected by the electromagnetic field.

Keywords: *• Bio heat transfer, Hyperthermia, Thermal effect, Electromagnetic field exposure, Pennes' Bio Heat Transfer Equation, Electromagnetic effects on muscle tissue*

Öz

Elektromanyetik alanlar ve biyolojik kütleler arasındaki etkileşim her geçen gün artmaktadır. Literatürde bu etkileşimle ilgili binlerce çalışma bulunmaktadır. Şimdiye kadar biyo ısı transferi üzerine yapılan çalışmaların çoğu elektromanyetik alanların neden olduğu hasara odaklanmıştır. Ancak elektromanyetik alanların tedavi edici yönü ihmal edilmiştir. Bu çalışma yeni bir bakış açısı getirmeyi amaçlamaktadır. Biyo ısı transfer denklemi kullanılarak, elektromanyetik alan nedeniyle farklı parametrelerin sıcaklık etkisi araştırılmıştır.

Bu çalışmada, Pennes'in biyoısı transferi denkleminin analitik çözümü, gerçek kas dokusu parametreleri ile birlikte değerlendirilmiştir. Farklı parametre varyasyonları denenerek perfüzyon sabiti ve termal iletkenlik katsayısı gibi parametrelerin doku ısınmasına etkisi gözlemlendi. Bu çalışma ışığında fizyoterapide uygulanan manyetik ısıtma işlemleri için cihaz tasarımları yapılabilecektir. Doku parametreleri ve elektromanyetik alan değerleri girildikten sonra bu çalışmada elde edilen formülasyon sonucunda ne tür bir sıcaklık değişiminin gözlemlenebileceğini bulmak mümkün olmuştur.

Anahtar Kelimeler: *Biyo ısı transferi, Hipertermi, Termal etki, Elektromanyetik alan Maruziyeti, Pennes' Bio Isı Transferi Denklemi, Elektromanyetik alanların kas dokusuna etkisi*

1. Introduction

With the spread of wireless communication, the interest in electromagnetic fields has increased. This interest has brought with it two more emotions to the present day. The first was curiosity, the other was fear. The sense of curiosity made people ask the question for what useful works wireless energy can be used and has led to the development of many devices. On the other hand, fear made us think that the rapidly increasing number of wireless devices could be the cause of many diseases, especially in the 20th century. As a matter of fact, when the literature is examined, it has been investigated whether there is a relationship between electromagnetic fields and diseases [1-11]. Some of the studies carried out in this context are presented as examples below.

Zamorano and Torres investigated whether the 900 and 1800 MHz radiation emitted by mobile phones affects the brain tissue and reached two important conclusions. i) Electromagnetic field absorption emitted from cellular phones is strong, so the specific absorption rate coefficient is higher than the classical model,. ii) Inverse skin effect occurs at 1800 MHz [1].

In another study, the effect of oxidative stress on antioxidant systems was presented in a review. In this study, it is reported that exposure to EMF causes oxidative stress in many tissues of the body. [2].

Christ et al. detected two different effects in their study to investigate electromagnetic near field characterization in biological tissue layers at frequencies between 30 MHz and 6000 MHz. It has been observed that when the distance between the tissue and the antenna is long, the continuous wave effects depend on the frequency and the thickness of the adipose tissue, and when the distance is close, the electromagnetic field reactive fragments cause high local absorption on the skin. [3]. Although they found that it causes high absorption in the skin, Christ and his team observed the amount of absorption in the skin, or the amount of heat generated in the skin.

Researchers, who think that the electromagnetic field has an increasing effect on daily life, wanted to investigate whether the electromagnetic field emitted from the hair dryer has an effect on sperm. carried out this study with rats that they divided into 9 groups. It was reported in the study that sperm count and morphology were not affected by the hair dryer. However, it has been determined that sperm motility is affected by electromagnetic fields. [4].

In [5,6], it has been emphasized that the potential risks are high due to the electromagnetic field emission of devices such as telecommunication, medical equipment, and many other apparatus that we use in our daily lives. Some studies even show an association between exposure to EMF and increased Leukemia, cancer, and brain tumors. For this reason, it was emphasized that the interaction between EMF and the human body should be investigated. It has been recommended that measures should be taken now in order to prevent more important problems in the future.. In another study, Researchers investigating the effect of pulsed electromagnetic fields (PEMF) frequency and exposure time on peripheral nerve regeneration found that PEMF increased peripheral nerve regeneration [7]. Studies carried out with electromagnetic fields are carried out in many different ways. In another study [8], the effect of high voltage and low frequency electromagnetic field on rabbit teeth was investigated. It has been observed that ELF-EMF exposure can alter the content of certain TEs in teeth.

Comlekci studied dielectric materials in biological tissues. At the end of his work, he concluded that radio frequencies cause an increase in temperature in living tissues and that electric fields are responsible for the excited and directed polarization [9]. In investigating the relationship between EMF and the nervous system [10], it was suggested that low-intensity microwave EMFs produce neuropsychiatric effects, sometimes called microwave syndrome. The starting point of this study is based on researches made especially in Soviet Russia. It has been mentioned that sleep disturbance, depressive mood and concentration impairment may be related to low-intensity emf exposure. Another important aspect of this study is the analysis of the relationship between EMF and the nervous system in the last 50 years, independent of thermal effects..

It is known that one of the most rapidly observed effects of EMF in the human body is oxidative stress. In this sense, the relationship between oxidative stress and electromagnetic fields was systematically investigated in the study number [11] carried out. During this review, current articles from the last 10 years were scanned. The study was carried out separately for many different branches. However, the result did not change and it was reported that RF-EMF caused oxidative stress.

As can be seen from the literature summary above, there is a serious concern in this regard. World Health Organization (WHO) and International Commission on Non-Ionizing Radiation Protection (ICNIRP), two important organizations that do not find these concerns unfounded, warn the humanity to take their caution to long-term effect of electromagnetic fields. Indeed, the common point of numerous studies in this issue in the literature is that continuous exposure is the most dangerous type of exposure [12]. In the last quarter century, the interaction between humanity and electric devices is increasing. Since, almost all devices which use electricity emit electromagnetic fields around them. Therefore, this issue attracts the attention of the scientist. According to Pubmed statistics, around 212 scientific publications have been published on average every year on the keywords "electromagnetic power density" or "electromagnetic pollution" or "electromagnetic radiation" in the last 10 years (Fig. 1). Hundreds of studies conducted every year are proof of the continuing interest in this field.

In the other hand, electromagnetic fields are not only shown as the cause of diseases. It is also known to be used in many treatments. There are dozens of studies on this subject in the literature. It is practically impossible to present all of them within the scope of this article. For this reason, a few examples are presented below. Electromagnetic field therapy has proven beneficial in certain neurological, psychological and chronic diseases [13]. Uzunca et al. compared the treatment options applied in lateral epicondylitis with PEMF (Pulsed Electromagnetic Field) in terms of pain. It was determined that there was a significant decrease in pain in the group that received local steroids and anaesthetics compared to the group in which magnetic field was applied, and in the group that was applied magnetic field, compared to the placebo group [14]. Another study, in which a sciatic nerve injury model was created, it is reported that PEMF and swimming exercise contributed to sciatic nerve recovery [15]. Beneficial results of PEMF have been observed in cases of delayed union and union of the tibia or long bones. In addition, it is also used in the healing of wrist, ankle and vertebral fractures, although its superiority over other fracture techniques is not clear [16, 17].

As can be understood from the literature presented above, electromagnetic fields also attract attention due to studies on their possible beneficial effects. These studies are concentrated in the field of dosimetry and hyperthermia. However, it is not appropriate to carry out these studies on the human body in terms of academic work ethics. For this reason, mathematical models are used. For the same reason, SAR calculations are not performed on the human body. For this reason, experiments are carried out on tissue-like liquids or SAR calculations are made mathematically.

Transportation of thermal energy caused by electromagnetic field in biological tissues is a compherensive mechanism such as, convection, radiation, evaporation, interior metabolism and inherent temperature regulation. Also, the main distinction between living tissues and ordinary tissues abiological materials is the remarkable effect of blood. The effect of perfusion on the temperature field in the body differs between various tissues and organs. As a result It is very difficult to create universally valid models for fully describe the heat transfer process. So that, most of the proposed bioheat equations are very complex . For this reason, many heat transfer equations and heat transfer equation solutions have been developed in the last 60 years.

In 1978, Foster et al. applied the Fourier transform to Pennes' bio heat transfer equation and determined the temperature increase in the tissue area [18]. However, they could not determine the analytical expression of the temperature field. Later, Nelson et al [19] tried to solve the bio heat transfer equation with the Laplace transform, but they could not create a clear formulation for regions other than the skin surface. Subsequently, in studies with Green's functions, exact solutions were obtained with infinite series [20-23]. However, none of the studies carried out in the past could provide a clear analytical solution of the pennes equation.

The fact that there are many different solutions in the literature and the parameter selections used in these solutions are not standardised causes each study to be original.The effects of the main thermal parameters of

biological tissues on the temperature distribution are reviewed, where the most important parameter values considered in the bio heat transfer equation [24, 25]. Indeed, the effect of these basic parameters was examined in this study.

The main motivation of this study is modeling and interpretation of temperature increase in tissues. The main phenomenon investigated in this article is the investigation of the thermal effect that may occur in different tissues due to the electromagnetic field. In this context, setting a general template will be very important for future studies. A lot of work has been done on this subject so far. However, the common aspect of most of these studies was that they made general assumptions and used numerical methods. In this study, different from the literature, a differential equation analysis was carried out. With this analysis, it was possible to perform a general analysis for all tissues. The most commonly used method in the literature for this analysis is Pennes Bio Heat Transfer Equation [26]. The biggest difference of this heat transfer equation of Pennes from other heat transfer equations is that it includes the perfusion effect of the blood entering and leaving the tissues into the calculation.

2. Method

2.1. General Form of Bio Heat Transfer Equation (BHTE)

The fundamental equation form of Pennes' bio heat transfer equation is as follows [26];

$$\rho_t C_t \frac{\partial T}{\partial t} + w_b C_b (T - T_a) = k \frac{\partial^2 T}{\partial x^2} + Q_m \tag{1}$$

where ρ_t, C_b and k are density of tissue (kg/m^3), specific heat of the tissue (J/(kg.K)) and thermal conductivity (W/(m.K)), respectively. wb is the mass flow rate of the blood per unit volume of tissue (Kg/(s.m^3)).C_b is the blood specific heat. Q_m is the metabolic heat generation per unit volume, (W/m^3). T_a is the temperature of arterial blood (^{o}C). T is the temperature rise above the ambient level and ∂T/∂t is the rate of temperature rise [27].

The main advantage of Pennes model is that the added blood perfusion term is linear with the temperature, which makes the equation easy to solve. Heretofore, it is proven that Pennes' equation is the most successfully used bioheat transfer equation among those applied [28].

As mentioned above, there are many studies in the literature about the pennes bio heat transfer equation. These studies were conducted on different tissue types. Different numerical methods were used in almost all of these studies. These methods, which are frequently used in the literature, some of them can be listed as follows: Finite element methods (FEM), finite difference methods (FDM) and Monte Carlo method [29-36].

In addition to literature, one of the recent studies in the literature can be presented as one of the previous works of the author [27]. In this study, Pennes bio heat transfer equation analysed analytically. The analytical analysis of the bio heat transfer equation obtained in previous study is presented as follows. No numerical method was used, while obtaining this analytical result.

$$T(x,t) = \left(\frac{h(T_{out}-T_a) - k\frac{Q_m}{w_b C_b}\sqrt{\frac{w_b C_b}{k}}e^{-\sqrt{\frac{w_b C_b}{k}}h}}{k\sqrt{\frac{w_b C_b}{k}}[\![e]\!]^{\sqrt{\frac{w_b C_b}{k}}h} + e^{-\sqrt{\frac{w_b C_b}{k}}h}]} \right) e^{-\sqrt{\frac{w_b C_b}{k}}x} - \left(\frac{h(T_{out}-T_a) - k\frac{Q_m}{w_b C_b}\sqrt{\frac{w_b C_b}{k}}e^{-\sqrt{\frac{w_b C_b}{k}}h}}{k\sqrt{\frac{w_b C_b}{k}}[\![e]\!]^{\sqrt{\frac{w_b C_b}{k}}h} + e^{-\sqrt{\frac{w_b C_b}{k}}h}]} + \frac{Q_m}{w_b C_b} \right) e^{-\sqrt{\frac{w_b C_b}{k}}x} + T_a + \frac{Q_m}{w_b C_b}$$

As can be seen from the analytical result, there is no need for any assumptions for the solution of the equation. After that, mathematical operations can be carried out by determining the tissue parameters.

3. Results

3.1. Application of the Thermal Parameters to BHTE

In this study, one-dimensional analysis was performed. In order to perform detailed analysis, the steady-state temperature distribution in muscle tissue can be examined using the analytical solution. The parameters presented in table 1 are used in the main equation to perform a real theoretical analysis. There are many articles in the literature on the electrical properties of tissue types. In these articles, it has been noticed that different electrical values are taken for the same tissue. For this reason, while determining the data set to be used in the evaluation of the results, the data from the most cited study was utilized.

As known, the change of each parameter can affect the theoretical analysis results. Therefore, the effects of thermal conductivity, blood perfusion, metabolic heat generation and heat transfer coefficient on temperature distribution are investigated and shown in Figure 3,4,5, respectively.

Table 1. Muscle Tissue Parameters [37]

w_b [Kg/(s.m^3)]	C_b (J/(kg.^{o}C))	k W/(m ^{o}C)	T_a (K)	h_A W/(m^2 ^{o}C)	Q_m W/m^3
3	3850	0.48	310	10.023	1085

As mentioned above, There are many tissues and organs in the body. The electrical parameters (thermal conductivity, blood perfusion, heat coefficent) of each of these organs and tissues are different from each other. Therefore, it can be understood from here that the effect of the electromagnetic field will be different for each tissue. In order to understand this effect, randomly determined thermal conductivity coefficients, blood perfussion and heat coefficent values were determined and it was stated in which direction the temperature changes that may occur in the tissues in case of their changes. Figure 1-2-3 shows the temperature effect of each parameter on the tissue. There is no fundamental motivation for the random selection of electrical parameters of the tissues. Since, there is no consensus in the literature on this issue. On the other hand, since there are countless tissues and organs in the body, it is practically impossible to evaluate all of them within the scope of this article.

As seen in the figure 1, the temperature drops sharply in the radial direction as the thermal conductivity constant increases (within a certain distance). This significant decrease seen in the graph is also compatible with the literature. Since, high thermal conductivity has better heat transfer capacity. However, it should not be overlooked that the constant k can be evaluated within a certain range for living tissues. Additionally, it is not an expected situation for the k constant to take a value above 1 in living tissue. For this reason, experiments were made for 3 different values in the graph above. However, no matter how large the k value became, its effect on temperature was limited.

The effect of different blood perfusion rates on the temperature distribution was also obtained with this study. It is shown in Figure 2. The perfusion event can be described as the regulation of the external temperature change in the tissue by blood flow. Perfusion is an effective and powerful parameter on the temperature distribution in tissues. As can be seen in the figure 2, it is seen that the temperature in the tissue decreases more slowly as the perfusion coefficient increases. In addition, the following information can be given, the larger the blood perfusion rates, the smaller the differences in their effects on temperature distributions

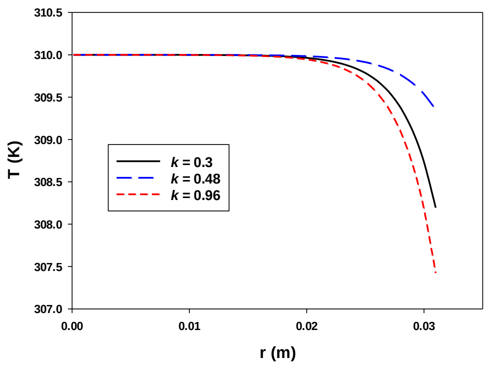

Figure 1. Effects of the thermal conductivity on Temperature distribution

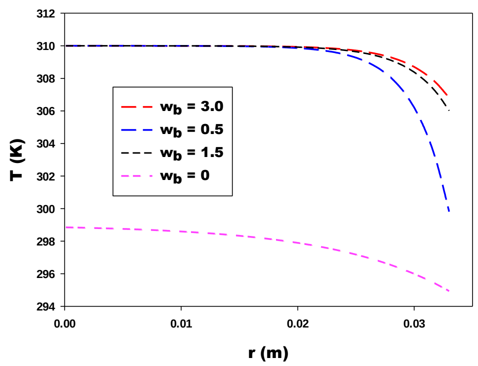

Figure 2. Effects of the blood perfusion on Temperature distribution

The effect of different blood perfusion rates on the temperature distribution was also obtained with this study. It is shown in Figure 2. The perfusion event can be described as the regulation of the external temperature change in the tissue by blood flow. Perfusion is an effective and powerful parameter on the temperature distribution in tissues. As can be seen in the figure 2, it is seen that the temperature in the tissue decreases more slowly as the perfusion coefficient increases. In addition, the following information can be given, the larger the blood perfusion rates, the smaller the differences in their effects on temperature distributions.

From Figure 3 it can be concluded that the higher the heat transfer coefficient, the lower the temperature close to the body's border. Since, as the heat transfer coefficient increases, the temperature wants to pass through the skin area quickly and reach deeper. Thus, no temperature is formed in the skin area with the increased heat transfer coefficient. For example, if a device is to be developed, the depth at which this device will create temperature is directly related to the heat transfer coefficient. For this reason, the heat transfer coefficient should be taken into account when setting the frequency and power.

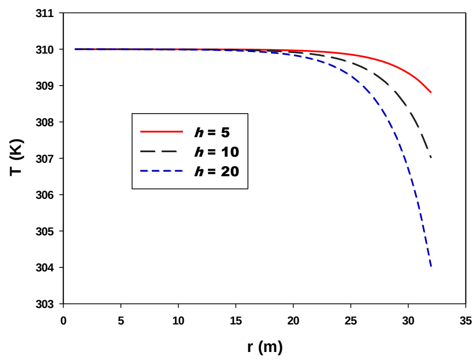

Figure 3. Effects of the heat coefficient on Temperature distribution

While the analytical solution of the main equation and the effects of the parameters in the analytical solution on temperature are examined, it is seen that the effect of perfusion is more than all other parameters. As a matter of fact, the perfusion effect is expressed as the strongest aspect of the bio heat transfer equation. In fact, its perfusion feature is the reason why it differs from many other heat transfer equations in the literature.

4. Conclusion

In this paper, a very serious theoretical knowledge base is presented. Firstly, in the case of interaction of electromagnetic fields with biological tissues, a literature summary is presented regarding both its adverse and therapeutic aspects. Subsequently, the bio heat transfer equation was analyzed analytically. Then, the real muscle tissue parameters and the equation were customized and solved. Parameters valid for any tissue can be tested in the obtained analytical solution. In this respect, this study provides useful information for other researchers.

The effects of thermal conductivity coefficient, blood perfusion value and heat transfer coefficient on temperature distribution were analyzed one by one, respectively. The effect of each variable on the temperature distribution is presented graphically. When different thermal parameters are evaluated, the results are interpreted. This study can be used when investigating the temperature relationship between different tissue types and electromagnetic fields.

The findings obtained as a result of this study can be used to develop a new device. In methods such as pulsed magnetic field therapy used in physiotherapy, each tissue is usually intervened with the same frequency band. However, the states of the tissues being affected by the electromagnetic field are different from each other. In this context, using the results of this study, a device that will show a different characteristic for each tissue can be developed. Since, with the findings obtained from this study, it will be possible to determine how much temperature increase can be achieved in which tissue.

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