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The Effect of Return Electrode Position on Induced Electric Fields for Electrical Stimulation of Retinal Ganglion Cells

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Age-related macular degeneration and retinitis pigmentosa are the most countered eye diseases that damage photoreceptors and cause to lose the visual sense. To regain the visual sense, studies are focused on the electrical stimulation of nerve cells remain intact. The electrical stimulation is carried out with the electrode arrays that include a certain number of stimulation electrodes and a common return electrode. In this study, the retinal stimulation is modelled using a computational model to investigate stimulation performance depending on the return electrode position and its geometrical properties. Stimulation induced electric field, current density and temperature over the retinal tissue are examined. It is seen that closer placement of return electrode and stimulation electrodes causes high electric field intensity and current density between electrodes, which is quite risky for long term chronic implementation by the reason of the increase in the temperature beyond the safe limits. It is concluded that there is an indispensability for the distances, three to five times of the electrode diameter, between electrodes to avoid electrode corrosion and tissue damage.

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PACS/topics: electrical stimulation, electric field, current density, temperature, retina, visual prostheses

1. Introduction

Vision initiates with the light coming from outside to the eye. The light is firstly transformed to electrical signals and then follows visual pathway in which it is subjected to different signal processing steps to form the vision. The healthy vision could be damaged because of degenerative retinal diseases such as age-related macular degeneration (AMD) and retinitis pigmentosa (RP). They affect negatively retinal layers, especially photoreceptor layer, then cause to loss of vision. Different research groups are focused on the efforts for the restoration of the vision which is lost by the degenerative diseases. The impact of the blindness increases and affects much more people day by day all over the world. AMD and RP are the most common retinal diseases leading to blindness in the world [1]. AMD damages retinal pigment epithelium (RPE) layer in the eye and leads to tunnel-like vision just before complete blindness and affects 30% of population which is above 70 years of age [2, 3]. The patients with RP become fully blind over time after the damage to photoreceptor layer of the retina. Despite there is not detailed research which have been carried out yet on the diseases causing loss of vision in Turkey, it is reported that more than 30% of cases seen is associated with these two diseases [4].

The developing technology in recent years makes the restoration of vision enable for the patients suffering from these diseases. The developments in bioengineering and microtechnology provide the innovation of highly sophisticated microelectronic devices designed to stimulate the appropriate nerve tissues which remain intact for severe patients to elicit the functionality in a certain level, then restore the vision. Any devices that enable visual perception, point lights called phosphene, could be called as visual prosthesis. Visual prosthesis is used to electrically stimulate intact nerve cells through visual pathway. Bypassing damaged parts and focusing healthy regions of the visual pathway, visual restoration could be provided in the brain. Visual prosthesis could be classified as retinal prosthesis and non-retinal prosthesis [5]. Retinal prosthesis covers the restorative studies related with impairments in retinal layers. It is divided into subretinal and epiretinal prostheses. Non-retinal prosthesis aims to provide the visual restoration by using outer parts of visual pathway, which includes optic nerve and cortical prosthesis. The most advanced device developed uses epiretinal approach among them.

In this study, three-dimensional retina stimulation environment is developed to investigate electric field distributions over the retina. Under quasi-static conditions, electric field is calculated with the Maxwell equations, its derivatives. Stimulation electrodes and return electrode are positioned on the three-dimensional retina tissue. When the stimulation current is applied to the electrodes, field distributions are seen on it. The effect of return electrode on electric field distribution near the stimulation electrodes is examined.

2. Three-dimensional retina stimulation model

The model geometry is simplified and consists of $9\ \mathrm{mm} \times 9\ \mathrm{mm} \times 250\ \mu\mathrm{m}$ domain as a retina tissue. Stimulation electrodes and return electrode are placed on retina tissue as a different domain. While stimulation electrodes have diameter of $200\ \mu$m and 1 mm center to center electrode spacing, return electrode of diameter $500\ \mu$m is

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placed far away from stimulation electrodes which is complied with the real devices. After placing the electrodes an activation region could be generated between them and electric field intensity could be examined through retina tissue, Fig. 1.

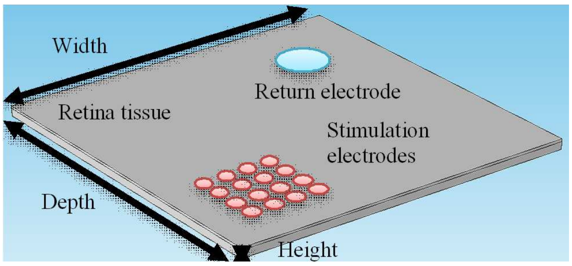

Fig. 1. Stimulation electrodes and return electrode placed on retina tissue.

It is assumed that retina is homogeneous and isotropic. Under quasi-static conditions, electric field is calculated according to the Maxwell equations and its derivatives. Differential equations that describe and solve the problem are presented. Electric field behavior produced by electrical stimulation of the tissue is stated using the Maxwell equations and its derivatives [6-11]. Electric field is calculated by solving the Maxwell equations under quasi-static conditions

$$\nabla \cdot \boldsymbol{J} = 0, \tag{1}$$

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon}, \tag{2}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E}, \tag{3}$$

$$\boldsymbol{E} = -\nabla V, \tag{4}$$

$$\nabla^2 V = 0. \tag{5}$$

Under quasi-static approach, the electric potential V is found using the Poisson equation. The Poisson equation means that there is at least one source in isotropic heterogeneous medium. If there is no source and the medium has homogeneous electrical conductivity, then the Poisson equation becomes the Laplace equation, Eq. (5). On the other hand, to determine the temperature rise on the tissue bio-heat equation is used. When biological tissues are electrically stimulated, temperature increases due to the Joule and metabolic reactions [12–14]. The Joule effect is formed by the presence of electric field. The calculation of the temperature rise over the tissue is calculated by the Pennes bio-heat equation

$$\nabla \cdot (-k \nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{met} Q_{ext}, \tag{6}$$

where k, ρ_b, C_b, ω_b, Q_{met}, Q_{ext} represent respectively thermal conductivity [W/(m K)], density [kg/m^3], specific thermal capacity [J/(kg K)], blood volume flowing per second [1/s], heat source of metabolism and external heat source [W/m^3].

3. Results

Typical stimulation current waveform is applied to the stimulation electrodes. Stimulation electrodes are placed 4 by 4 layout which is convenient with the developed devices. An activation region is formed between stimulation and return electrode. The cutline is defined over the tissue to follow the value of the parameter that we examine in its position. The cutline defined is presented in the figures. 1 μA stimulation current is used to apply the signal to the electrodes. The effect of return electrode diameter is analyzed for different diameters such as 100 μm and 500 μm Fig. 2).

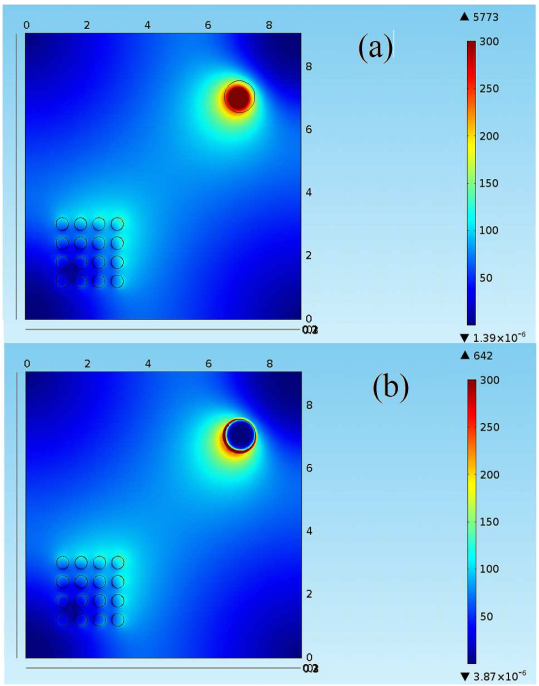

Fig. 2. Electric field distribution for different return electrode diameters: (a) $d = 100$ μm, (b) $d = 500$ μm.

Electric field intensity is much higher up to a certain electrode diameters. Near the return electrode electric field is quite high when it is compared to larger electrode diameter. The increase in the electric field causes the possibility of thermal damage to the tissue because of the temperature rise. So, limiting electric field intensity on the tissue is needed to use visual prosthesis devices long term. The temperature rise on the tissue is presented Fig. 3).

The temperature rise on the tissue is about 0.726 °C. The presence of electric field causes the Joule heating and it results as temperature rise. The increase in the temperature could be vital when it is 2–3 °C or more. When the electric field norm is investigated, it is quite high near the stimulation electrodes and return electrode which faces stimulation electrodes. The retinal stimulation system usually includes just one and large return electrode as distinct from the number and size of the stimulation electrodes. Therefore, the superposition of the electric fields which arise because of each stimulation electrode firing is intensified in regions near the return electrode. The current completes its route with this

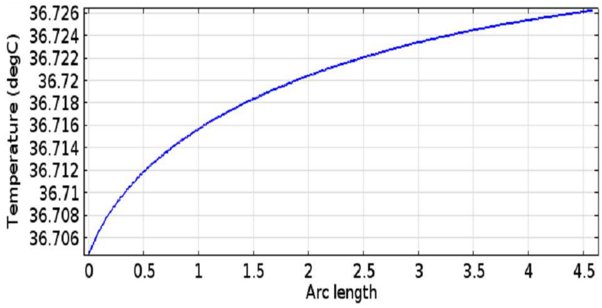

Fig. 3. Temperature rise on the tissue.

electrode near side. To increase the resolution of the visual prosthesis systems, localized electrical stimulation is needed. Localized electrical stimulation could be partly provided using the configuration that includes one large return electrode. Because the large return electrode gathers all the currents, the electric field produced by different sources is overlapped, which means electrode interaction. There is a tradeoff between system resolution and complexity. During design phase of a system, both electrode placements and return electrode geometry play critical role. To increase the resolution, instead of a large return electrode it is needed to use several return electrodes for a group of stimulation electrodes.

4. Conclusion

In the field of visual prosthesis, collaborative studies gain importance over the world and it is getting more interest. There are a number of physiological and biological constraints that should be taken into consideration to obtain high resolution system. Studies using realistic simulation models save both time and unnecessary expenses because simulation environment is a great tool to examine the effect of electrical stimulation on the tissue and biologic tissue responses. Design phase of a system creates a tradeoff between the resolution of the system and system complexity. To increase the resolution, instead of a large return electrode, there is a need for a system which includes several return electrodes for a group of stimulation electrodes. Each parameter should be taken into consideration for an efficient high resolution system development.

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