Finite Element Analysis of Microscale Luminescent Glucose Sensors in the Skin Dermis

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Introduction

With the rising predominance of diabetes, successful management of blood glucose levels is increasingly important. Key efforts have focused on the development of optical microscale glucose sensing systems based on the encapsulation of glucose oxidase within microspheres coated with polyelectrolyte multilayer nanofilms. A phosphorescent oxygen indicator is co-encapsulated with the enzyme inside the microspheres in order to report local oxygen levels, which can be related to blood glucose concentration. The intended application of these sensors is as implantable devices for glucose monitoring in subjects with diabetes; the sensors would be implanted intradermally and interrogated transdermally using light [1]. When implanting these glucose sensors in the dermis, acute host responses to the implant such as inflammation and fibrous encapsulation have to be considered. A two-substrate mathematical model of microscale optical glucose sensors in the skin dermis was developed using COMSOL™ (Figure 1) and utilized to predict the response of sensors with varying density of the sensors and the physiological characteristics of the surrounding dermal tissue. The utility of the model to predict the performance and efficacy of the sensors after the incidence of an immune response to the sensor implants is also demonstrated.

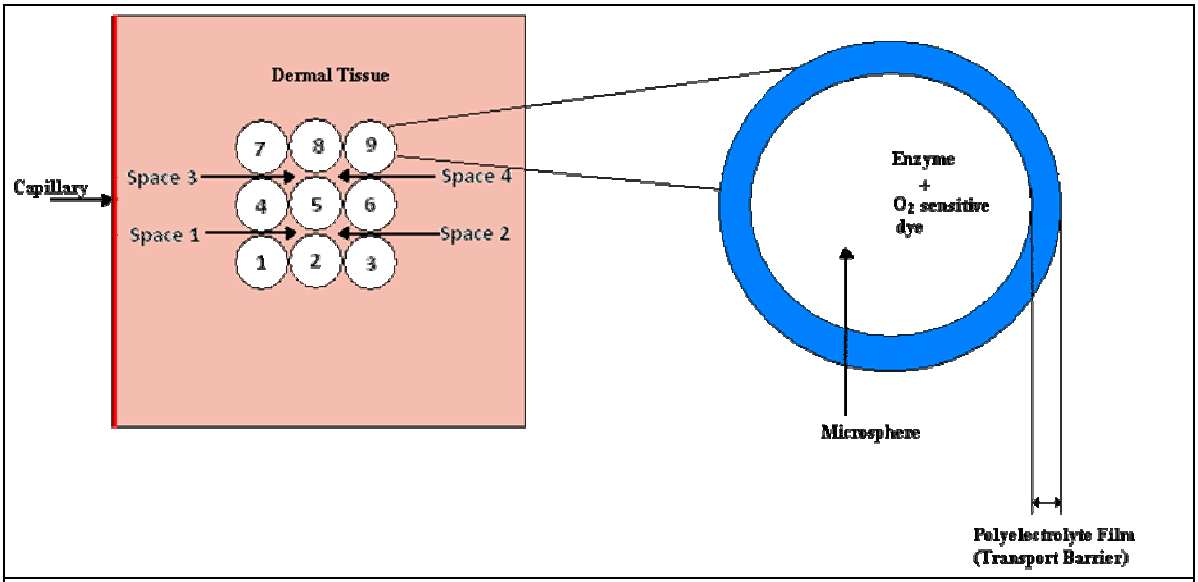

Figure 1:Schematic of microsphere sensors in the dermis

Use of COMSOL Multiphysics

The effects of varying the configuration shown in Figure 1 on sensor response and performance are currently being investigated using the chemical engineering module within transient analysis on the COMSOL Multiphysics software. Specifically, the space between the sensors is varied, and boundary conditions of the skin dermal tissue are altered in the model to set additional capillaries around the microsphere sensors. The model is two-dimensional and has been designed to mimic the dermal layer of the skin by accounting for tissue consumption rates of glucose and oxygen, capillary density, and tissue area. The average oxygen concentration is determined using integration coupling within the sensor area.

Furthermore, the simulation will be utilized to evaluate the effect of immune response (inflammation and fibrous encapsulation) on the sensitivity and performance of the sensors over a long duration.

Expected Results

Figures 2 and 3 illustrate the simulation results. Figure 2 shows the change in average oxygen concentration over time until steady-state is achieved within each sensor. The results from the simulation are expected. Figure 3 confirms that sensors closer to the capillary, which acts as a constant supply of bulk oxygen and glucose, have a shorter response time. Due to the slow diffusion of glucose through the dermal tissue space, the steady-state concentration for sensors farther away from the capillary seems to be higher since the rate of tissue consumption of glucose is faster than the rate of glucose diffusion through the tissue space.

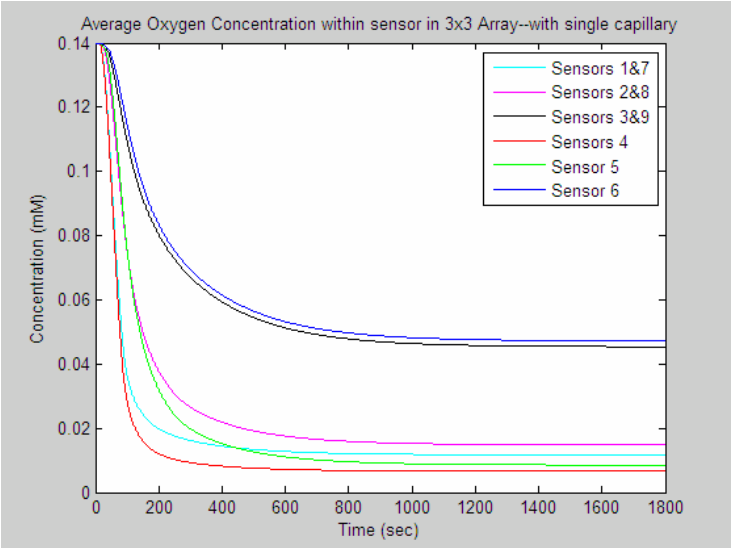

Figure 2. Results of average oxygen concentration within each sensor in the 3x3 array

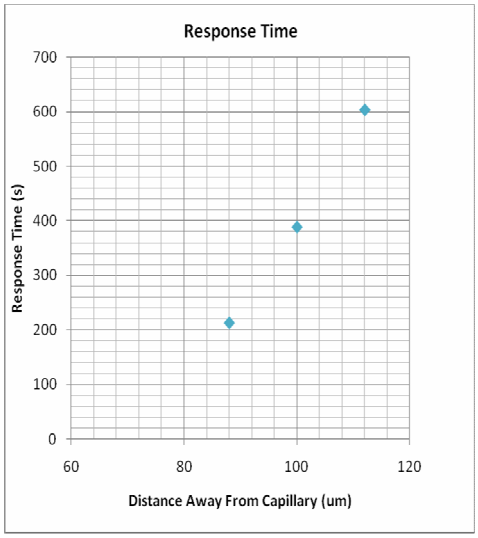

Figure 3. Response Time vs. Sensor location away from capillary

Results obtained from further COMSOL simulations will assist in determining the appropriate combination of physical dimensions and material properties for an optimal, rapid glucose sensing device.

Reference

1. McShane, M.J., Russell, R.J., Pishko, M.V., Cot´e, G.L., Towards Minimally-invasive Glucose Monitoring Using Implanted Fluorescent Microspheres. *IEEE Eng. Med. Biol. Mag*. **19**, 36–45 (2000).