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Simulation of heat exposure and damage to the eye lens in a neighborhood bakery

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A R T I C L E I N F O

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A B S T R A C T

Epidemiological studies indicated a link between high temperature environment and cataract. The purpose of the study was to investigate if the high temperature in neighborhood bakeries can cause damage to the eye lens. Measurements were done to determine the temperature and exposure time in the neighborhood bakeries during a workday. Thermal analysis was done using finite volume and finite element Computational Fluid Dynamics (CFD) codes in order to determine the temperature in the eye lens when exposed to environmental temperature fluctuations. A simulation of heat exposure was carried out using a bovine lens organ culture system. Two-hundred and seventy bovine lenses were divided into five groups. (1) Control group kept in culture for 11–14 days (2) Lenses exposed to 39.5 °C, 6 h daily starting on the second day of the culture and kept in culture for 13 days (3) Lenses exposed to 39.5 °C, 4 h daily starting on the second day of the culture and kept in culture for 11 days (4) Lenses exposed to 39.5 °C, 2 h daily for 3 days starting on the second day of the culture and kept in culture for 12 days (5) Lenses exposed to 39.5 °C, 1 h on the second day of the culture and kept in culture for 14 days. Lens optical quality was assessed during the culture period. At the end of the culture lens damage was demonstrated by inverted microscopy. Lens epithelial samples were taken for analysis of Catalase activities. Control lenses maintained their optical quality throughout the 14 days of the culture. Exposure to heat caused optical damage to the cultured lenses. The damage appeared earlier in the 6 h exposure group and progressed from the lens anterior suture to its center. Optical damage was recovered in lenses exposed 1 h to 39.5 °C, but the damage remained in the lens epithelial cells. Our study indicates that exposure to heat in bakeries can cause damage to the eye lens and that the damage is dependent on the length of exposure.

1. Introduction

Epidemiological and clinical observations have indicated a link between heat exposure and cataract. Workers in the glass industry, which involves high environmental temperatures, are at 2.5 higher risk to lose 30% of their sight as a result of cataract, compared with people from the same group of age who are not exposed to high temperature stress (Lydhal and Philipson, 1984). There has been evidence for cataract formation following exposure to infra-red radiation, radiation emitted from hot material (Okuno, 1990). It was reported that workers in the molten metal industry are at higher risk for cataract formation (Lankatilake and de Fonseka, 1990). It was not indicated what regulation regarding temperatures and time exposure is recommended.

There is also a lack of information regarding the temperatures that eventually reach the eye lens in a high temperature environment such as a bakery. In the present study we followed the thermal effects on the lens and the damage it causes as a result of heat exposure in a neighborhood bakery after we measured and calculated the temperature distribution in the eye.

The originality of this work is the study of the effects of heat on the intact lens in long-term culture conditions, and following the ability of the intact lens to recover form heat damage, in contrast to the effects of heat on isolated proteins from the eye lens (Horwitz, 1992; Horwitz et al., 1992; Borkman and McLaughlin, 1995).

2. Materials and methods

2.1. Determination of temperatures and exposure time in the neighborhood bakery

In order to simulate the conditions of bakery workers subjected to high environmental temperatures in their work place, the

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temperatures and exposure time were measured in a bakery during six working days. In the bakery, workers are exposed to high temperature when working close to the electrical oven. The workers lack any eye protection. As part of the daily work, workers push their heads into the electrical oven. The measurements were taken by attaching a thermometer probe to the temporal side of the eyeball of the worker, and following the temperature changes during a working day.

2.2. Thermal analysis of the heat reaching the eye lens

A finite element simulation of the bio-heat transfer equation in the human eye was first conducted by Scott (1988a,b). This method was used to determine the temperature in the human eye induced by infra-red radiation (Scott, 1988a,b). Later on, it was used by Okuno (1990, 1993) to study the thermal effects of visible light and infrared radiation. In the present study Galerkin finite element formulation and conservative finite volume scheme were used to solve the bio-heat transfer equation predicting the conductive heat transfer in steady-state and the history of the temperature distribution in the lens as a function of surface changes conditions over time.

For the purpose of the computational model the eye is divided into several sub-domains. Each sub-domain is assumed to be isotropic and homogeneous. The eye is assumed to be symmetric about the papillary axis. It is then convenient to formulate the problem in cylindrical coordinates.

With some simplifying assumptions concerning the geometry and structure of the eye, and the eye's heat transfer mechanisms (Scott, 1988a), the governing differential equation for the temperature distribution is the bio-heat transfer equation in the interior of the eyeball

$$\rho c \times \frac{\partial T}{\partial t} - \nabla(\kappa \cdot \nabla T) = 0 \quad \text{in } \Omega, \quad \text{and } \forall t > 0 \tag{1}$$

where Ω is the solution domain (the interior of the eyeball), T, unknown temperature, ρ, density, c, specific heat capacity, κ, thermal conductivity, and t, time. The symmetry boundary condition

$$\kappa \frac{\partial T}{\partial n} = 0 \quad \text{on the papillary axis} \tag{2}$$

The other boundary conditions are of convective type on all outer boundaries (the sclera and the anterior corneal surface)

$$\kappa \frac{\partial T}{\partial n} = h(T - T_{\text{outer}}) \quad \text{on the outer surface} \tag{3}$$

The initial temperature distribution is found by solving the corresponding steady state bio-heat transfer equation

$$\nabla(\kappa \cdot \nabla T) = 0 \quad \text{in } \Omega \tag{4}$$

where n is the unit outer normal to the surface and h is the convective heat transfer coefficient. On the sclera: h, convective heat transfer from the sclera to the body core and T_{outer}, blood temperature. On the anterior corneal surface: h is an equivalent radiation heat transfer coefficient and T_{outer} is given by the temperature history that the worker is exposed to. The values of physical constants h, κ, ρ, and c are taken from Scott (1988a):

On the cornea: $h = 20\ \text{w/m}^2\ \text{K}$ to include convection, radiation and evaporation of tears.
On the sclera: $h = 100\ \text{w/m}^2\ \text{K}$ (recommendations for eye to blood heat transfer are for $h_{\text{sclera}} = 65, \ldots, 110\ \text{w/m}^2\ \text{K}$).

In the present study both a Galerkin finite element formulation with bi-quadratic iso-parametric elements and a conservative finite volume scheme (Fluent CFD software) were used to resolve the bio-heat transfer problem, Eqs. (1)–(4), and to predict the conductive heat transfer in steady-state, and the history of the temperature distribution in the lens as a function of changes in surface conditions and time.

The eye is modeled as shown in Fig. 1A; dimensions were taken from Scott (1988a). A typical unstructured mesh consists of 5500 elements. The mesh is gradually refined towards the cornea, where most of the heat transfer takes place.

The model allows predicting the history of the temperature distribution in the human eye as a result of the cornea being transiently exposed to different types of external boundary conditions (mainly temperature).

2.3. Simulation of heat exposure using a lens organ culture system

Based on the thermal analysis results, a simulation in the laboratory was done using bovine lenses in an organ culture system. Bovine lenses were carefully excised from eyes obtained from animals up to 1-year-old, 2–4 h after enucleation. Each lens was placed in a specially designed culture cell with two compartments (Dovrat et al., 1986). Both lens surfaces were bathed in the culture medium (24 ml) consisting of M199 with Earle's salts, antibiotics (Penicillin 100 U/ml and Streptomycin 0.1 mg/ml) and 3% fetal bovine serum. All lenses were incubated at 35 °C. Experimental treatments were initiated after pre-incubation of 24 h. Only non-damaged lenses were included in the study.

2.4. Lens optical quality monitoring

The optical quality of the lenses was analyzed each day of the culture using a low power laser scanner. The scanner consists of a 2 mW, 670 nm helium-neon diode laser mounted on a computer-controlled *X*–*Y* table, and a television camera with a video frame digitizer (Sivak et al., 1990). The laser beam was parallel to the axis of the lens and was directed towards the cultured lens along one meridian in 0.5 mm increments. After passing through the lens, the laser beam is refracted and the system determines the back vertex focal length for every beam position. Each scan consists of measurements of the same beam from 22 different points across the lens. A lens of good optical quality is able to focus the laser beam from the various locations. When the lens is damaged its ability to focus the laser beam at the various locations is altered.

2.5. Lens photography using inverted microscopy

Photographs of five lenses from each treatment group and their contralateral control eye lenses were performed using an inverted microscope. We took pictures of the lenses periphery and centers using a final magnification of ×25 and ×100.

2.6. Analysis of catalase activities in lens epithelium

Lens epithelium was dissected under a binocular stereomicroscope. The lens capsule and its adherent epithelium were removed from the entire lens. The tissue was immersed immediately in a 200-μL volume of 50 mM phosphate buffer, pH 7.0. All further work was carried out at 0–4 °C. The tissue was sonicated in an MSE 150 W ultrasonic disintegrator (MSE; UK) at 50 W for 10 s twice followed by centrifugation at 14,000*g* for 10 min. Catalase activities of the supernatant were measured. Catalase activity was measured according to the method of Beers and Sizer (1952) by spectrophotometer recording of the cleavage of H_2O_2 at 240 nm.