Transient temperature distribution on the corneal endothelium during ophthalmic phacoemulsification: a numerical simulation using the nodeless variable element

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Background: During cataract operation (phacoemulsification), a phaco needle-tip is inserted into the anterior chamber of eye. Then, heat is generated by the oscillation of the phaco needle, which may injury the corneal endothelial cells. There are no data available for temperature responses at the corneal endothelium to heat from the phaco needle during phacoemulsification.

Objective: Investigate temperature distribution on the corneal endothelium during ophthalmic phacoemulsification using numerical simulation, and compare the transient temperature response to heat between balanced salt solution (BSS) and ophthalmic viscoelastic device (OVD), Viscoat®.

Methods: Heat flux from a phaco needle was measured with thermal properties of BSS and AVS in an experimental setting. Then, nodeless variable finite element method was applied to predict temperature changes in the eye by the phaco needle inserted into the anterior chamber. The transient temperature distribution on the corneal endothelium was calculated at 10, 20, and 30 seconds after heat generation by the needle.

Results: The heat generation of phaco needle without sleeve cover was 1.6 kW/m². The numerical simulation showed that the maximum temperature occurs on the wound location at all times after heat generation by the phaco needle. Especially, at time 30 seconds, it was 49.2 and 41.7°C in BSS and OVD, respectively. The temperature elevation by the phaco needle was lower in OVD than BSS.

Conclusion: Phacoemulsification is a heat-generating procedure performed between the anterior chamber structures of eye. During this procedure, OVD may protect the corneal endothelium against heat better than BSS.

Keywords: Balanced salt solution, corneal endothelial cell, nodeless variable element, numerical simulation, phacoemulsification, ophthalmic viscoelastic device

Cataract is the most common cause of blindness [1]. This is effectively confronted with by cataract operation called phaco-emulsification. The ophthalmic operation accounts for more than 80% of the ophthalmic field.

A well-known serious late complication of the operation is corneal blindness called pseudophakic bullous keratopathy (PBK). The PBK patient progressively suffers from many annoying symptoms such as irritating foreign body sensation in the affected eye, photophobia, tearing, and decreased vision due to corneal haze. As a result, PBK is the leading causes of corneal transplantation [2].

Corneal endothelial cells are an important non-regenerative corneal innermost layer to
maintain corneal transparency processes. The corneal endothelial cells are often injured by phacoemulsification during the operation for PBK. Many factors are involved in the cell injury during the operation, including free radical, shock wave, and direct mechanical trauma [3, 4]. Thermal factor during such operation is also serious in the operative complication.

During ophthalmic phaco-emulsification, a surgeon-controlled oscillating phaco needle-tip is inserted into the anterior chamber to emulsify lens materials. The oscillation of phaco needle-tip is driven by the attached piezoelectric crystal at variable presented stroke length, at a certain frequency, i.e. 28.5 or 40 Hz (For a phaco needle-tip inserted in the eye, see Appendix). Then, heat is generated by the oscillation of the phaco needle. This heat generation has been directly examined using thermal cameras [5-8]. It has been demonstrated that phaco needle generates heat along its entire length. However, the heat responses have been limited by experiment. There is no data available for temperature changes on the corneal endothelium during ophthalmic phacoemulsification.

The corneal endothelium exists as a monolayer of cell at the innermost part of cornea. Heat collection from the phaco needle that is inserted may be responsible for corneal endothelial cell injury [9]. In fact, when the phaco needle tip is inserted is fully occluded by lens material fragment in the anterior chamber, biofluid or solution cannot flow in and out of the chamber while the oscillating phaco needle emulsifies the engaged lens fragment and generates heat. Therefore, the highest risk of heat-induced cell-injury occurs during this particular period and many times during each operation.

In this paper, we simulated temperature changes in the eye chamber during performing phaco-emulsification. Based on heat transfer and two-dimensional (2D) finite element equation, computational procedure was carried out to predict the transient temperature distribution in the eye chamber. Defining two cases of phacoemulsification where the anterior chamber was fully filled by balanced salt solution (BSS) or ophthalmic viscoelastic device (OVD), we compared the transient temperature response at the corneal endothelium between BSS and OVD.

Methods

Experiment

The specific heat capacity and the thermal conductivity coefficient of BSS and OVD were tested using the differential scanning calorimeter (DSC) (Mettler-Toledo Inc, Columbus, USA) and hot disk thermal constants analyzer (TCA) (Hot Disk AB, Gothenburg, Sweden), respectively [10]. The TCA power started at 0.05 W for five seconds. To measure the heat generation from a phaco needle, we used as shown in Fig. 1. The fluid media was distilled water. For heat generation, the Millennium® phaco machine (Bausch & Lomb Co, New York, USA) was used. During the experiment we get the piezoelectric crystals at its maximum power 400% phaco-power-setting a 160 micron stroke length. To measure the temperature on the phaco needle surface, the resistance temperature detector PT100 was used as a temperature sensor. The phaco needle was operated with and without sleeve cover.
Numerical simulation

We investigated temperature changes on the median plane of eye where a phaco needle was inserted in the anterior chamber during performing phaco-emulsification. We assumed that temperature \( T \) in the eye obeys 2D transient heat transfer equation [11] and boundary conditions given by specified temperature, convection heat transfer, and specified heat flux, as shown in the Appendix.

In the numerical computation, we used element interpolation functions and finite element matrices [12-14] where triangular element consists of three nodes and three nodeless variables, as shown in Appendix. We drew a two-dimensional CAD (Computer-Aided Engineering) model to follow the ocular anatomy [15]. Figure 2 shows the finite element model that was constructed with 9,311 elements.

Result

Thermal properties of BSS and AVS, and heat generation by the phaco needle

Table 1 shows the measured specific heat capacity and thermal conductivity coefficient of BSS and OVD.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Specific heat capacity (J/gK)</th>
<th>Thermal conductivity coefficient (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance salt solution (BSS)</td>
<td>2.45</td>
<td>0.65</td>
</tr>
<tr>
<td>Alcon viscoat solution (OVD)</td>
<td>3.91</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Transient temperature distribution by simulation

In the numerical simulation, heat generation \( q_s \) from the phaco needle was assumed to be the heat flux of 1.6 kW/m². Temperature \( T_\infty \) at the outer surface of the cornea was assumed to be the room temperature (25°C). The anterior chamber was fully filled with BSS or OVD. Using their thermal properties measured (Table 1), we calculated the thermal diffusivity \( \frac{k}{\rho c} \) as follows: 2.36 \times 10^{-9} \text{(m²/sec)} for BSS, 1.19 \times 10^{-8} \text{(m²/sec)} for OVD.

These values were used for solving the finite element equations. For the thermal properties of eye, we used those employed by Cicelki [16].

Figure 3 shows the temperature response using BSS at the time of 30 seconds.
With initial temperature of 37°C at t=0, the transient temperature response at the time of 30 seconds was computed. The time-interval required for this computation was approximately 0.1 second. Figure 4 shows the transient temperature response plotted along inner corneal surface at 10, 20, and 30 seconds for BSS and OVD. Interestingly, the computed temperature on the corneal endothelium was lower in OVD than in BSS at any time and location. The maximum temperature occurred on the wound location at all presenting times. Especially, at time 30 seconds, the maximum temperature in BSS and OVD were 49.2°C and 41.7°C, respectively. The maximum temperature difference between BSS and OVD, on the wound location at time 10, 20, and 30 seconds were 4.0°C, 6.2°C, and 7.5°C, respectively.
Discussion

Numerical approaches using computer fluid dynamics (CFD) is most useful for biomedical studies in various organs including brain [17] and nose [18]. In some earlier numerical studies involving ocular models, the finite difference method was used to solve human eye heat transfer [19, 20]. The temperature rise in the human eye exposed to electromagnetic waves was modeled by the finite different time domain method [21, 22]. Bioheat transfer in human eye was also studied by the boundary element method [23, 24] and finite element method [16, 25-28].

During ophthalmic phacoemulsification operation, the phaco needle produces heat by oscillation as soon as the electric power is applied. In our experiment, the heat flux from the phaco needle without sleeve cover was 1.6 kW/m². When the anterior chamber is fully filled with solution (BSS or OVD), heat from the outer surface of the cornea is conducted to the air at the room temperature.

In the present measurement of the thermal properties of BSS and OVD, the thermal diffusivity in BSS was much greater than that in OVD, that is, approximately 20 times. This indicates that OVD may adjust its temperature to its surroundings more rapidly than BSS.

Based on the transient heat transfer theory and boundary conditions, the 2D nodeless variable finite element method was applied to predict the transient temperature distribution in the eye chamber during a fully occluded phacoemulsification. For two solutions fully filled in the chamber, transient temperature distributions were computed at the time of 10, 20, and 30 seconds. At 30 seconds, the temperature on the corneal endothelium was elevated at maximum up to 49°C or 42°C in BSS or OVD, respectively. Interestingly, the temperature elevation by the phaco needle was always lower in OVD than BSS. It is likely that OVD may protect the endothelium against heat better than BSS. The present result correlates well with in vivo-rabbit study using thermal camera by Jurowski et al. [29].

It is not certain whether these levels of elevated temperature by the phaco needle may injury the corneal endothelial cells or not. However, our computed temperatures are important for the selection of a solution to reduce the risk of corneal endothelial cell injury.

![Fig. 5](image_url) The structure of the eye where a phaco needle is inserted in the anterior chamber during phacoemulsification (upper) and phaco handpiece components (lower).
In conclusion, the 2D nodeless variable finite element method offers a capability of in-vivo simulation to predict transient temperature response for reducing the risk of thermal-induced blindness during ophthalmic phacoemulsification. The present results may give us a rationale to postulate another mechanism for corneal endothelial cell injury and handout the caution of different ophthalmic solution responses to heat. Further investigation of thermal-induced corneal endothelial injury will be crucial for improving the phaco-emulsification safety guideline.

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Appendix
The structure of eye and a phaco needle inserted during phacoemulsification (Fig. 5).
The piezoelectric crystal is displaced at a certain ultrasonic frequency of 28.5 or 40 kHz depending on the machine. For a thermal aspect rationale, 28.5 kHz tool generates heat less. The ultrasonic frequency of the Millennium® phaco machine (Bausch & Lomb Co, New York, USA) is 28.5 kHz. The oscillation of phaco needle-tip is driven by the attached piezoelectric crystal (transmit by the transducer horn) at variable stroke length with the maximum stroke length of 160 micron [30, 31].

Basic equations for simulation
In general, temperature (T) on the median plane of eye changes in time (t) and is distributed in space (x, y). The transient temperature behavior is described by the heat transfer equation as follows:

\[ \rho c \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \]  

where \( \rho \) is the density of tissue, \( c \) is the specific heat capacity of tissue, and \( k \) is the thermal conductivity coefficient of tissue. The boundary condition is given by specified temperature of \( T_o \), convection heat transfer, and specified heat flux \( q_s \) as follows:

\[ T(x,y) = T_o, \quad \frac{k}{\partial x} n_x - k \frac{\partial T}{\partial y} n_y = h(T(x,y) - T_\infty), \]

\[ \frac{k}{\partial x} n_x - k \frac{\partial T}{\partial y} n_y = q_s, \]

where \( n_x \) and \( n_y \) are the direction cosines of the vector normal to the surface, \( h \) is the convection coefficient, \( T_o(x,y) \) is temperature along the boundary, and \( T_\infty \) is the surrounding medium temperature.

In the present simulation, we use triangular element (3 nodes and 3 nodeless variables) as shown in Fig. 6.

![Fig. 6 Nodeless variable element.](image)

Then, its element interpolation functions are as follows:

\[ N_i(x,y) = \frac{1}{2A} \left( a_i + b_i x + c_i y \right), \quad i = 1, 3 \]

\[ N_4 = 4N_1 N_2; \quad N_5 = 4N_2 N_3; \quad N_6 = 4N_1 N_3 \]

In the above Eq. (5), \( a_i = x_j y_k - x_k y_j, \quad b_i = y_j - y_k, \quad c_i = x_k - x_j \) for \( i,j=1,2,3 \), and \( A \) is the element area.

The Galerkin approach and the recurrence relations are applied to Eq. (1) leading to the finite element equations in the form:
\[
\frac{1}{\Delta t} [C] \left[ \begin{array}{c}
T_1 \\
T_2
\end{array} \right]_{k+1} = \left( \frac{1}{\Delta t} [C] - [K] \right) \left[ \begin{array}{c}
T_1 \\
T_2
\end{array} \right]_k + \left[ Q \right]_k - \left[ Q \right]_{k-1} \, .
\]

where
\[
[C] = \int_\Omega \{ N \} pc \{ N \} \, d\Omega
\]
\[
[K] = \int_\Omega \left( \frac{\partial \{ N \} }{\partial x} + \frac{\partial \{ N \} }{\partial y} \right) \frac{\partial \{ N \} }{\partial x} \, d\Omega + \int_\Gamma \left( \frac{\partial \{ N \} }{\partial x} + \frac{\partial \{ N \} }{\partial y} \right) \frac{\partial \{ N \} }{\partial x} \, d\Omega + \int_\Gamma h \{ N \} \{ N \} \, dA
\]
\[
[Q]_k = \int_\Gamma \{ N \} \left( \frac{\partial T}{\partial x} n_x + \frac{\partial T}{\partial y} n_y \right) \, dS
\]
\[
[Q]_{k-1} = \int_\Gamma \{ N \} q \, dS
\]

and \( \Delta t \) is the time step.

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