Optical Characteristics of Corneal Nanostructure According to the Angle of Collagen-fiber-layer Arrangement

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Collagen fibers tens of nanometers in size, which constitute most of the corneal volume of the human eye, are layered in a uniform direction, and adjacent fiber layers are arranged at an angle of 90° to each other. According to the results of this study, the transmittance at 45° of interlayer rotation angle is highest, and higher than that of the 90° body structure. The transmittance is examined, concerning the polarization state of the incident light; circularly polarized light case shows higher transmittance than linearly polarized. Through this, a simulation to confirm the deformed structure of collagen fibers, which show higher transmittance than the anatomical structure of the cornea, is attempted.

Keywords : Collagen fibril, Light transmittance, Nano-structure, Polarization
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I. INTRODUCTION

The optical properties of nanostructures have attracted much attention recently [1–6]. While the utilization of nanostructures is increasing, in highly precise experiments their use may be limited due to the lowering of the light transmittance. The light transmittance of the nanoscale collagen that constitutes the cornea of a human eye, which is an insulator, is very high. Collagen and the waterproofing that fills the interior of the cornea are also insulators. The cornea of the human eye is an outer membrane occupying about 1/6 of the eyeball’s total area, and is a concave meniscus lens. The cornea accounts for about two-thirds of the total refractive power of the eye and plays an important role in the refraction of the light beam, and has high transmittance for the light entering the eye [7–9]. The cornea is composed of corneal epithelium, Bowman's layer, corneal stroma, Descemet's membrane, and corneal endothelium [10].

The corneal stroma accounts for 90% of corneal thickness and has the greatest effect on light transmittance. It is composed of collagen fibers having a diameter of about 20 to 30 nm and forming a fibrous layer with a thickness of about 1 to 2 μm. These layers are stacked to depths of 250 plies or more. The structural characteristics of the corneal stroma greatly affect the overall transparency of the cornea [7–12]. In this study, based on the results of previous studies the structure of the collagen-fiber layer with the highest transmittance is analyzed by studying the lattice structure of the collagen-fiber layer, and the change in transmittance according to the polarization type of the incident light. Currently, artificial corneas of various materials and designs are being developed around the world, but they do not reach a satisfactory level of biocompatibility. This study is intended to be helpful for the nanostructure of an artificial cornea based on biocompatible collagen.

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II. METHODS

To investigate the effect of nanostructure on the transparency of the corneal stroma, we use a three-dimensional (3D) simulator (OptiFDTD, Optiwave Systems Inc., Canada) based on the finite-difference-time-domain (FDTD) method. The boundary conditions of an unsplit perfectly matched layer (UPML) are used in this simulation analysis, allowing electromagnetic waves to be absorbed at the boundary of the simulation space and minimizing the reflection of unwanted rays from the side.

The incident light has a Gaussian distribution of wavelengths, with a center wavelength of 589 nm. The refractive indices of the simulated space and collagen fibers were 1.335 and 1.55 respectively, corresponding to the actual aqueous solution and real fibrils.

The optical transmittance of the cornea is 95% or greater, which yields a very efficient optical system [13]. To analyze its light transmittance, the nanostructure is modeled as shown in Fig. 1. It is known that the diameter of the nanocollagen constituting the cornea of the human eye is 20 to 30 nm. According to a previous study, the structure with highest light transmittance has a collagen diameter of 22.5 nm [14]. Therefore, the light transmittance is analyzed here by fixing the diameter of the nanostructure and the collagen gap to 22.5 nm. The actual thickness of human-cornea collagen is 400 μm, but this is too large to be modeled by simulation analysis, as the size of the simulation space is sensitive to computer-analysis time. However, if the simulation area is too small, the computer calculation time will be reduced, but the simulation result may not reflect the real situation. Therefore, in this study, an appropriate size of the simulation area was derived by analyzing the results according to the change in the size of the simulation area. Each layer is composed of 10 lines of collagen fiber, and the simulation is for 20 layers in total.

![Simulation model](image)

(a)

(b)

FIG. 1. Simulation model: (a) the simulation model is composed of 20 collagen-fiber layers with adjacent layer designed to be 90° from each other and (b) zoom image.

The size of the simulation space is set to 1.0 μm, 1.0 μm, and 13.95 μm in the x, y, and z directions respectively. The input plane (the starting point of the incident ray) is fixed at 1.2 μm in the z direction. The incident light is a Gaussian modulated continuous wave with a center wavelength of 589 nm and a beam half-width of 0.5 μm. The light is incident upon the xy plane, traveling in the z direction and passing through the collagen-fiber layer. The transmittance is analyzed for wavelengths from 300 to 900 nm. The detector to check the intensity of the transmitted light passing through the collagen-fiber layer is positioned at 12.95 μm, 1 μm after the point where light has passed through all collagen-fiber layers in the z-direction. The lengths in the x and y directions are the same as the size of the x-y plane in the simulation space.

Collagen-fiber layers adjacent to each other inside the corneal stroma of a human eye are arranged at 90° to each other, as shown in Fig. 1(b) [7]. It is necessary to analyze the optical characteristics of various structures to increase a nanostructure’s utilization as an optical element. Therefore, in this study the light transmittance according to the angle between the collagen-fiber layers is investigated. We investigate the optical characteristics of the output light according to the change of angle, by the two methods of cross arrangement and rotation arrangement.

III. RESULTS

3.1. Cross Arrangement of Collagen Fibril Layer

In this section we analyze the light transmittance of the cross arrangement of the collagen layer, concerning incident light that is linearly polarized in the y-axis direction. Figure 2 shows the cross-arrangement structure of the collagen-fiber layer. In the cross arrangement, the second layer of collagen is rotated by a certain angle θ relative to the first layer. The third layer is rotated in the opposite direction by the same angle, and thus is arranged in the same direction as the first layer. Therefore, the collagen fibers constituting the even layers all lie in the same direction, while those constituting the odd layer are rotated by a certain angle from the even-layer collagen fibers. In this simulation, the transmittance is analyzed by modeling 20 layers of the cross arrangement. To analyze the transmittance according to the rotation angle, the intensity of the transmitted light is examined up to 90° at an angle of rotation of 0° to 5°. When the rotation angle is 0°, all of the collagen fibers are arranged side by side in the same direction.

The first collagen fibers are parallel to the x axis. Figure 3(a) shows the light-intensity distribution of the outgoing light according to wavelength, for the cross-arrangement rotation angle. Similar light-intensity distributions are observed for all rotation angles, but the emitted light’s intensity is somewhat different. Figure 3(b) is the graph of the maximum intensity value according to the rotation angle as it increases from 0°. The transmittance of the structure in which the collagen layers are inclined at a certain angle is higher than that of the structure in which all of the lay-
ers are aligned in the same direction. Thereafter, the peak value repeatedly changes according to the change in rotation angle. The transmittance is highest when the cross-arrangement angle between collagen fibers is 45°.

Comparing the wavelengths corresponding to the highest intensity of transmitted light, there is no significant difference from 0.53 to 0.55 μm, but there is a slight change according to the interlayer rotation angle. Figure 3(c) shows the wavelength corresponding to the highest intensity in Fig. 3(a). The wavelength graph along with the rotation angle shows a tendency to change repeatedly, and the central wavelength of the output light was generally reduced compared to the central wavelength of the input light. Considering that the center wavelength of the incident light is 589 nm, the wavelength of light with the highest light transmittance is lowered by about 10%. It can be seen that this wavelength is longest at 45°, which seems to be related to the highest intensity of transmitted light, as can be seen in Fig. 3(b).

3.2. Rotation Arrangement of the Collagen-fibril Layer

Figure 4(a) shows the conceptual diagram of the rotation arrangement for the fiber layer, and Fig. 4(b) shows the 3D-simulation model. The collagen fibers constituting the first layer are oriented in the x direction. The second layer is rotated at a certain angle to the first layer, and the third layer is continuously rotated at the same angle in the same direction as the second layer. Therefore, every layer is arranged in a direction rotated by a certain angle, compared to the preceding layer.

Here, the light transmittance is analyzed by varying the angle between collagen-fiber layers from 0° to 90° in 5° increments. Figure 5(a) shows the output light-intensity distribution according to wavelength, for the rotation arrangement. The intensity of transmitted light exhibits a slight difference according to the angle change. Figure 5(b) shows the maximum intensity of the transmitted light according to the rotation angle. When the angle is 45° the transmittance is the highest, and the transmittance oscillates at approximately 15° intervals. As a whole, the transmission characteristics of the cross and rotation arrangements are similar.

As a result of comparing the wavelengths corresponding to the maximum transmittance for the rotation arrangement, as shown in Fig. 5(c), there is no significant difference in wavelength from 0.53 to 0.55 μm, but the phenomenon of

![FIG. 2. Collagen-fibril-layer structure of the cross arrangement: (a) concept and (b) simulation model.](image)

![FIG. 3. For the cross arrangement: (a) output intensity distribution according to wavelength, (b) peak intensity versus layer-rotation angle, and (c) wavelength corresponding to the highest intensity.](image)
increasing or decreasing concerning the rotation angle is repeated. At 45°, the change in the center wavelength of the output light from the center wavelength of the incident light was the smallest in both cross arrangement and rotational arrangement.

3.3. Amplitude of Electric Field inside the Collagen Fiber

To investigate the cause of the change of light transmittance according to the nanostructure, the electric field distribution inside the nanostructure is analyzed. Figure 6 shows the electric-field-intensity distribution inside the nanostructure, concerning the rotation angles of 20° and 45°. In Fig. 3(b), the highest light transmittance was obtained when the rotation angle was 45°, while the transmittance was lowest at 20°. Therefore, we compared the field-strength distributions inside the optical fiber for the rotation angles of 45° and 20°. Figure 6 shows the distribution of the electric field component $E_z$ intensity on the $xz$ plane, and the central axes for the cross and rotation arrangements respectively. Comparing Figs. 6(a) and 6(c) to Figs. 6(b) and 6(d), it can be seen that the electric-field-intensity distribution is slightly different in the latter parts. The amplitude of the electric field intensity is larger at 45° of rotation, and it is activated for a longer time period; as a result, the transmittance is considered to be high.

3.4. Polarization Effect

Since natural light is unpolarized, in this simulation analysis we attempt to analyze the transmittance characteristics in natural light by calculating the transmittance of circularly polarized light as well as linearly polarized light, in various directions. The light transmittance is analyzed by varying the rotation angle of both the cross arrangement and the rotation arrangement in intervals of 5°.

Figure 7 shows the results of light transmittance according to the angle of rotation, when the incident light is linearly polarized or circularly polarized. The transmittance of circularly polarized light is higher than that of linearly polarized light at the same rotation angle, for the cross arrangement. In the case of circularly polarized light, the results for clockwise and counterclockwise polarizations coincide. On the other hand, in the case of linearly polarized light there is a slight difference between the results for $x$-direction and $y$-direction linearly polarized light. For both
linearly and circularly polarized light, the transmittance is highest when the angle of rotation is 45°. It can be said that the polarization state does not affect the transmittance.

In the rotation arrangement, the transmittance of circularly polarized light was higher than that of linearly polarized, at the same rotation angle as in the cross arrangement. In the case of the rotation arrangement, the results for clockwise and counterclockwise polarizations coincide. In addition, the results for light linearly polarized in the x-axis and y-axis directions are identical, which is different from the result for the cross arrangement. However, it can be seen that the polarization state does not significantly affect the transmittance, as in the cross arrangement, as the highest transmittance is for an angle between collagen fibers of 45°.

IV. DISCUSSION

In this study, the light transmittance according to interlayer rotation angle was analyzed for 22.5 nm of collagen-fiber diameter and collagen-fiber spacing. In addition, the
output light characteristics were compared and analyzed in the cases where the incident light was linearly polarized or circularly polarized. First, when the linearly polarized light was incident, the output light characteristics were analyzed concerning the rotation arrangement and cross arrangement of the collagen-fiber layer.

The transmittance changed periodically concerning the rotation angle, and the cycle was 15° in the case of the rotation arrangement, whereas the cycle was slightly longer than 15° in the case of the cross arrangement. In both cases, however, the transmittance was highest at 45°.

Not only did the light transmittance change according to the rotation angle, but also the wavelength of transmitted light having the highest intensity changed. The center wavelength in the intensity distribution of the incident light was 589 nm, but the center wavelength of the transmitted light was consistently shorter. The wavelength corresponding to the highest transmittance was longest at a rotation angle of 45°, but this is considered to be related to the highest transmittance at 45°.

To analyze the light transmittance according to the polarization state, the output light characteristics were compared and analyzed for incident light of linear and circular polarizations. In the case of circularly polarized light, the optical characteristics of the transmitted light for clockwise and counterclockwise polarizations were the same. Furthermore, the output light characteristics were consistent with the fiber-layer arrangement.

In the case of linearly polarized incident light, when the rotation angle was small the transmittance was different according to the direction of the linear polarization, in the case of the cross arrangement. On the other hand, in the case of the rotation arrangement the output light characteristics were the same, regardless of the polarization direction.

The intensity of the output light was about twice as high for circularly polarized incident light as for linearly polarized. As a result, it was confirmed that the transmitted light’s characteristics depend more on the arrangement of the nanostructures than the polarization state of the incident light. This study was intended to provide reference data for research on applied nanostructure design, such as for an artificial cornea.

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DISCLOSURES

The authors declare no conflicts of interest.

DATA AVAILABILITY

Data underlying the results presented in this paper are not publicly available at the time of publication, which may be obtained from the authors upon reasonable request.

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