The present investigation was undertaken to obtain some knowledge about the submicroscopic structure of the cornea based on thermoelastic properties and polarization characteristics. Previous workers have reported that the cornea exhibits a birefringence of uniaxial type. But as their observations were made in parallel polarized light only, it is desirable to make conoscopic observation as well in convergent polarized light. The general appearance of the cornea between crossed nicols is such that the birefringent elements are predominantly arranged in a radial manner, although no anatomical evidence of such a radial arrangement has been reported.

In the present investigation, isolated whole corneas were examined from the direction normal to the surface. In parallel polarized light, the corneal fibers were ascertained to be arranged radially. In convergent polarized light, a biaxial interference figure was obtained in place of a uniaxial one.

The cornea consists chiefly of collagen, which is composed, like that elsewhere in the body, of long chain molecules, some of them aggregated together to form micelles (5 per cent. of the corneal substances, Naylor 1953). Consequently, birefringence may be considered as due to only a small proportion of the corneal substances.

As the second approach to the problem, the fine structure of the cornea was analysed from the point of view of its mechanical behavior. The analysis of thermoelastic properties has, in particular, been quite successful in a number of cases.

In the present work, the last method was applied to the study of the cornea, and the molecular interpretation led to the conclusion that the cornea is composed of many layers of two-dimensional networks of long chain molecules. Further, it was shown that the temporary impairment of transparency due to an applied pressure to the cornea may be considered as a sort of crystallization.

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a Yoshizo Kikkawa

b Cogan (1) and Stanworth and Naylor (2) reviewed the relevant literature on polarized light studies of cornea.

c Botts and Morales (4), Hill (5) and Meyer (6) cited the relevant literature on rubber-like elasticity of several biological systems.
Experimental Method

An excised rabbit cornea, in which four short cuts have been made at the periphery (fig. 2), was spread on a slide glass. Being placed upon the stage of a polarizing microscope, it was examined between crossed nicols in parallel, or convergent, polarized white light.

A band-shaped strip was also used to study the effects of a deforming force on the birefringent properties.

Orthoscopic Observations

Peripheral region: Many fibers, arranged in a radial manner, were observed between crossed nicols (fig. 1). These fibers were seen to the best advantage by turning the stage back and forth past the extinction position (the field of view was darkest), where the fiber direction was parallel with the plane of vibration of either nicols. To ascertain the orientation of the vibration direction of the fibers, the stage (consequently the fiber direction) was turned 45° (diagonal position) from the position of extinction either clockwise or counterclockwise, and a sensitive tint plate was inserted. When the fiber direction was parallel with the direction of vibration of the fast ray (X') in the sensitive tint

FIG. 1. Radially arranged fibers between crossed nicols, at an extinction position.

FIG. 2. Plane spread cornea between crossed nicols in parallel polarized light with superposed gypsum plate. The fibers are arranged in a radial manner. X' coincides with the fiber direction. G—Gypsum plate, B—Blue (interference color), Y—Yellow (interference color).
plate, the interference color was raised (blue); when parallel with that of the slow ray ($Z'$), it was lowered (yellow). It is evident from these facts that the vibrational direction of the fast ray ($X'$) in the cornea coincides with the fiber direction, and that of the slow ray ($Z'$) is at right angles to the fibers (fig. 2).

Central Region: The radially arranged fibers were observed to intersect crosswise at the central region. On rotating the stage, although those fibers which were in maximum illumination became dark, and those which were at extinction became bright, the brightness of the field of view as a whole was not changed during the rotation of the stage.

Conoscopic Observations

Peripheral Region: An interference figure obtained at the periphery of the cornea was equivalent to that produced by a biaxial crystal plate cut perpendicularly to the acute bisectrix. The figure consisted of two isogyres, which together formed a dark cross, broad and poorly defined, in a certain stage position. On rotating the stage, the dark cross was divided into two hyperbolas in opposite quadrants; on further rotation, they formed a dark cross again. At a position of the stage, where they form a dark cross, the optic plane, including the optic axes, is parallel with the plane of vibration of either nicols (fig. 3, I a, c). At 45° from the planes of the nicols, the optic axes lie in the vertices of the two hyperbolas, which have their convex sides turned toward the acute bisectrix (fig. 3, I b, d) (7).

![Fig. 3, I a-d. Biaxial acute bisectrix interference figure with superposed gypsum plate; rotation counter-clockwise. a-0°, b-45°, c-90°, d-135°.](image1)

![II a-b. Uniaxial interference figure with superposed gypsum plate.](image2)

- ○: A rise in interference color.  ●: A fall in interference color.

Chain line—Z-axis, Optic plane. Solid line—Vibration plane of nicol.

The fibers seen under orthoscope are illustrated in the same figure. The Z-axis is at right angles to the fiber direction.

The acute bisectrix is normal to the plane of cornea, and lies in the center of the field of view.

A sensitive tint plate was superposed over this interference figure with the direction of vibration of its fast ray ($X'$) parallel with the optic plane in the position at 45°, and the interference color on the concave sides was raised, while on the convex side it was lowered (fig. 3, I d). When the slow ray ($Z'$) was parallel with the optic plane, all these were reversed (fig. 3, I b). These
figures indicate that the acute bisectrix coincides with the direction of vibration of the fastest ray, that is, the ellipsoid axis $X$. Therefore, the direction of vibration of the slowest ray, the $Z$-axis, coincides with the line connecting the vertices of the two hyperbolas in the position at 45° (fig. 3, I b, d), and the $Y$-axis, that of the ray of intermediate velocity, is at right angles thereto. In this case, the sign is negative.

After the $Z$-axis had been located from an interference figure, the condenser and Bertrand lens were removed so that the fibers might be seen. Thus the $Z$-axis located from an interference figure was found to be at right angles to the fibers observed in parallel polarized light (fig. 3, I).

The relations between a fiber and its ellipsoid axes are illustrated in fig. 4. The direction of vibration of the fastest ray, the $X$-axis, is normal to the surface of the cornea, that of the slowest ray, the $Z$-axis, is at right angles to a fiber, and the $Y$-axis, that of the ray of intermediate velocity, is parallel with the fiber.

![Ellipsoid axes of a fiber.](image)

When such a fiber is examined in parallel polarized light passing through the cornea parallel to its $X$-axis, as is the case with the observation in parallel polarized light just described, the $Y$-axis may be $X'$, and the $Z$-axis consequently may be $Z'$, since the ray vibrating parallel to the $Y$-axis travels more rapidly than that vibrating parallel to the $Z$-axis.

**Central Region:** An interference figure obtained in the central region of the cornea was a dark cross, broad and poorly defined, the arms of which were parallel with the planes of nicols.

On rotating the stage, the dark cross exhibited no change; furthermore, lateral movement of the slide glass produced no change in the dark cross, so long as the central region occupied the field of view (fig. 3, II).

This interference figure is equivalent to that produced by a uniaxial crystal plate cut perpendicular to the optic axis; accordingly, the optic axis is normal

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$^a$ Light passing through any crystal not parallel with the optic axis is divided into two rays which vibrate in planes at right angles to each other and travel with unequal velocities. The vibration direction of the fast ray is represented by $X'$ and that of the slow ray by $Z'$. While the direction of vibration of the fastest ray in any biaxial crystal is designated as the axis $X$, that of the slowest ray as the axis $Z$, and that of the ray of intermediate velocity as the axis $Y$; these axes are at right angles to each other.
to the plane of the cornea. A sensitive tint plate being superposed over this interference figure, the dark cross was changed to a violet cross. The color between the arms fell to yellow in two quadrants, and rose to blue in the other two. The line connecting the centers of the blue quadrants made a negative sign with the direction of the fast ray in the sensitive tint plate \((X')\) as shown in fig. 3, II, and the sign is negative \((8)\).

The distance between the vertices of the hyperbolas at the 45° position in a biaxial interference figure varies with the size of the apparent optic angle.

If the angle between the optic axes is supposed to diminish to 0°, the distance between the vertices of the two hyperbolas may diminish to zero, and a uniaxial interference figure may be produced.

Within a fiber some of the molecules must aggregate together to form micelles; these micelles are considered to be distributed in such a manner that the ellipsoid axes of all micelles are in parallel to each other.

At the central region, the radially arranged fibers were observed to intersect each other. This results in a random distribution of the micelles with regard to their \(Y\) and \(Z\) axes, but the \(X\)-axis will remain in the same direction. Hence, the refractive indices in the \(YZ\) plane are equal in all directions, and an apparent uniaxial interference figure may be produced under these conditions.

At the border of the central region, where the arrangement of the fibers was not completely at random, a dark cross was divided into two hyperbolas, with only a slight separation between them; and the separation into two hyperbolas becomes more and more distinct as one moves the view toward the periphery where the fiber arrangement becomes more completely radial (fig. 5).

These facts can be explained by considering the summation of the effects of the micelles, the arrangement of which goes imperceptibly over from random to radial.

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**FIG. 5.** Interference figures and their optic angles in different regions of the cornea. In the central region, the optic axis is normal to the surface of the cornea, but the acute bisectrix is normal to it at the periphery.

\(a\)—A cross section of the cornea.
\(b\)—A surface view of the cornea.
Chain line—Optic axis.
Solid line—Acute bisectrix.
**Rotation of the Z-axis by Stretching**

A band-shaped strip was excised in such a way that its length was, as far as possible, parallel to that of the fibers (fig. 8, a), and the strip was examined between crossed nicols in parallel polarized light.

With a sensitive tint plate inserted with its direction of the fast ray \((X')\) parallel to the fiber direction, the interference color was raised to blue. But when the strip was stretched in the fiber direction, the interference color changed from blue to yellow; namely it was lowered.

The direction of vibration of the slow ray \((Z')\) in the strip which was at right angles to the deforming force at the outset, was changed to the direction of the force by stretching (fig. 6, I a, b). When the deforming force was removed, the interference color returned to blue again at once.

Another strip was excised so that its length was crosswise to the fibers (fig. 8, b), and the strip was examined between crossed nicols in parallel polarized light.

With a sensitive tint plate inserted with its direction of the fast ray \((X')\) parallel to the fibers, namely at right angles to the length of the strip, the interference color was blue.

Then the strip was stretched at right angles to the fibers, but no remarkable change occurred in interference color (fig. 6, II a, b). In other words, when the deforming force was applied parallel to the direction of vibration of the slow

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**FIG. 6.** Effects of stretching on the ellipsoid axes.

I a. A strip of cornea between crossed nicols in parallel polarized light with superposed gypsum plate.

b. *Ditto.* Stretched parallel to the fiber direction.

c. The same strip between crossed nicols in convergent polarized light. The fibers seen under orthoscope are illustrated in the same figure.

d, e. *Ditto.* Stretched parallel to the fiber direction.

II a. A strip of cornea between crossed nicols in parallel polarized light with superposed gypsum plate.

b. *Ditto.* Stretched at right angles to the fiber direction.

c. The same strip between crossed nicols in convergent polarized light.

d, e. *Ditto.* Stretched at right angles to the fiber direction.

\(B\)—Blue (interference color), \(Y\)—Yellow (interference color).

Arrow—Direction of the force, Chain line—\(Z\)-axis.
SUBMICROSCOPIC STRUCTURE OF CORNEA

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ray (Z'), the original state was not disturbed by stretching.

Further, when these strips were examined in convergent polarized light, a
biaxial interference figure was obtained. The line connecting the vertices of
the two hyperbolas at 45° the position, Z-axis, was at right angles to the fibers
(fig. 6, I c, fig. 6, II c).

On stretching the strip in the fiber direction, the two hyperbolas approached
the center of the field of view, formed a dark cross, and finally divided again
into two hyperbolas, but in different quadrants (the Z-axis was not at right
angles but in parallel to the fiber direction) (fig. 6, I d, e). When the deforming
force was removed, all these were reversed at once.

It is evident from the above facts that the Z-axis rotates about the X-axis
to the direction of a deforming force, and returns to the original state when
released.

But when stretched at right angles to the fibers, the two hyperbolas moved
toward the edge of the field of view, eventually they disappeared out of the
field of view; in other words, there occurred no rotation of the Z-axis, since the
Z-axis was in the direction of the deforming force in the original state. Simply
a widening of the optic angle takes place (fig. 6, II d, e).

It was confirmed, moreover, that the Z-axis rotates about the X-axis until
it coincides with the direction of the deforming force, when the strip is stretch-
ed in a direction inclining by a certain angle to the fibers, and returns to
the original state when released (not shown in fig.).

It was found, in addition, that the Z-axis cannot easily return to the original
state on releasing when stretched with a strong force. Therefore, it must be
noted that the characteristics in polarization optics may be quite different from
usual conditions, if a strong force is applied accidentally to a cornea during
preparation. On the other hand, on stretching a strip of cornea, a remarkable
cloudiness was observed, which, however, disappeared instantly when released.

STUDIES ON THE THERMOELASTIC PROPERTIES

The Thermodynamic Treatment of Thermoelastic Properties (9)

In the interpretation of the phenomena of rubber-like elasticity, the study
of the changes in internal energy and entropy which accompany an extension
is of particular importance. These quantities may be derived from the tempera-
ture dependence of the elastic force or from the heat evolution on stretching.

Consider an object of length l acted on by an elastic force K. In a small
displacement dl, the work done on the object is Kdl. Assuming constancy of
temperature, this work is, by definition, equal to the change dA in the Helmholtz
free energy, i.e.

\[ K = (\partial A/\partial l)_T. \] (1)

This may be written in the equivalent form,

\[ K = (\partial E/\partial l)_T - T(\partial S/\partial l)_T, \] (2)

*e In some cases, a cross-shaped figure may be unobservable as reported by Cogan 1940
(1), unless the micelles take the normal orientation by means of swelling.
where $E$ is the internal energy and $S$ the entropy.

(This equation neglects the effects of possible volume change.)

The entropy of extension at constant temperature may be related to observable quantities by the following equation:

$$\left(\frac{\partial S}{\partial l}\right)_T = -\left(\frac{\partial K}{\partial T}\right)_l$$

Over a small range of temperature, $K$ may be treated as a linear function of $T$ (the curve $K=f(T)$ is replaced by its tangent).

The equation of this straight line is then,

$$K = a + bT,$$

where $a = \left(\frac{\partial E}{\partial l}\right)_T$ and $b = \left(\frac{\partial K}{\partial T}\right)_l = -\left(\frac{\partial S}{\partial l}\right)_T$.

In terms of the mechanical theory of heat, $\left(\frac{\partial E}{\partial l}\right)_T$ represents the change in the potential energy of molecules or parts of molecules, which takes place during an isothermal change in length of an object. Moreover, the entropy of the system is related to the thermodynamic probability by the equation

$$S = R \ln P.$$

$P$ provides a measure of the possibilities of movement and rearrangement open to the kinetic units. If, therefore, the entropy ($S$) increases on stretching the object, this means that deformation provokes a transformation from a more ordered (less probable) to a less ordered (more probable) condition—the sphere of movement of the kinetic units is increased.

Conversely, if $S$ diminishes on stretching (as happens in the case of rubber, muscle and other rubber-like high polymers at moderate elongation), the possibilities of rearrangement and of movement of the units are limited by the stretch—the system becomes more orderly.

**Experimental Method**

The immediate aim of the experiments being to determine the temperature coefficient of the elastic force exerted by a piece of cornea stretched at constant elongation, the dynamometer of Polanyi (12), already used for rubber, muscle and other substances, was also used here. In practice, a change in the force

![Image of Dynamometer of Polanyi](image_url)

FIG. 7. Dynamometer of Polanyi.
A strip of cornea, which is tied to a pair of glass shafts with cotton threads, and kept at constant length in a moist chamber in which the glass shafts are protected from temperature change with pieces of cork.

A change in tension of the strip varies the curvature of a steel spring, which is magnified by a system of optical levers.

$M$—Mirror, $S$—Steel spring, $G$—Glass shaft, $C$—Cornea, $M_C$—Moist chamber.

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Footnote: The derivation and detailed discussion of these equations will be found in Meyer and Ferri 1936 (10) and Meyer, Lotmar and Pankow 1936 (11).
exerted by a stretched object modifies the curvature of a steel spring. This change in curvature is then magnified by a system of optical levers (fig. 7). By this means, it is possible to measure tension change in the object under practically isometric conditions. In the present work, it was possible to measure forces with an accuracy of ±0.01 g.

A strip of cornea of 4 mm width was excised, and the both ends were tied with cotton threads to a pair of glass shafts, the surface of which had been covered with colophonium wax to keep the binding firmly. Thereupon the preparation was mounted vertically to the apparatus: the upper shaft hung on a steel spring and the lower was firmly screwed to a support, which was adjustable in the vertical direction with a fine pitch screw. The preparation was kept in a moist chamber as protection against swelling or shrinkage, and the temperature of the chamber was changed by passing heated or cooled water through a bath, in which the chamber had been installed (fig. 7). The temperature of the chamber could be changed from 15° to 30° C. in about 10 min.

In no case was the chamber heated above 30° C., since there is a tendency for the tension to fluctuate at the higher temperature. To avoid any thermal effect on the tension of the glass shafts inserted in the chamber, two pieces of cork were used to cover the inserted portions. At the end of the experiments, the preparations were checked for physiological conditions.

Thermoelastic Phenomena

The thermodynamic conclusions, based on thermoelastic behavior, are only valid under conditions of reversible equilibrium. These conditions are never completely satisfied, even with rubber, which is more perfectly elastic than most biological structures, the experimental difficulties arising from relaxation and other non-equilibrium effects have been extremely difficult to overcome. In order to obtain equilibrium conditions as nearly as possible, the elastic force was allowed to settle to a steady value at the highest temperature employed, in this way the reasonably reversible force-temperature curves have been obtained (Meyer and Picken 1937 (9), Treloar 1952 (13)).

In the present work, preceding to the experiment on the tension-temperature relations, a preparation was stretched and kept at a constant length at 30°C, during which the tension fell gradually, and eventually became constant; thus an equilibrium was reached. This steady value is termed initial tension.

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**Fig. 8. Two modes of the excision of a strip from cornea.**

**Tension-temperature Relations when Stretched in the Fiber Direction**

A strip was excised so that the cornea could be stretched in the fiber
direction, as shown in fig. 8a. After a state of equilibrium was reached, the temperature was changed. Fig. 9 shows the effects of a change in temperature on the force exerted by a strip of cornea at intermediate elongation. The tension increases gradually by raising the temperature, eventually a steady value is obtained, i.e. the second equilibrium is reached, and these are reversed on cooling. But at 30°C, there is a tendency for the tension to fluctuate, so the mean value is taken as the tension. This effect was observed by Meyer and Picken 1937 (9) with non-living materials as well as with muscle. The tension-temperature relations at different elongations are summarized in fig. 10, I. Since the initial and final values for the elastic force do not coincide, in general, the tangents are drawn to the upper portions of the ascending limbs to represent the force.

![Fig. 9. The effect of a change in temperature on the force exerted by a strip of cornea excised parallel to the fiber direction at an initial tension of 0.76 g. (an elongation of ca. 5%) The figure shows simultaneously the change in temperature and the change in elastic force with time.

There is a tendency for the tension to fluctuate at 30°C. The elastic force is given for a sectional area of the strip of 4 mm. width (not for per unit area).

The elastic force increases with rising temperature at slight or intermediate elongations, the temperature coefficient of the elastic force at constant length being positive, but it decreases for greater elongations, a negative coefficient being obtained.

_Tension-temperature Relations when Stretched at Right Angles to the Fibers_

A strip was excised so that the cornea could be stretched at right angles to the fiber direction, as shown in fig. 8, b. The tension-temperature relations were entirely similar to that described above (fig. 10, II).

_The Molecular Interpretation (9)_

At slight and intermediate elongations, the elastic force increases with rising temperature, so the constant $b$ in equation (4) is positive, and as $b = -(\partial S/\partial l)\gamma;$
the temperature coefficient of the elastic force is positive. Therefore, isothermal stretching of the cornea produces a diminution in the entropy \((S)\) of the system \((dS\) is negative\), \(i.e.\) the arrangement of the atoms or groups becomes more ordered and less probable. During an isothermal contraction, the entropy \(S\) increases, \(i.e.\) the ordered system passes into a less ordered and more probable condition.

The tangent drawn to the curve representing force as a function of the absolute temperature makes a negative intercept on the \(K\)-axis, \(i.e.\) \(a\) in equation (4) is negative, and \(a = (\partial E/\partial T)_T\). Therefore, the internal energy \((E)\) diminishes during isothermal stretching \((dE\) is negative\); it follows that the decrease of \(TS\) must be greater than the increase of the free energy \(A\), since \(dE = dA - TdS\). As the heat given off equals \(TdS\), this heat is greater than \(dA\), the work absorbed (6), (14).

In brief, during an isothermal stretch, the tendency for a more ordered arrangement of the kinetic units to supervene is so great that more heat is given off than is absorbed as work; this means that during an isothermal stretch the increase in orientation proceeds with evolution of latent heat. In other words, a sort of crystallization takes place as a result of stretching; on allowing the cornea to contract, \(dE\) becomes positive, so that the “crystallites” melt with disorientation of the ordered system.
Such disorientation is accompanied by a macroscopic contraction of the stretched cornea. This fact leads to the conclusion that the atoms or groups of atoms are bound together by strong bonds in the direction of stretch, namely the cornea is built up of chain molecules. The rearrangement on stretching consists, therefore, in a straightening and parallel orientation of the chains.

The elastic force of a deformed cornea is due to the thermal motion of segments of long, flexible chain molecules stretched by deformation. On releasing, the straightened chains tend to return, through free rotation about valence bonds, to any statistically more probable (twisted) form.

Furthermore, the cornea shows limited relaxation when held stretched at constant length, i.e. the tension falls to a constant level above zero. This indicates that the chains are united by chemical bonds to form a loose network.

At greater elongations, the elastic force decreases with rising temperature, so \( a \) in equation (4) is positive, and as \( a = (\partial E/\partial l)_T \), the temperature coefficient of the elastic force is negative. Therefore, the internal energy increases during isothermal stretching and decreases during contraction.

The chain molecules are fully stretched and completely orientated at high elongations, and further elongation by rotation about the primary bonds is impossible, accordingly, no more diminution of \( S \) is possible, i.e. elongation can only take place if the kinetic units are displaced from their troughs of minimal potential energy. Hence, stretching is accompanied by an increase in the potential energy of the system, and the sign of the temperature coefficient of the elastic force becomes negative.

**SUBMICROSCOPIC STRUCTURE OF THE CORNEA**

It has been shown by studies with polarized light that the cornea is composed of radially arranged fibers, the \( Z \)-axis lies at right angles to the fiber direction, and the \( Z \)-axis rotates about the \( X \)-axis to the direction of a deforming force on stretching. Moreover, from the thermodynamic analysis, it has been concluded that the cornea is built up of loose networks of flexible long chain molecules.

On the basis of these data, the submicroscopic structure of the cornea is represented diagrammatically in fig. 11. On stretching such a network parallel to the fiber direction, the chains are straightened and orientated, and the arrangement of atoms or groups of atoms becomes more orderly and less probable, and the micelles are caused to rotate to the direction of the force (fig. 12, I). The behavior of the network, when stretched at right angles to the fiber direction, is essentially the same as that described above except that there occurs no rotation of the micelles (fig. 12, II).

On rotation of the micelles, the \( Z \)-axis rotates about the \( X \)-axis to the direction of the force, but the \( X \)-axis remains unchanged. This fact means that the micelles rotate in one plane and leads further to the supposition that a corneal lamella is a sheet of two-dimensional network composed of radially arranged long chain molecules.

If a lamella were built up of a three-dimensional network, not only the \( Z \)-
Fig. 11. Diagram of a lamella showing a loose network composed of radially arranged long chain molecules.

Fig. 12. I. Straightening and parallel orientation of the chains with rotation of the Z axis when stretched parallel to the fiber direction.
II. Straightening and parallel orientation of the chains with no rotation of the Z axis when stretched at right angles to the fiber direction.

--- micelle, twisted line—long chain molecules, F—Direction of the force.

axis, but also the X-axis should rotate on stretching, and the phenomena in polarized light should be more complicated. The cornea may be assumed to be built up of many layers of two-dimensional network. A remarkable increase in thickness on swelling may well be explained on the assumption that these layers are not united by strong chemical bonds with each other. The cornea, however, does not expand in other directions on swelling, since the chain molecules in a network are united by stronger chemical bonds.
DISCUSSION

A cross figure observed between crossed nicols, which was discussed in particular by previous investigators, has led to the conclusion that the birefringent elements are arranged predominantly in a radial manner, but no anatomical evidence has been found in the corneal lamellae. A preferential orientation of the fibers in different strata in the cornea was put forward by Kokkot 1938 (15). According to Naylor 1953 (3), beside such an orientation, crosslinking occurs between different strata, so that the direction in which the fibers run in successive lamellae is random for the cornea as a whole. In the present work, the radial arrangement of the fibers was obviously shown by the observation made normal to the surface of an isolated cornea.

The birefringence of the cornea has been believed to be uniaxial, but, so far as is known, no observation was made with convergent polarized light. The interference figure obtained at the periphery of the cornea was no doubt a biaxial one; the optic angle decreased as the central region was approached and, as a limiting case, a uniaxial interference figure was produced in the central region.

In the present paper, these facts were explained in terms of intersection of the fibers. So far as the central region is concerned, the cornea is apparently uniaxial; this agrees with the results of the previous investigators (1), (2). However, the author found that the optic axis is normal to the plane of cornea, instead of along the fiber direction. Therefore, the incident light normal to the cornea shows no effective birefringence in the central region, since the light is travelling parallel to the optic axis. But it produces a certain magnitude of effects at the periphery, where the light is travelling parallel not to the optic axis but to the acute bisectrix of the optic angle. These results agree with those obtained by Stanworth and Naylor 1950 (2) to the effect that the effective birefringence varies from zero in the center to a gradually increasing value at the periphery.

From the polarization study, the fibrous structure of a corneal lamella was shown. But from the analysis of thermoelasticity, it became clear that a corneal lamella should be regarded as a two-dimensional network consisting of long chain molecules. A diagram of lamellar structure based on the above two sets of data has been given already. This schema, the author believes, covers a wider range of optical and thermoelastic information of the cornea than Naylor's proposal (3).

The temporary impairment of transparency due to an excess pressure applied to the cornea, is believed to be caused not only by imbibition of fluid, but also by physical changes in the stroma, since the cloudiness disappears immediately when the pressure is lowered (Adler 1950) (16).

On the other hand, the transparency of the cornea is explained by assuming a uniform change in the index of refraction in each fiber, as well as from the fiber to the surrounding medium (3), (16). In the present work, it was shown that a sort of crystallization is accompanied by reversible cloudiness in stretching.
In this case, the reversible cloudiness may be considered as due to an abrupt difference in refractive index between the "crystallites" and the surrounding medium.

SUMMARY

Isolated corneas were investigated with both parallel and convergent polarized light.

The cornea is composed of radially arranged fibers.

The interference figure obtained at the periphery is biaxial; the Z-axis is at right angles to the fiber direction, the Y-axis is parallel thereto, and the X-axis is normal to the plane of cornea; the X-axis coincides with the acute bisectrix, therefore, the sign is negative.

In the central region, the interference figure is uniaxial. A change in optic angle is discussed in terms of the arrangement of the fibers.

The Z-axis rotates to the direction of the force when stretched, but the X-axis remains unchanged.

The effect of temperature on the elastic force of a stretched cornea at constant length has been investigated.

At slight and intermediate elongations, the temperature coefficient of the elastic force is positive, and the tangent drawn to the curve representing force as a function of the absolute temperature makes a negative intercept on the K(force)-axis. From these data, it may be concluded:

(a) The cornea consists of flexible, long chain molecules, the arrangement of which becomes more ordered and less probable on stretching. Thermal motion tends to provoke a return to the original state;
(b) Latent heat is set free during stretching and may be considered as a sort of heat of crystallization.

These results indicate that a corneal lamella is a sheet of two-dimensional network composed of radially arranged long chain molecules, some of which are aggregated together to form micelles, whose long axis is at right angles to the fiber. The reversible cloudiness caused by an excess pressure may be considered as due to a sort of crystallization.

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