Finite Element Analysis on Friction Developing on Contact Surfaces between Eyeball and Eyelid during Blink

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***Abstract*— BAD (Blink Associated Disorder) such as SLK (Superior Limbic Keratoconjunctivitis) or LWE (Lid Wiper Epitheliopathy) decreases QOL(Quality Of Life). Therefore, it is very important to investigate their cause. Then, FEA (Finite Element Analysis) was carried out for the friction developing on contact surfaces between an eyeball and an eyelid. As the calculated results, deformations and shearing stresses on the ocular surface and the eyelid's one were shown. Finally, the relationship between the friction and BAD was discussed. As a result, BAD is thought to be caused by the friction occurred at blinking.**

***Index Terms*— Blink Associated Disorder, Dry Eye, Finite Element Analysis, Friction**

I. Introduction

In the recent past, as the information technology progresses, the opportunity to see screens of information devices such as a personal computer or a smart phone for a long time is increasing. For this reason, the number of people who develops a dry eye syndrome has been increasing. When a person whose ocular surface is dry blinks, the friction between an ocular surface and an eyelid may become large. This friction may damage the ocular surface. Therefore, it is thought that the friction is one of causes that develop BAD (Blink Associated Disorder) such as SLK (Superior Limbic Keratoconjunctivitis) or LWE (Lid Wiper Epitheliopathy). The BAD decreases QOL（Quality Of Life）because it causes various symptoms such as foreign-body feeling during blink, discomfort and visual loss.

Some researches on dry-eye syndrome have been carried out. Michael A. Lemp, et al. [1] have shown that a dry eye syndrome is mainly caused by a deficiency of tear fluid and an excessive evaporation of the tear. Korb, et al. [2] have reported that the tear fluid is deficient to separate the eyelid and ocular surfaces in dry eye patients. Moreover, Monica Berry, et al. [3] have shown that the eyelid surface where the tear fluid is deficient could be harmed due to the friction between the eyelid and ocular surfaces during blinking. In addition, M.B. Jones, et al. [4] have reported that the eyelid pressure during blinking may change the shape of cornea. Thus, various instruments have been developed by researchers to measure the eyelid pressure on the ocular surface [5]-[7]. One of the instruments, the blepharo-tensiometer that uses a tactile pressure sensor for measuring eyelid pressure was developed by the authors [8].

In the past research by the authors, the ocular surface tribometer was developed for measuring frictional coefficients of human ocular surfaces [9].The ocular surface tribometer consists of the frictional coefficient measuring apparatus and the device to measure the moving velocity of the probe. However, the ocular surface tribometer has low accuracy in the measurement of frictional coefficients of human ocular surfaces because a strain gauge was used as the two-axis force sensor (TL701 Handy Rub Tester, Trinity Lab, Japan). Moreover, the data on normal forces, frictional forces, and frictional coefficients measured by the previous ocular surface tribometer could not be synchronized completely with the data on rotational angle by the encoder since the apparatus for measuring normal forces, frictional forces, and frictional coefficients and the device for measuring the moving velocity of the probe work independently. Then the computational program employing the genetic algorithm and the LSM was developed to determine frictional characteristics of human ocular surfaces [9]. Then, the computational program employing BSG-Starcraft of PSO and LSM was developed to determine frictional characteristics of human ocular surface [10]. Furthermore, the new ocular surface tribometer was developed in order to increase the accuracy in measuring the frictional coefficients by the authors [11]. Although some researchers have been conducted to examine the friction between the ocular surface and the eyelid, there is no study using the finite element analysis (FEA) to clarify a problem of the friction between the ocular surface and the eyelid as far as the authors know.

Therefore, in the present research, the FEA was carried out in order to clarify a mechanism of the friction between an ocular surface and an eyelid generated during blink. Firstly, the computational models of an eyeball and an eyelid were created. Then, the linear static analysis dealing with a contact problem was carried out. Finally, the deformations and the shearing stresses on surfaces of an eyeball and an eyelid were shown as the calculated results of FEA.

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II. Modeling of ocular surface and eyelid

Figure 1 shows the constitution of an ocular surface and an eyelid. The computational model of an ocular surface and an eyelid was created considering Fig.1.

Figure 2 shows the computational model of an ocular surface and an eyelid. It is very difficult to perform the calculation in the case that contact surfaces are curved ones and they slide. Therefore, the cornea was modelized by a circular plate. Then the conjunctiva, the levator palpebrae muscle, the tarsus and the orbicularis oculi muscle were modelized by rectangular flat plates.

III. Calculation method

A. Mesh division

All components of the computational model were divided by the quadratic tetrahedral elements. The value of 0.7, 0.8, 1.0, 1.2, 1.6 or 2.0 [mm] was used as the length of a side of each finite element. Figure 3 shows the computational model mesh-divided with quadratic tetrahedral elements having sides of 0.8 [mm].

B. Material properties

The value of 0.34 [MPa] was used as Young's modulus of the cornea referring to the conventional research [12]. Poisson's ratio of the cornea was not yet investigated. The value of 0.49 was used as Poisson's ratio of the cornea as with human skin that has a material property like super elastic body or rubber. Young's moduli and Poisson's ratios of the conjunctiva, the tarsus, the levator palpebrae muscle and the orbicularius ocuil muscle were also not yet investigated. As Young's modulus of a conjunctiva, the value of 0.17 [MPa] which is half of that of a cornea was used, because it is known that a conjunctiva is more flexible than a cornea. Then the value of 0.49 was used as Poisson's ratio of a conjunctiva. As for Young's moduli of a tarsus, a levator palpebrae muscle and a orbicularius ocuil muscle, the value of 0.42 [MPa] that is the same one as that of human skin [13] was used. Then the value of 0.49 was used as Poisson's ratios of them.

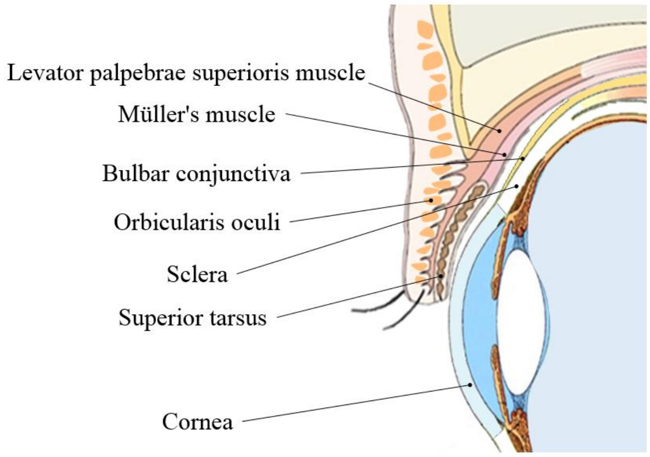

Fig. 1. Constitution of ocular surface and eyelid

C. Boundary conditions

The bottom surfaces of the cornea and the conjunctiva were fixed completely.

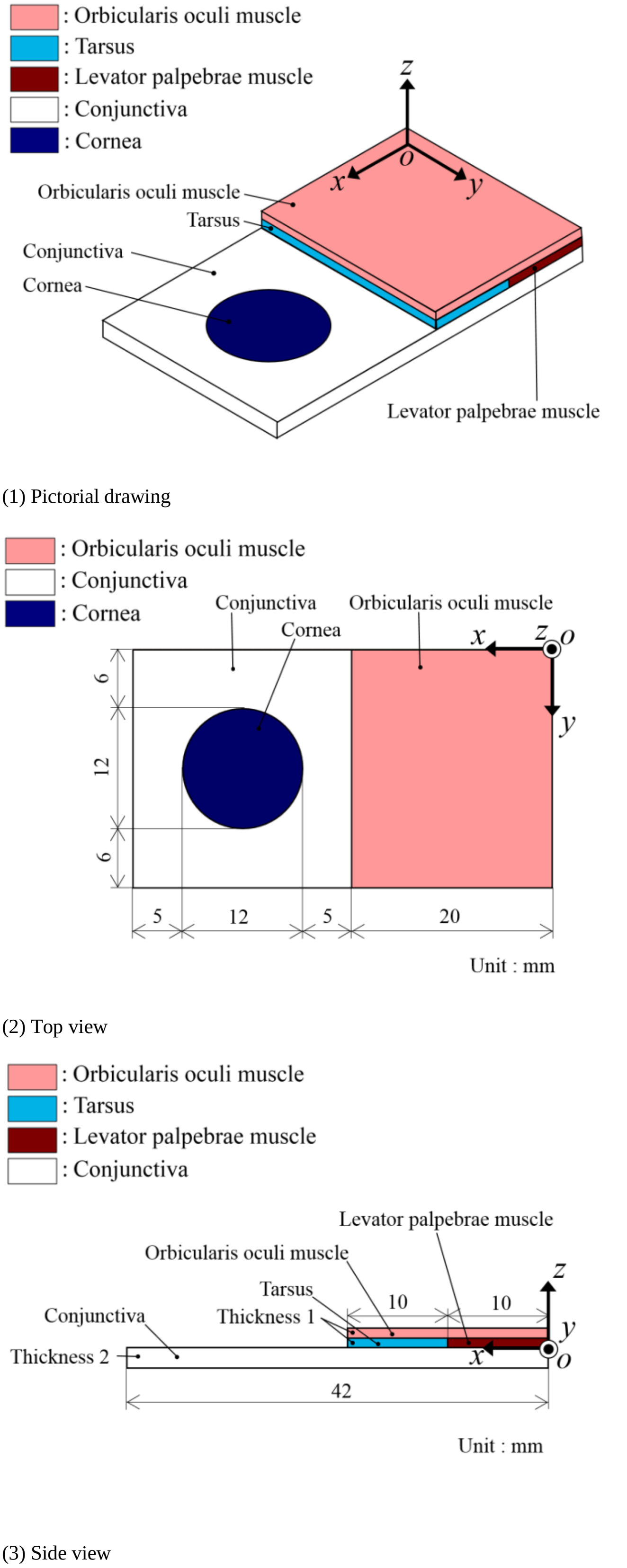

Fig.2. Computational models of ocular surface and eyelid

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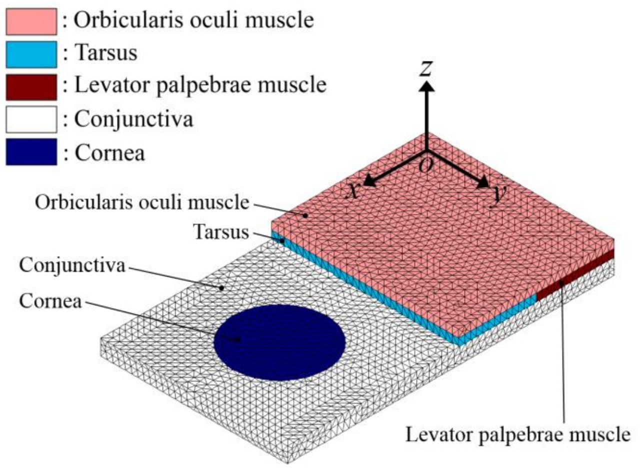

Fig.3. Computational models mesh-divided with quadratic tetrahedral elements having sides of 0.8 [mm]

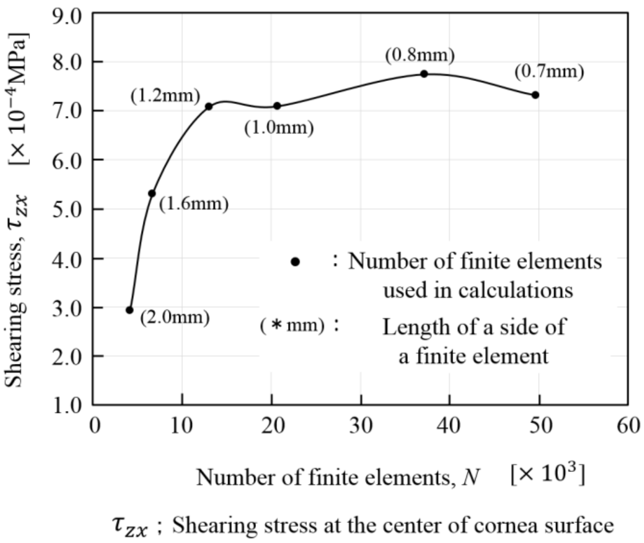

Fig.4. Proper number of finite elements

D. Contact surfaces

The surfaces where the cornea is in contact with the conjunctiva were connected rigidly. The surfaces where the tarsus, the levator palpebrae muscle and the orbicularius ocuil muscle contact each other were also connected rigidly.

The dynamic friction coefficient of the contact surface between the ocular surface and the eyelid was set to 0.1. The value of 0.1 was decided referring to the previous research by the authors [9].

E. Enforced displacements

A blink was reproduced by making the levator palpebrae muscle move in the *x* direction by a forced displacement. The values of 2, 5, 11, 15 and 20[mm] were used as the forced displacements.

F. Analysis type

The linear static analysis dealing with a contact problem was carried out.

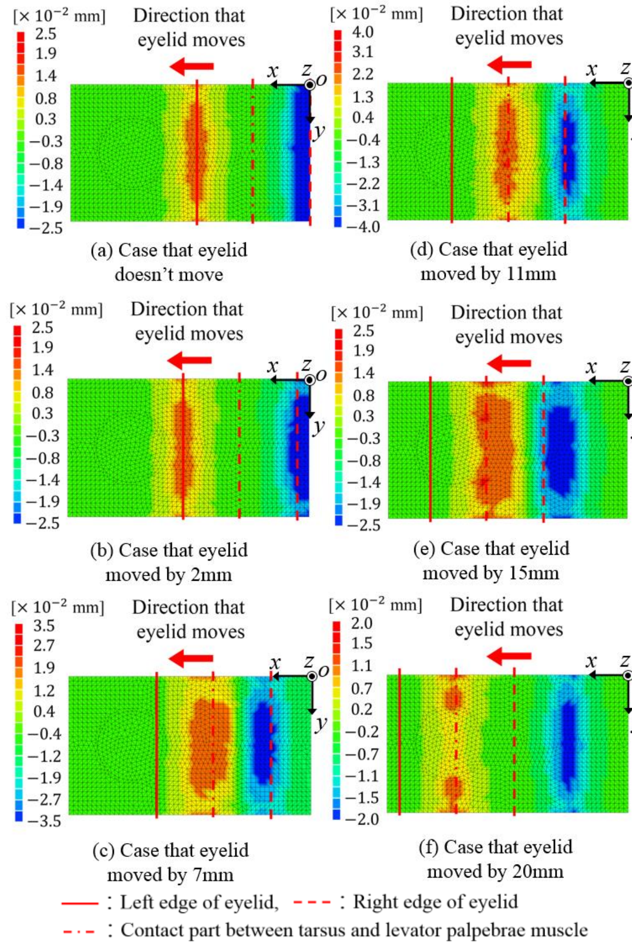

Fig. 5. Deformations in *x*-direction in ocular surface

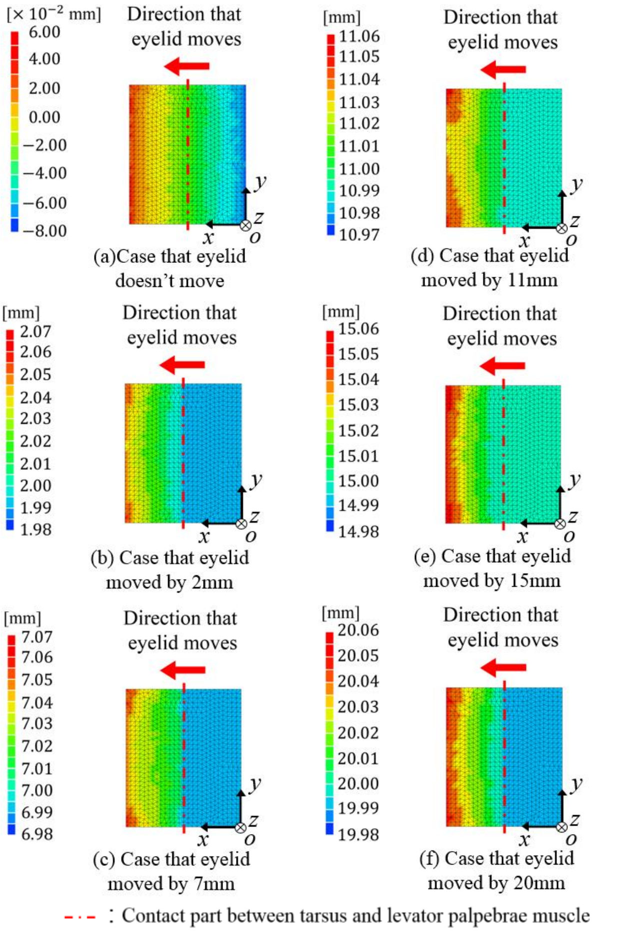

Fig. 6. Deformations in *x*-direction in eyelid

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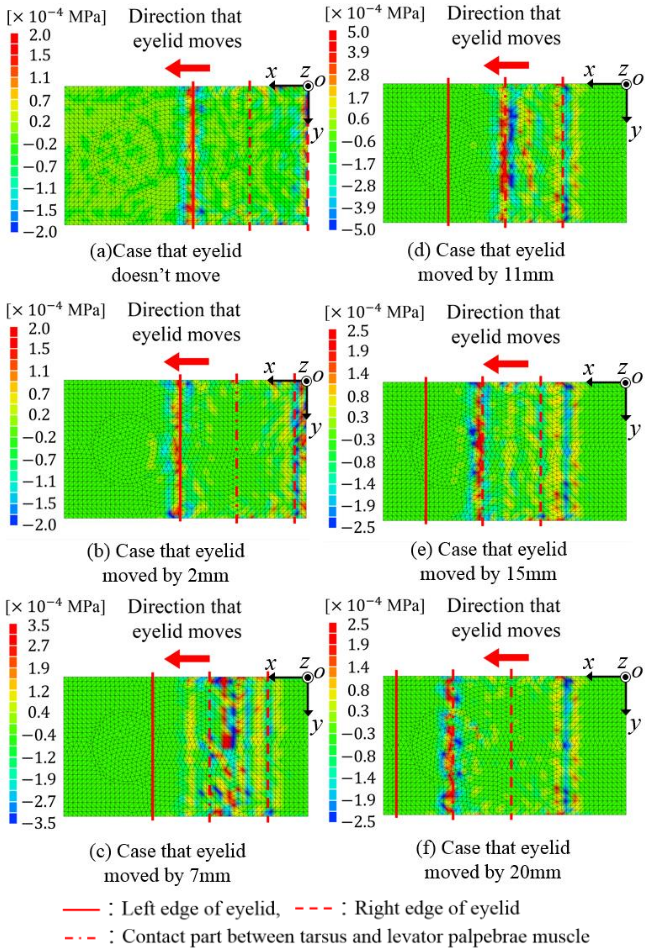

Fig. 7. Shearing stresses, τ_{zx} in ocular surface

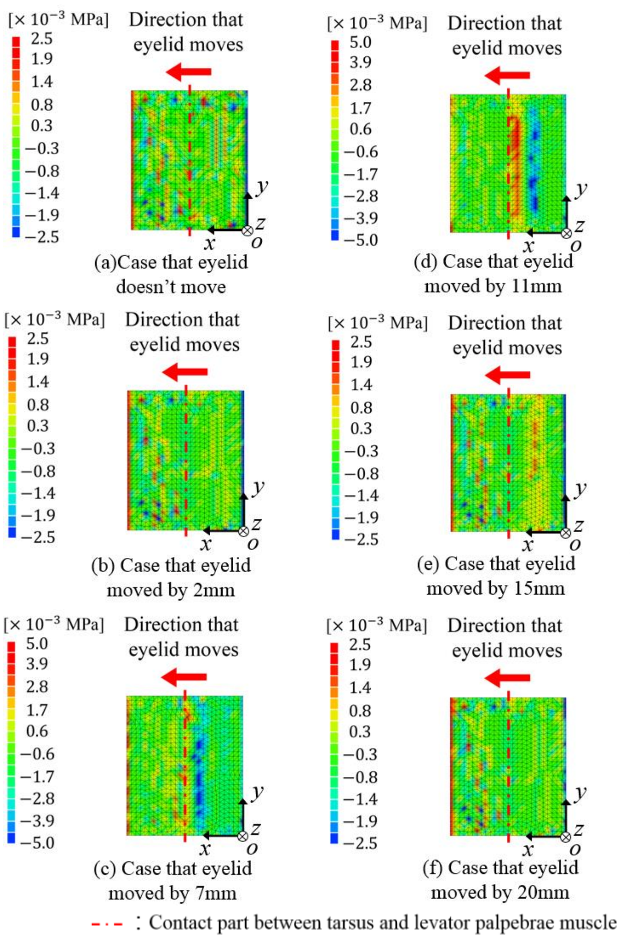

Fig. 8. Shearing stresses, τ_{zx} in surface of eyelid

G. *Calculated results*

Figure 4 shows the results to examine proper number of finite elements. The results of Fig. 4 are those when the levator palpebrae muscle is moved by 20 [mm]. It can be found that the shearing stresses, τ_{zx} hardly change when the length of a side of the finite element is 0.8 [mm] or more from Fig. 4. Therefore, the values of 0.8 [mm] was used as the length of a side of the finite element in the following calculations.

Figure 5 shows the calculated results on deformations in *x*-direction in the ocular surface. The result that the eyelid moved by 20mm in Fig. 5 shows that the deformations of the conjuctiva are larger than those of the cornea. The parts where the friction causes large deformations will get injured easily. Therefore, a conjunctivitis like SLK may occur due to the friction.

Figure 6 shows the calculated results on deformations in *x*-direction in the eyelid. Large deformations generate in the left side of eyelid. A lesion like LWE may also cause due to the large frictional force.

Figure 7 shows the calculated results that is the shearing stresses, τ_{zx} in the ocular surface. It can be seen that the large shearing stress, τ_{zx} generated at the left edge of the eyelid until the eyelid moved by 2 [mm]. It can be seen that the large shearing stress, τ_{zx} generated at the boundary between the tarsus and the levator palpebrae muscle when the eyelid moved more than 7 [mm], namely the eyelid began to move through the cornea. It shows that the large frictional force occurs at the boundary between the tarsus and the levator palpebrae muscle when the eyelid moves through the cornea.

Figure 8 shows the calculated results on shearing stresses, τ_{zx} in the surface of the eyelid. It can be seen that the large ~~a~~ shearing stress, τ_{zx} generated at the left edge of the eyelid. A lesion like LWE may also cause due to the large frictional force.

IV. CONCLUSION

The FEA was carried out in order to clarify a mechanism of the friction developing on an ocular surface and an eyelid's one during blink. As the calculated results, the deformations and the shearing stresses on their surfaces during blink were shown.

The results are summarized as follows.

(1) The large deformations generated on the conjunctiva rather than the cornea during blink. The large shearing stresses also generated at the edge of the eyelid until the eyelid reached the cornea durling blink. Then, after the eyelid reached the cornea, the large shearing stresses generated on the ocular surface on the boundary between the tarsus and the levator palpebrae muscle. In this situation, the conjunctiva may be damaged because the parts where the large deformations generate must be injured. It is thought that SLK developes due to the mechanism described above.

(2) The large deformations and shearing stresses gennerated at the edge of the eyelid during blink. The edge of the eyelid may be damaged because the parts where the large deformations and shearing stresses gennerate must be injured. It is thought that LWE developes due to the mechanism described above.

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Appendix

Figure a-1 shows the Lid-wiper epitheliopathy (LWE) that is defined as an epitheliopathy of a portion of the marginal conjunctiva of the upper and lower eyelid. It has been suggested that high shear stress at the lid-wiper region of the eyelid may be the cause of LWE. Figure a-1 shows the lissamine green staining of LWE.

Figure a-2 shows the Superior limbic keratoconjunctivitis (SLK) that is a chronic and recurrent inflammatory disease of the upper palpebral, upper bulbar and superior limbic conjunctiva. It has been suggested that the chronic inflammation due to high shear stress between bulbar conjunctiva and upper tarsus during blinking may be the cause of SLK. Figure a-2 shows the rose bengal staining of SLK.

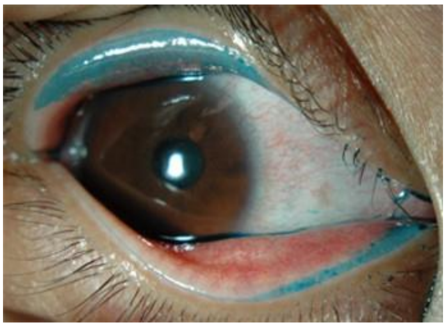

Fig. a-1 Lid Wiper Epitheliopathy (LWE)

Fig. a-2 Superior Limbic Keratocomjuntivitis (SLK)

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