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Examination of tear film smoothness on corneae after refractive surgeries using a noninvasive interferometric method

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Abstract. A lateral shearing interferometer was used to examine the smoothness of the tear film. The information about the distribution and stability of the precorneal tear film is carried out by the wavefront reflected from the surface of tears and coded in interference fringes. Smooth and regular fringes indicate a smooth tear film surface. On corneae after laser *in situ* keratomileusis (LASIK) or radial keratotomy (RK) surgery, the interference fringes are seldom regular. The fringes are bent on bright lines, which are interpreted as tear film breakups. The high-intensity pattern seems to appear in similar location on the corneal surface after refractive surgery. Our purpose was to extract information about the pattern existing under the interference fringes and calculate its shape reproducibility over time and following eye blinks. A low-pass filter was applied and correlation coefficient was calculated to compare a selected fragment of the template image to each of the following frames in the recorded sequence. High values of the correlation coefficient suggest that irregularities of the corneal epithelium might influence tear film instability and that tear film breakup may be associated with local irregularities of the corneal topography created after the LASIK and RK surgeries. [DOI: 10.1117/1.3275850]

Keywords: tear film; tear film breakup; laser *in situ* keratomileusis surgery; radial keratotomy surgery; interferometry; low-pass filter.

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1 Introduction

The popularity of refractive surgery has grown exponentially over the past several years. Procedures, such as laser *in situ* keratomileusis (LASIK) or radial keratotomy (RK), permanently reshape the corneal curvature in order to reduce the overall refractive error of the eye. In LASIK, a thin flap of the corneal epithelium is cut, and the underlying corneal tissue is adequately reshaped by the excimer laser. The flap is then repositioned and adheres.[1,2] In RK, on the other hand, a number of radial incisions are made to flatten the central cornea. Nowadays, this procedure has become obsolete due to many postoperative complications and has been replaced by photorefractive keratectomy (PRK).

It is well known that refractive surgeries can cause dry eye symptoms—unstable tear film, which is associated with morphological and physiological changes in ocular surface and the tear function.[3,4] The tear film is responsible for the ocular lubrication. Optically, its function is to form a smooth and regular surface over the irregular corneal epithelium.[5] With every blink, the eyelid movement distributes a new portion of tears and builds up an optical surface on the cornea. Stability of this surface can be examined with noninvasive methods such as high-speed videokeratoscopy,[6–8] dynamic aberrometry,[9–13] and interferometry.[14–16]

Postoperative dry eye syndrome is caused by a number of factors. After LASIK, corneal sensation could be decreased if significant damage to nerves occurred during creation of the corneal flap.[17–19] The reduction of corneal sensitivity may result in loss of a reflex tear response, decrease of the tear secretion,[4,20,21] as well as in changes in blink dynamics.[22] Patel et al.[18] showed that the lipid layer is thinner after LASIK and hence it may predispose to symptoms of dry eye.

Changes in central corneal topography can be a factor for tear film instability observed after refractive surgery. The flattened corneal surface may worsen its interaction with eyelids and may alter surface tension.[18,23] In some corneae, central islands are formed—the local convexities of the corneal surface.[3] Macrofolds can be easily seen by slit-lamp examination,[24,25] while confocal microscopy reveals microfolds at the Bowman's layer.[26] Studies on vision quality after refractive surgery have shown that some folds may adversely affect vision, while others with similar appearance may be asymptomatic.[3]

We applied a lateral shearing interferometer (LSI), pro-

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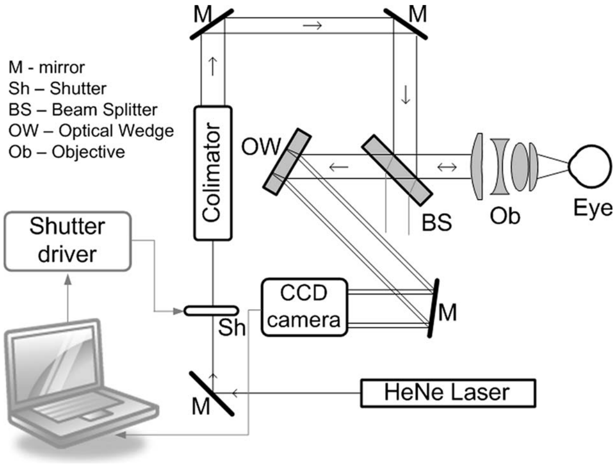

Fig. 1 Scheme of the lateral shearing interferometer.

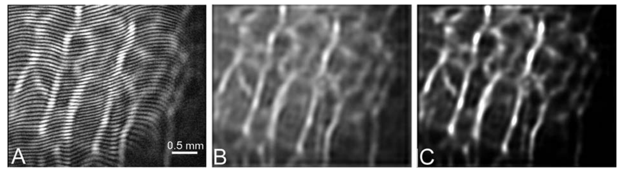

Fig. 2 Procedure of visualization of the fringes' background. (a) The interferogram, (b) the frame after filtering of the first- and higher-order Fourier spectra, and (c) the frame after applying the square procedure of element of matrix after filtration.

posed by Licznerski et al.,[27] for *in vivo* noninvasive measurement of the tear film kinetics. Our measurements on about 100 subjects with different corneal conditions clearly indicated that the recorded interferograms do not present regular fringes on dry eyes and corneae after refractive surgery, while on normal, healthy eyes, the irregular fringes observed immediately after the eye blink become more regular with time.[16,28,29] Tear film breakups appear as high-intensity patterns (bright lines) in the background of the interferogram. The interference fringes are irregular then, and they change their orientation on the bright lines. In the case of dry eye subjects, the bright lines appear semirandomly. However, in the case of postsurgical corneae, such structures were observed to appear periodically.

The aim of this work was to numerically analyze the shape of this background pattern to verify its repeatability in time and to ascertain whether tear film breakups in post LASIK and RK subjects can be associated with the local irregularities of the corneal topography. This paper is our primary description of the interesting phenomena observed on corneae after refractive surgery.

2 Subjects and Instrumentation

The authors have measured five subjects, aged between 21 and 32, after myopic LASIK surgery from which three suffered from dry eye syndrome after the surgery while the remaining two were satisfied with the effect of surgery and did not feel any ailments. We measured also a 55-year-old man after RK surgery, which was carried out twice by Prof. Fiodorov, 20 and 22 years and ago. This subject's visual acuity had been gradually improving over the years. Only the right eye of each subject was used for the quantitative analysis.

The measurements were performed at Sahlgren's University Hospital in Mölndal, Sweden, and in the laboratory of the Visual Optics Group at the Wroclaw University of Technology in Wroclaw, Poland. All subjects gave informed consent for the study.

The LSI scheme with the schematic ray tracing is presented in Fig. 1. The operational principle has been described in detail in our previous papers.[16,30] The shape of the wavefront reflected from the central area of the cornea (approximately 4 mm in diameter) carries information about regularity of the tear film surface. With the optical wedge (OW), two coherent wavefronts are received, and the effect of their interference is recorded by the CCD camera with the frequency of 25 fps and stored on the computer.

3 Method of Analysis

The size of the recorded images is $M \times N = 352 \times 288$ pixels. In order to analyze the high-intensity pattern in the background of the interferogram [Fig. 2(a)], the image is first represented in the frequency domain by calculating the fast Fourier transform. In the Fourier domain of an image, each point represents a particular frequency contained in the spatial domain image. The information about the background is contained in lower frequencies. By applying the low-pass filter with cutoff normalized frequency of 0.135, the higher frequencies are covered, and only the surrounding of the zeroth harmonic of the spectrum is left. In the next step of the numerical procedure, the inverse fast Fourier transform is calculated, and the image as shown in Fig. 2(b) is received. To enhance the contrast of such a grayscale image, each pixel is raised to a power, after which the new image is normalized [Fig. 2(c)]. This procedure results in better diversification of batches of higher intensity.

When recording a sequence of interferograms after a blink, the area of cornea covered by the overall interferogram frame changes slightly with time due to naturally occurring eye movements. The aim is first to locate corresponding subareas in successive frames and, second, to explore their changes with time. An early frame from the sequence is chosen as a template frame, and a subimage $A(m,n)$ containing $m \times n$ pixels is selected from this for analysis (Fig. 3, left). The

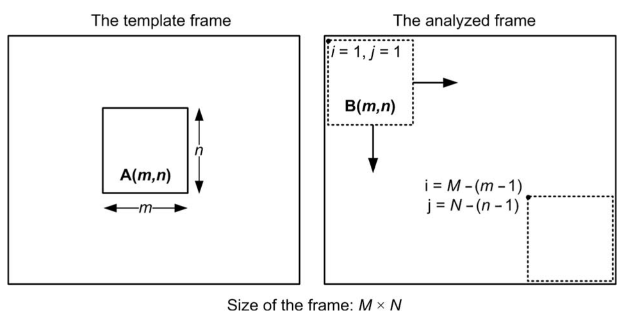

Fig. 3 Procedure for calculating the correlation coefficient of the subimage A of the template frame and the subimage B of the analyzed frame.

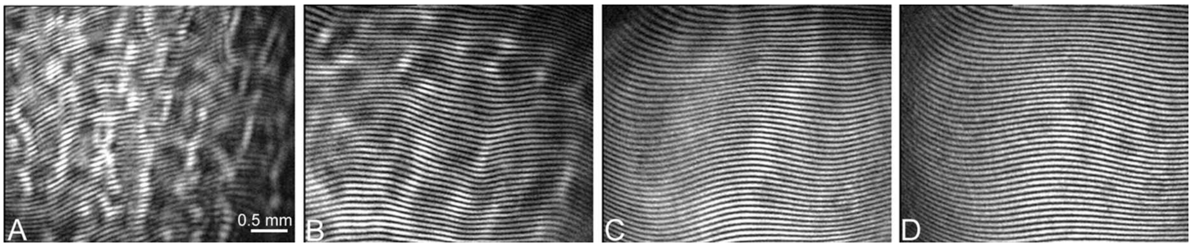

Fig. 4 Sequence of interferograms of the tear film recorded on a normal eye: (a) 0.08, (b) 0.60, (c) 2.88, and (d) 19.60 s after blink.

correlation between this subimage and a set of subimages $B_{i,j}(m,n)$ from the analyzed successive frame is then calculated as

$$corr(i,j) = \frac{\sum_m \sum_n [A(m,n) - \bar{A}][B_{i,j}(m,n) - \bar{B}_{i,j}]}{\left(\left\{ \sum_m \sum_n [A(m,n) - \bar{A}] \right\}^2 \times \left\{ \sum_m \sum_n [B_{i,j}(m,n) - \bar{B}_{i,j}] \right\}^2 \right)^{1/2}}, \quad (1)$$

where $A(m,n)$ is the subimage of size $m \times n$ from the template frame, and (i,j) are the coordinates of the pixel of the subimage $B(m,n)$, where $1 \leqslant i \leqslant M-(m-1)$ and $1 \leqslant j \leqslant N-(n-1)$, $\bar{A}$ is the average intensity value of the pixels in the subimage A, and $\bar{B}$ is the average intensity value of the pixels in the subimage B.

Starting from the top-left corner of the analyzed image, a sliding window $A(m,n)$ moves horizontally and vertically through all the rows and columns of the image until the bottom-right corner is reached. The correlation coefficient *corr* is calculated between the subimage $A(m,n)$ (Fig. 3—continuous frame) and every subimage B of the analyzed frame (Fig. 3—dotted frame). The highest value of the coefficient—max(*corr*)—denotes the region in the analyzed image with the most similar pattern to the template structure. Maximal values of coefficient *corr* in consecutive frames of recorded sequence describe changes in similarity of the pattern in time.

4 Results

Normally, after a blink, one can observe the stabilization of the tear film—i.e., some dark and high-intensity pattern is seen in the background of the interferogram. On healthy, normal corneae, the tear film becomes smooth after a few seconds—builds up—and the tear film surface is very often stable and smooth to the end of the recording.[30,31] After about 1 to 2 s, regular and nearly parallel fringes on homogeneous background can be observed, as shown in Fig. 4.

The sequence of interferograms in Fig. 5 presents an example of the LSI measurement for the cornea after RK surgery. Although the surgery was carried out more than two decades ago, the tear film does not create a smooth layer over the cornea. In all images, two high-intensity spots are seen, from which high-intensity lines spread out. A similar result was observed after every eye blink and in images registered on the other eye, on which the surgery was also performed. Note that due to the principle of lateral shearing interferometry, images are horizontally doubled, forming apparently two similar structures.

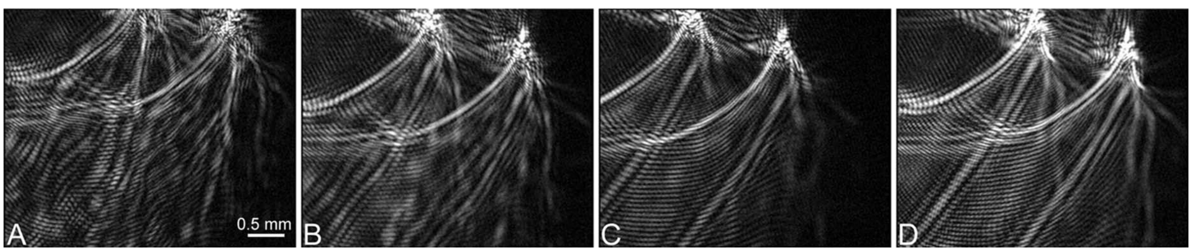

Fig. 5 Sequence of interferograms of the tear film recorded on the cornea after RK surgery: (a) 0.32, (b) 2.88, (c) 6.60, and (d) 10.00 s after blink.

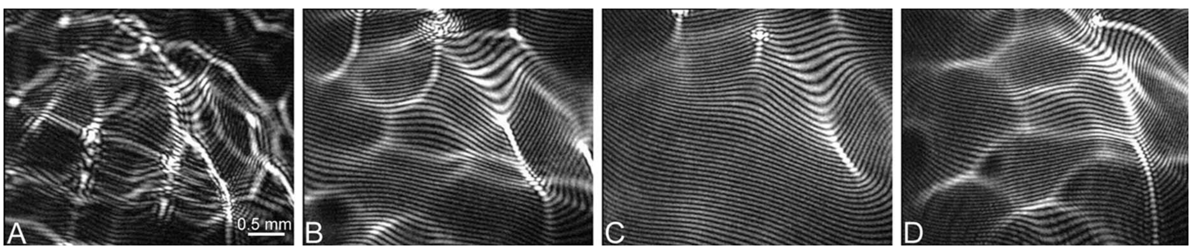

Fig. 6 Sequence of interferograms of the tear film recorded on the cornea after LASIK surgery: (a) 0.40, (b) 3.0, (c) 7.20, and (d) 14.08 s after blink.

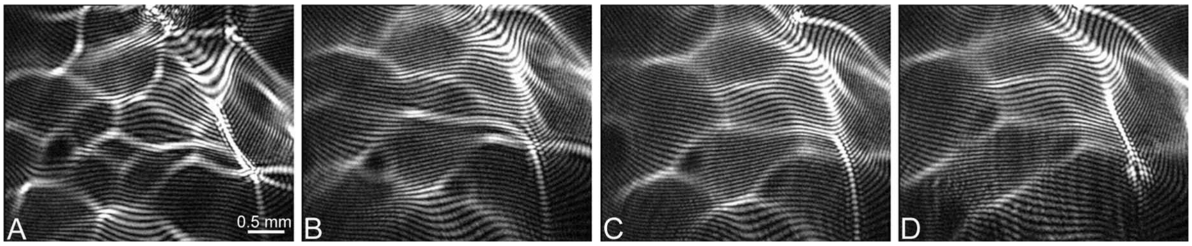

Fig. 7 Changes of smoothness of the tear film surface on the cornea after LASIK surgery. Frames recorded (a) 2.00, (b) 13.00, (c) 14.08, and (d) 17.80 s after blink.

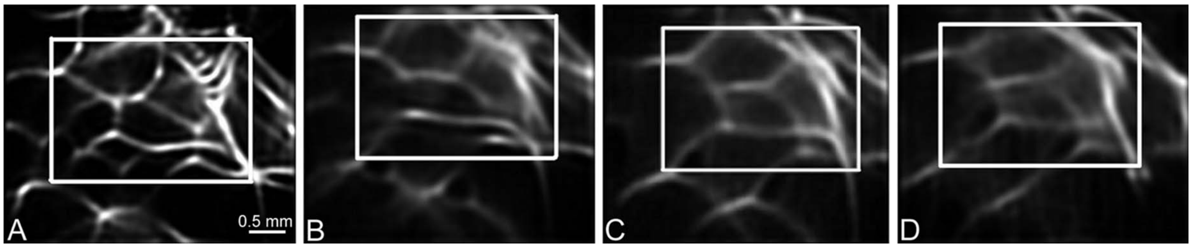

Fig. 8 Sequence of frames from Fig. 7 after low-pass filtering with marked fragment showing the best matching.

In the case of corneae after LASIK surgery, the tear film also creates a relatively smooth surface over an irregular corneal epithelium during the buildup process. However, after a while, a high-intensity pattern appears and disturbs the regularity of the interference fringes (Fig. 6). The example of sequences presented in Figs. 6 and 7 were recorded for a subject who was suffering from dry eye syndrome after the LASIK surgery. The surgery was carried out 3 months before the examination of tear film stability. In none of our examinations was the subject's tear film surface as smooth as in the interferograms acquired from normal subjects. We noted that the smoothness of the tear film was disturbed during the whole recorded sequence. However, a few moments can be distinguished when the bright pattern under the interference fringes disappears and appears again. This pattern fluctuation appeared to be characteristic for the tear film on corneae after LASIK surgery.

In Fig. 7, selected frames from the sequence with well-visible high-intensity pattern are presented. The same frames after low-pass filtering are shown in Fig. 8. They present the nonuniform intensity of the background of the given frame. In this case, the rectangular subimage of size 240×170 pixels including the characteristic pattern was selected for comparison and marked by the white rectangle in the figure. The template frame was recorded 2 s after a blink [Fig. 8(a)].

Next, the similarity of the appearing pattern was calculated for the following frames from the sequence, according to the procedure described earlier. The best fitted fragments, which have the highest value of the correlation coefficient, are marked by a white rectangle [Figs. 8(b)–8(d)]. The coefficient *corr* for the example frames is 0.66, 0.68, and 0.64, respectively. The values of *corr* coefficient for this sequence are presented in Fig. 9. High value of the maximum of *corr* coefficient indicates high correlation between the analyzed patterns.

The chosen template fragment from the first sequence [Fig. 8(a)] was compared also to the frames from the sequence recorded after the next eye blink (Fig. 10). For the best matched fragment of the frame in the presented example [Fig. 10(b)] the calculated *corr* coefficient is equal to 0.76.

The diagram in Fig. 9 shows the numerical results of the comparison for two sequences recorded on the same eye. The calculation was done only for the frames with a well-visible pattern, which appeared in entirety. Note that some frames may not contain the entire pattern because of natural eye movements. Figure 9 shows that the underlying low spatial frequency pattern in the interferograms remains remarkably stable with time after a blink and between successive blinks, suggesting that the underlying epithelium and cornea might have significant influence on the regularity of the tear layer surface.

5 Discussion

The disturbance of the regularity of interference fringes varies across subjects. In normal eyes, the irregular fringes run through the bright stripes, and in eyes after refractive surgeries, the regular interference fringes band on the bright stripes and change their orientation. We interpret the local discontinuity of fringes as a tear film breakup—the local discontinuity of the tear film layer.

One of the anatomic complications after LASIK surgery is the appearance of flap folds.[3,24] They can be observed in confocal microscopy as wrinkles in Bowman's layer or in the epithelial basement membrane. It is likely that the tear film is too thin to fill the unevenness of the cornea after LASIK to create a smooth layer of tears. The folds might be too high and become uncovered because of the evaporation. The folds are usually present in the central area of cornea, and this was observed in our measurements. The relatively high values of *corr* coefficient for compared frames in the case of LASIK subjects suggest that some high-intensity patterns are permanent. Their shape is repeatable in different interblink intervals. This permanent similarity of the high-intensity pattern after

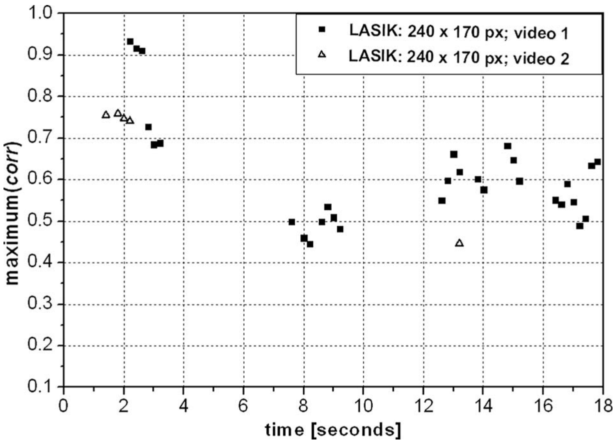

Fig. 9 Value of the *corr* coefficient as a result of comparing every subsequent frame with the selected part of a chosen frame recorded for a LASIK eye. Squares: first sequence; triangles: the sequence after next blink. All frames are compared to the frame recorded 0.44 s after blink [Fig. 8(a)].

sufficiently long time after blink and even after next blinks suggests that it could be associated with the local corneal topography. The change of direction of interference fringes on the high-intensity pattern in the background of interferograms means that the tear film surface is uneven. The irregularities of the corneal epithelium after LASIK and RK surgeries have some influence on the rise of breakups of the tear film between blinks.

The *corr* coefficient calculated for the normal corneae revealed that the similarity of the bright structure decreases in time with the stabilization process of the tear film surface after blink.[29] Also, by comparing the sequences of images recorded on the same cornea but after the next blink,[29] it can be noticed that the shape and location of the high-intensity pattern differs from other sequences. The only common features are the semivertically oriented bright lines, indicating that the observed pattern is likely to be related to movements of the upper eyelid wiper. The bright lines are reversed tilts for right and left eyes, which suggests the temporal direction of the upper eyelid movement.[31]

The pattern in the interferograms recorded on normal corneae immediately after the blink appears to be similar in form to the corneal mosaic observed by Bron on a dried cornea.[32,33] However, its relationship to that mosaic has not been ascertained. We suggest, however, that the corneal mosaic might have an influence on tear film instability in the case of corneae after LASIK and RK surgeries.

In most cases, the cause of dry eye can be related to the disturbance of corneal structural integrity and secretion of tears. The proposed analysis revealed that the irregularities of the corneal epithelium, arisen as a consequence of the surgery, might also influence tear film stability.

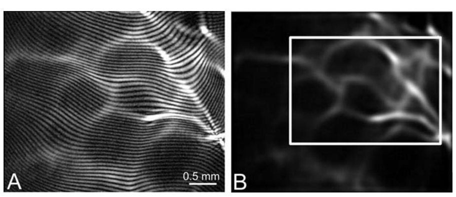

Fig. 10 Chosen frame from another sequence registered on the same cornea after next blink. (a) Interferogram registered 1.40 s after blink, and (b) the frame after low-pass filtering with marked fragment showing the best matching.

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