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Feasibility Study of Smartphone-Based Tear Volume Measurement System

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Abstract

Evaluation of tear volume is important for diagnosing dry eye disease. At the clinical site, dedicated devices such as slit lamp microscopy or Schirmer's test strip have been used to quantify tear volume by ophthalmologist. However, these devices have access only in medical office and therefore have limited availability for the public. Tear volume changes with environmental, physical or psychological situation. For that reason, measurement of tear volume regardless of location, time or circumstances can be beneficial. In this study, a tear volume measurement system based on the principle of meniscometry was developed and implemented on the smartphone, and its feasibility was evaluated. It was shown that tear meniscus radii of 22 human subjects were calculated to be mean 0.31 (SD 0.06) mm which was within the range of the previous study. The results suggested the feasibility of tear volume measurement system using the smartphone based on the principle of meniscometry as an IoT sensor.

Keywords: Smartphone, Tear volume, Dry eye, IoT device

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1. Introduction

The number of dry eye patients is increasing due to excessive use of visual display terminals (VDT), such as smartphones and personal computers [1]. Although evaluation of tear volume is indispensable for dry eye diagnosis, precise measurement is difficult because of the tiny amount and transparency of tears. It is known that tear volume is affected by environmental, physical and psychological situations, such as humidity, wearing contact lenses, being engaged in VDT work and having mental stress [2,3]. At the clinical site, tear evaluation is usually performed by either schirmer's test or tear breakup time (BUT) measurement. Shirmer's test places filter paper inside lower eyelid [4]. BUT measurement requires fluorescence instillation [5]. Therefore both measurements are invasive, i.e., with stimulus, which is not a desired condition for the dry eye evaluation.

Non-invasive meniscometer has been developed for measuring tear meniscus radius (TMR), which reflects tear volume [6,7]. However, the device has been used only in medical office and therefore has limited availability for the public. If eye condition could be self-checked outside medical office, this would also help the prevention of dry eye. Tear volume measurement system using the smartphone could be utilized as an IoT sensor for healthcare applications. In our former work, feasibility

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study of measuring TMR using both the smartphone and the tablet PC was conducted [8].

The objective of this study was to assess the feasibility of the tear volume measurement system using the smartphone based on principle of meniscometry. The organization of this paper is as follows. Some related works are investigated in Section 2. A conventional method is reviewed, and followed by the design of the prototype in section 3. In section 4, calibration of proposed method was performed by measuring known radii of glass capillaries (4.1). TMRs of 22 subjects were measured in order to investigate whether the proposed system can be applicable to human subjects (4.2). Finally, tear meniscus height (TMH) were measured by conventional method to validate TMR calculated by the proposed system. These results are discussed in section 5. Finally, the summary of the article and the future perspective are proposed in section 6.

2. Related Work

TMR measurement using the smartphone as a projector and the slit lamp microscope as a detector has been reported [9,10]. In the report, multiple lines displayed on the smartphone screen were reflected on the surface of tear meniscus (TM), and a reflected image through the slit lamp microscope was captured using a camera. TMR was calculated by applying concave mirror formula that used the line width reflected on the surface of TM based on previous study of reflective meniscometry [6]. However, this method needed the slit lamp microscope which is used generally in the medical office. Hence this method is not suitable for the personal use as an IoT sensor.

At present, some smartphone applications that can check the possibility of dry eye disease are available [11,12]. For example, some smartphone applications include the evaluation of subjective symptoms called Ocular Surface Disease Index (OSDI) questionnaire [13]. Other applications use the smartphone camera and measure visual function [14] or interblink interval [15] that are associated with severity of dry eye. However, these applications cannot evaluate tears directly. In order to discuss the pathology of dry eye, direct measurement of tears is indispensable, although the measurement is difficult using a conventional camera due to the intrinsic nature of tears; its transparency and tiny amount. So far, there has been no report yet, which evaluated tears directly using the smartphone camera. Moreover, there is no such system that allows self-checking of tears.

Measurement System

3.1. Principle of meniscometry

TM is a thin strip of tear fluid with concave outer surfaces at the upper and lower lid margins and contains approximately 75-90% of the overall tear volume [16]. In meniscometer, parallel black and white lines are projected horizontally to the concave surface of lower TM and reflected image from TM is captured. Then, TMR r is calculated by concave mirror formula (1) using projected line width t and measured line width i from detected image as shown in Fig.1 [6].

$$r = 2\,W\,(i / t) \tag{1}$$

Here W, i, and t are working distance between camera and TM surface, measured line width vertically against TM, and projected line width to TM, respectively.

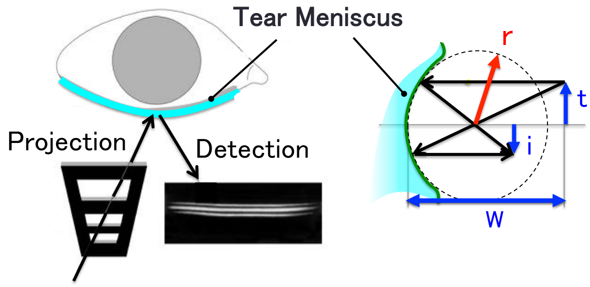

Figure 1. Diagram of meniscometry, edited image of [6].

3.2. Instrument development

To apply this principle to smartphones, studies have been conducted using the front camera as an image detector and the screen as a projector [17]. In order to improve measurement accuracy, the built-in flashlight of the device was used as a projector and the rear camera was used as an image detector in this study. The flashlight was projected to TM via three thin slit holes as in the conventional meniscometer. The rear camera was expected to provide greater accuracy than the front camera because it usually has much higher resolution. Moreover, the rear camera commonly has the auto-focus function that is also a great help for the measurement. Macro lens was placed to capture magnified image of lower lid margin. A positioning attachment was made using a 3D printer in order to keep the fixed distance from TM. This attachment also worked as a black cover that minimized the influence of ambient light. This attachment was fixed with adhesive bond to the half-cut smartphone case that could easily be detached from the smartphone. The specification of the system included auto measurement algorithm of TMR and data upload to the internet sever. Following these features, a prototype of the smartphone-based meniscometer “Meniscope” was developed.

First, the detection system used a macro lens (Focal length 24mm, #32-011, Edmund optics) attached to the rear camera of the iPhone 6s Plus (Apple, Inc.). As the projecting system, a shielding plate with three slit apertures was placed in front of the LED flashlight. Slit aperture width and length were 1 mm and 17 mm, respectively. The interval between the slits was 4 mm. In order to equalize the amount of light from each slit, a light diffusing plate (20 × 20 × 2 mm, SW-12, Nikon) was placed between the LED flashlight and the slit plate. Schematic diagram and appearance of the system are shown in Fig.2 and Fig.3. The working distance W was 24mm, and the target width t was 4mm. When taking pictures, digital zoom was set to the maximum. Luminance of LED flashlight was set to the minimum. The size of the obtained image was 4032 x 3024 pixels. From the measurement of the ruler, 1 mm / pixels was 0.0013055. Taking a photo was designed to be at the moment of releasing the shutter button in order for the user to avoid the device shake.

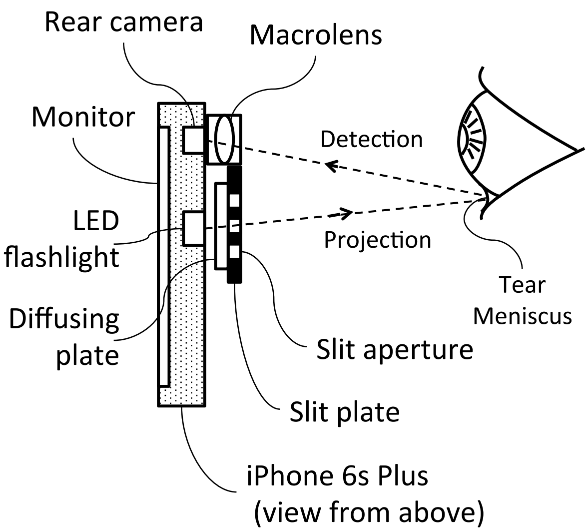

Figure 2. Diagram of the proposed system.

Figure 3. Front view of the proposed system.

The measurement values calculated in the proposed system were calibrated by cutting glass capillaries of known size in half in the longitudinal direction and by measuring radii of curvature of the exposed inner surfaces. According to a previous research, TMR values of dry eye patients were 0.17 - 0.314 mm, and that of healthy subjects 0.3 - 0.545 mm. For this reason, glass capillaries with five different radii of curvature within these ranges were used (0.15, 0.23, 0.32, 0.43, 0.60 mm, IntraMARK, BLAUBRAND). Among three lines reflected on inner surface of the glass capillaries, the vertical width of middle line was measured with Image-J software (Ver. 1.48).

The flow chart of the semi-automatic measurement algorithm is shown in Fig.4. When the captured image is magnified, the boundaries of the three lines shown on TM become blurred. Therefore, the system focuses on the maximum and the minimum peaks of brightness in the vertical direction of the area where three lines on TM, and automatically calculates TMR. First, the captured image was read in the application software. Then, the area where three lines clearly appear in TM (usually in the middle in the horizontal direction of lower eyelid margin) was pinched out, i.e., magnified, on the screen of the smartphone manually. Next, the area for the measurement was placed manually so that the three lines enter green vertical line drawn at the centre of the display.

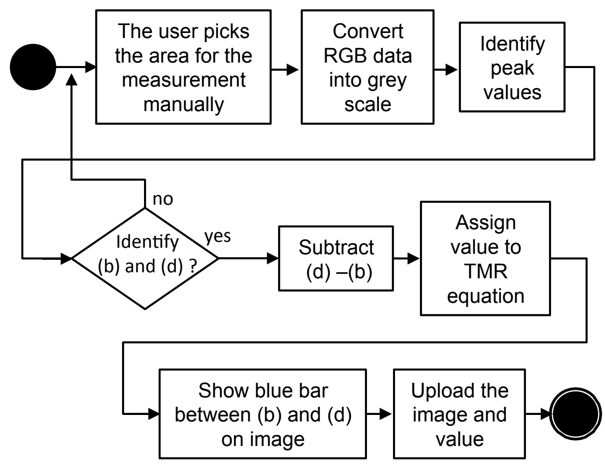

Figure 4. The flow chart of the semi-automatic measurement algorithm.

In the automatic calculation step, the RGB data were converted into grey scale. Next, the peak positions ((a), (b), (c), (d), (e)) of the brightness mountains and valleys were specified. The relationship between the three lines on the TM and the peak position is shown in Fig, 5. After that, the interval between the peaks of two valleys ((b) and (d)) was measured in the number of pixels, which was used in the formula of concave mirror to calculate TMR. The application drew the blue vertical line at the position between the measured two points in order to check if the calculation was conducted correctly. If the blue line was displayed at the position to be measured, image and measurement result were uploaded to the Internet server. If the blue line was displayed in the wrong place with a misrecognition of the peaks, the user was asked to reposition the TM area of interest. This process was repeated until the blue line appeared at a suitable position.

A schematic diagram of TMR calculation process after capturing image is shown in Fig.6.

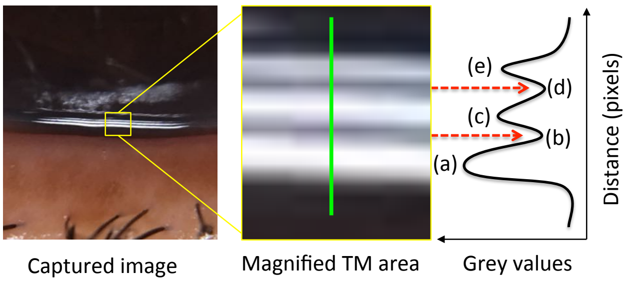

Figure 5. The relationship between the three lines on the TM and the peak position in the graph.

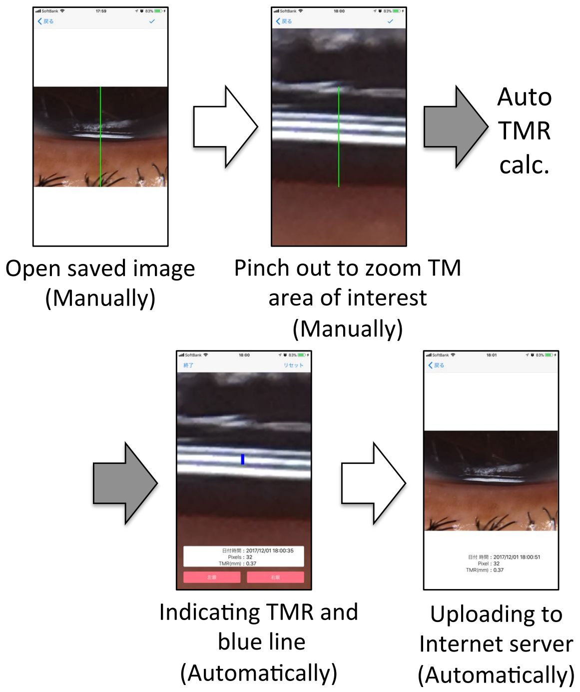

Figure 6. A schematic diagram of TMR calculation process after capturing image.

4. Preliminary study

4.1. Measurement of glass capillary for calibration

Fig.7 shows the relationship between the radii calculated by applying the measured values to the theoretical equation and the actual curvature radii of the inner surface of glass capillaries. Regression lines with high correlation ($y=0.77x + 0.18$, $R^2=0.99$) were obtained. Calibration was performed using this equation about TMR at the following part of this study.

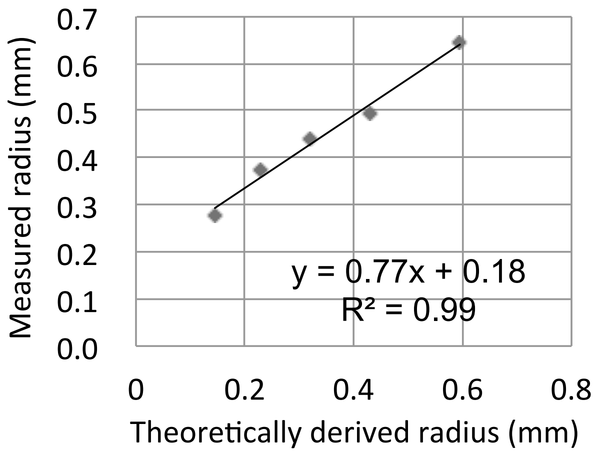

Figure 7. Relation between measured and theoretically derived radius of curvature of an individual glass capillary.

4.2. Measurement of TMR values of 22 human subjects

In order to investigate whether this method can be applied to human subjects, TMR values of 22 subjects were measured. In this experiment, the subjects excluded those who had a diagnosis of dry eye, surgical experience of the eye, or wore contact lens daily. The subjects were asked to put their jaws on the jaw stand in order to increase the stability and accuracy of the measurement. Then the examiner held smartphone horizontally with both hands, put the device close to the right eye of the subjects, adjusted the device position so that their eye was fully captured by the attached lens, and took a picture.

The pictures of lower eyelid margin of the right eye were taken after a few blinks. The experiment was conducted at the room temperature. There were 13 male and 9 female subjects, and their average age was 33.8 (SD 14.0) years. This test was conducted with the approval of Ethics Committee of the University of Tokyo. After photographing, TMR in three neighbouring areas were measured using developed smartphone application, and average values were calculated for each subject.

The average TMR value of the 22 subjects was 0.31 (SD 0.06) mm. Typical examples of the measured images are shown in Fig.8, and Fig.9. The three lines on the surface of TM indicate that the flashlight passed through the slit was reflected on TM and were captured by the camera successfully. The blue line displayed indicates that its height in the middle of the three lines was used for the TMR calculation.

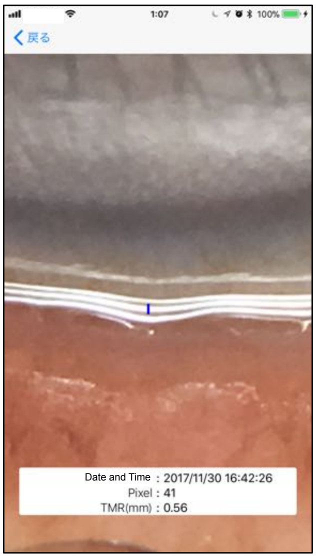

Figure 8. A representative example of smartphone screen after calculating TMR of human subject. Measured date, time, pixels of blue line and TMR were indicated at below.

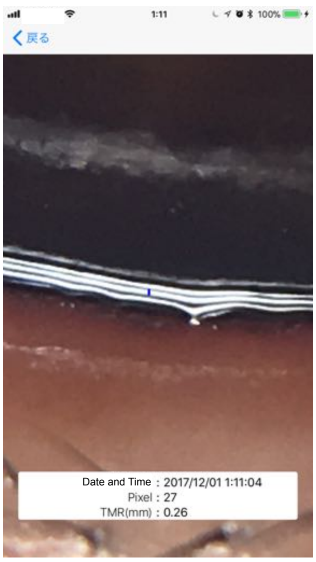

Figure 9. Another example of smartphone screen after calculating TMR of human subject. Measured date, time, pixels of blue line and TMR were indicated at below.

4.3 Comparisons between proposed and conventional method

Comparison between the conventional and proposed methods was conducted in order to verify the obtained result. It is known that TMH, an index of tear volume, correlates with TMR [18]. Therefore TMH was measured by the conventional method that used a slit lamp microscope at a medical office by an ophthalmologist. Four (2 male and 2 female) subjects among the 22 subjects participated in this comparative study. Their tears were stained by fluorescein instillation. One hour after the measurement of TMH, TMR was measured outside the medical office. The TMH measurement was conducted three times for each subject.

As a result, as shown in Table 1, there was a correlation between TMR measured by the proposed method and TMH measured by the conventional method ($R^2 = 0.69$). Since TMH and TMR are different indices, it is impossible to directly compare their numerical values. However, they showed the same tendency about the tear volume for each subject. This supports the obtained result to be reasonable.

Table 1. Measured TMR and TMH values in 4 subjects

	Sex	Age	TMR (mm)	TMH (mm)
1	Male	42	0.17±0.00	0.12±0.03
2	Female	48	0.35±0.04	0.17±0.03
3	Female	72	0.17±0.11	0.13±0.03
4	Male	36	0.36±0.03	0.27±0.03

5. Discussion

The average TMR value for 22 subjects was 0.31 (SD 0.06) mm, which was within the TMR range of normal eyes (0.128 - 0.736 mm; n = 45) measured by the conventional method [6]. This also supports the validity of the results of the proposed system, and indicates the feasibility of a tear volume measurement using the smartphone.

As described in section 4.3, the correlation coefficient R^2 was not so high. A possible reason for this was that reflective tears were secreted by stimulation from fluorescene staining or illumination of microscope when measured at the medical office.

During automatic TMR measurement, location outside of TM area such as skin or cornea sometimes obtained the target blue line mistakenly. The reason for this was that signals other than three lines on the surface of TM were recognized as a peak incorrectly when there were no clear boundaries of three lines due to the influence of head movement, blinking, camera shake, etc. It is necessary to increase the robustness of the automatic measurement algorithm so that the TMR can be reliably measured even with image noise and blur.

Even though subjects fixed their heads by placing their jaws on a jaw stand and the examiner photographed TM on behalf of them, taking a good photo was sometimes difficult. Even a small movement of either the subject or the examiner made it difficult to take a clear picture at a desired position. Then some of the subjects were asked to hold the smartphone and try to adjust focus themselves by watching the monitor reflected on the mirror. This often allowed more stable measurement, which suggests that the tear volume can be self-checked by the user and the system can work an IoT sensor.

6. Summary

In this study, a new tear volume measurement system using the smartphone was proposed based on the principle of meniscometry and its feasibility was evaluated. It was shown that the radii calculated by this proposed system were significantly correlated to the radii of glass capillaries ($r=0.994$, $P<0.001$). The mean value of TMR of 22 human subjects was calculated to be 0.31 (SD 0.06) mm, which was within the range of the previous studies. Moreover, the TMH values measured by the conventional method were correlated to the TMR values measured by the proposed system for 4 subjects ($R^2=0.69$). The result showed the feasibility of tear volume measurement system using the smartphone as an IoT sensor. Future work includes improving robustness of the TMR calculation algorithm and developing a health management system combining the data of the proposed system with other IoT data such as blood pressure, heart rate and so on.

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